High-Level Design of a Hydrogen Fuel Cell Powered Motorcycle.

Draft Report — Documentation
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MIT 2.70 FUNdaMENTALs of Precision Product Design
MIT Department of Mechanical Engineering

Notes. *I always want my work to be open source, we just haven't figured out the details for this project specifically. In the interest of full disclosure, since I've also been working on this for a class in graduate school (MIT 2.70), a refined version of this paper will likely turn into a conference paper of some sort within the next year. I want to clarify that this report specifically is NOT a conference-worthy paper, and even if we do write one for this project I still plan to open-source the design and the process for how I made the bike when we get to actual verification and testing.*

I. Introduction + Design Requirements

Ok so this is a super informal write-up documenting the engineering work done thus-far on the Hydrogen Fuel Cell powered motorcycle project. It'll present the high-level design requirements, how they were determined, and general system-level ideology. This will all trickle-down into more detailed aspects of the design.

I.1.0 High-Level Design Questions. It's likely already clear that we're designing a motorcycle, and further then that the basic functions of such a system are also likely clear. A motorcycle has to go, stop, and turn, and at the end of the day that's really it. But the questions start to become—how much go? How much stop? How much turn? And this is where we get the design requirements from. Now, additional requirements arise in terms of range, and other practicality concerns which we will also address.

Since we're planning to modify an existing bike for this project, the "stop" and the "turn" parts of our design requirements are at least partially fulfilled.

Figure 1—Ducati 900SS track bike we plan to convert to Hydrogen Power for this project.

The bike in question comes with mechanical brakes, and a steering system so our design can focus mostly on the "go" and any other practicality aspects we are interested in.

Past this, is the added question of how we will integrate a hydrogen fuel-cell (HFC) into a motorcycle. Most of the time HFC vehicles use a battery to power an electric motor (which drives the wheels), and the fuel cell charges the battery. But we could just as easily use a really large fuel cell and no battery, and it's interesting to investigate the trade-offs and possibility of these other ideas.

We can break these down into design questions that are presented below.

Design Questions LEVEL I—

- What should the top-speed be?
- What acceleration are we looking to achieve?
- What range are we going for?
- How does the fuel cell integrate with the system? Do we need a battery?

- Do we have regenerative braking, how do we handle regenerative braking?*

**Regenerative braking is a common method to recover energy in vehicles where mechanical brakes are NOT used and a negative torque is sent to the motor to slow the vehicle down. Since the torque is negative but the vehicle motion is still in the forward direction, the motor acts as a generator [2].*

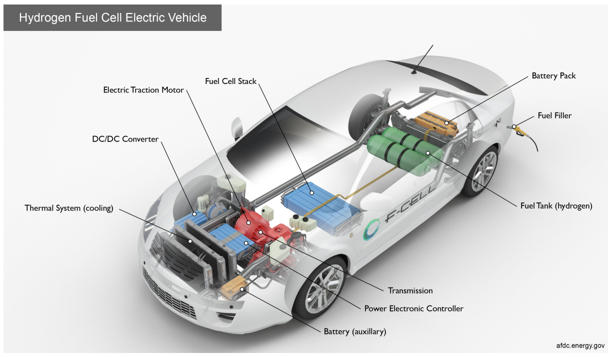


Figure 2—A typical Hydrogen Fuel-Cell Powered Vehicle layout from [1].

These high-level questions let us lay out what the system will look like and do a first-pass on the feasibility of the system.

I.1.1 Design Requirements. We start by estimating the performance we want from the bike and the desired range based on data from the Department of Transportation [3].

A not-so-rigorous article also reported around a 100-150mile (160-240km) range for a motorcycle on a single tank of gas [6].

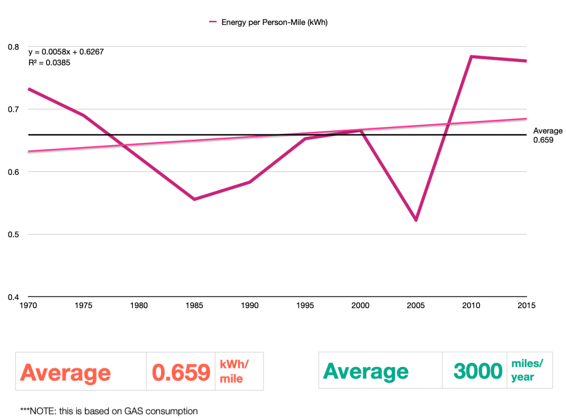


Figure 3—Data from [3] plotted for fuel use/person-mile, and miles/year travelled estimated from [4][5] for motorcycles.

Additional estimates of mass, cross-frontal area, drag coefficient, average acceleration and deceleration, energy densities of various fuel sources, efficiencies of components of the system all from various surveys and sources, are presented in the table below.

Now let's assume that we are using this bike to commute to work every day, and a motorcycle drives around 3000 miles/year, and there are 260 working days / year and we want to "fill-up" or "charge" the bike at most once / week.

$$3000\frac{\text{mi}}{\text{yr}}/260\frac{\text{work-days}}{\text{yr}} * 5\frac{\text{work-days}}{\text{wk}} \approx 58\frac{\text{mi}}{\text{wk}} \approx 94\frac{\text{km}}{\text{wk}}$$

Design Requirements—

- Range of 94km at minimum, 160-240km ideal of CITY driving.
- An acceleration of about 0.5Gs.
- A top speed of 60-110mph (100-170kph)

Table 1: General Estimated Constants

Parameter Name	Value	Unit	Source
Mass Bike	188	kgs	Hyosung GT250
Mass Rider	80	kgs	American Solar Challenge Regulations
Radius Wheel	0.125	m	Honda CB360 1974 Rear Tire Measurement
Energy Density H2	120	MJ/kg	rmi.org
Energy Density Propane	50.3	MJ/kg	energyeducation.ca
Energy Density Gasoline	47.5	MJ/kg	aps.org
Energy Density Lithium Batteries	400	Wh/L	washington.edu
Efficiency HFC	0.5	u-l	plugpower.com
Efficiency PFC	0.5	u-l	energy.gov
Efficiency IC	0.35	u-l	energy.gov
Engine Max Torque	20.6	Nm	Wikipedia Hyosung GT250
RPM @ Max Torque	7300	RPM	Wikipedia Hyosung GT250
Top Speed MC	110	mph	Wikipedia Hyosung GT250
MC MPG (highway)	74	mpg	Wikipedia Hyosung GT250
Drivetrain Efficiency	0.8	u-l	~70% for a bike (0.9x0.9x0.9 + SF)
Average Acceleration (based on 600cc)	0.5	Gs	https://www.datamc.org/data-acquisition/g-forces-and-acceleration/longitudinal-acceleration/
Average Deceleration	0.6	Gs	http://www.louispeck.com/motorcycle-braking
Typical H2 Pressure	350	Bar	https://en.wikipedia.org/wiki/Hydrogen_storage
Propane Density (lq.)	493	kg/m3	elgas.com
Cross-frontal Area	0.8	m^2	"Motorcycle Energy Consumption in Urban Traffic"
Coefficient of Drag	0.5	u-l	"Motorcycle Energy Consumption in Urban Traffic"

***NOTE: THIS TABLE HAS ESTIMATED PRELIMINARY VALUES FROM ONLINE SOURCES

Table 1—Data from the US Department of Energy, a representative small motorcycle, and [7] used as initial estimates of motorcycle performance requirements.

II. Feasibility

II.1.0 Determining Feasibility. Now we know that Hydrogen Fuel Cells are expensive, so for now (at least in the beginning) let's assume that we want to minimize the size of the fuel cell and we'll take the strategy that rather than powering the whole bike off the Fuel Cell, the motor will draw energy from the battery and the HFC will recharge the battery over some period of time. This is a typical design methodology for many Fuel-Cell vehicles [1].

Additionally, we can say the battery will store a certain amount of energy in kWh. The hydrogen tank will store a certain amount of gas with a certain amount of potential energy, also in kWh. And the HFC will convert the gas to electrical energy with an efficiency, η_{FC}. Let's also say we never want to charge the battery directly, we just want to be able to fill hydrogen in the tank each week. That means we can say that for any size fuel cell, the *absolute minimum* amount of H2 storage required can be calculated as shows.

$$E_{H2}\eta_{FC} = E_{batt} \tag{1}$$

Basically, the hydrogen tank needs to store the same amount of energy as the battery or more to always be able to fully recharge the battery.

Let's also make the assumption (for now), that the Fuel Cell can operate while the bike is stationary, and that after driving for a certain amount of time, the time the bike is stationary is enough for the fuel cell to fully recharge the battery. A small fuel cell will require time to fully charge the battery, for example.

Let's say the average power of the bike over a certain stretch is "P_bike" for a drive of length "t."

*P_bike * t = Energy in W drained from the battery…*

Let's also say we are using a fuel cell with "P_fc" power.

*P_fc * t2 = Energy delivered to battery over period "t2"*

Therefor the time required for the fuel cell to re-charge the bike is as follows.

*t2 = P_bike*t/P_fc* *(2)*

So, for example, if the bike requires 2kW to move @ 44.4kph as estimated in [7], and it drives for 120s, and we have a 1kW fuel cell on board, the total time required to recharge the bike with the fuel cell is as follows.

*t2 = 2000*120/1000 = 240s*

Now if the fuel cell is operational both while the bike is driving and while it's stationary, the time the bike must be stationary after the ride is defined as the *additional charge time*, which is calculated as follows.

t_ac = t2-t ~= 120s in this case…

But this is a little too complicated for right now, so let's just assume we have a small fuel cell and the limiting components will be the size of the tank and the size of the battery.

If we want a minimum range of 100km and the average gas energy used per person-mile of a motorcycle according to [3] is 0.659kWh/mile, the efficiency of a gas engine is η_{IC}, and the efficiency of the drive train is η_{DT}, then we can say the following.

$$E_{batt} = 62\text{mi} * 0.659\frac{\text{kWh}}{\text{mi}} * \eta_{IC} * \eta_{DT} = 11.44\text{kWh}$$

We can also use (1) to determine the amount of H2 energy storage required.

$$E_{H2} = E_{batt}/\eta_{FC} = 23\text{kWh}$$

Now, we can use these to estimate the size of the battery and size of hydrogen tank required to achieve the range performance of a typical motorcycle. We can then estimate if this project is first-pass-feasible by determining if both will fit on the frame of a typical motorcycle based on calculated sizes.

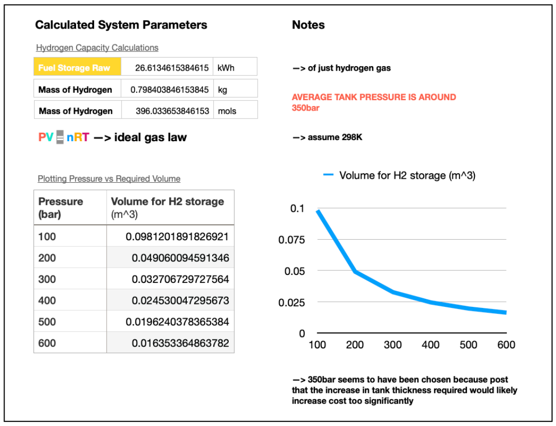
II.1.1 Battery Size Estimate. If the energy density of a Lithum-Ion battery cell is around 400Wh/L, then we can estimate the battery will take up around 28.6 Liters, which is around 8 gallon jugs of milk (see table 1).

II.1.2 Hydrogen Tank Size Estimate. We can use the ideal gas law (PV=nRT) to estimate the tank size of the hydrogen. For fuel cells hydrogen is generally stored in a compressed-air tank at around 350 bar [8]. The energy density of H2 gas is around 120MJ/kg (see table 1).

Graph 1 shows the volume requirement for the amount of H2 gas required versus pressure. At 350bar, we can estimate around 35L of H2 gas which is approximately 9 gallon jugs of milk.

So why are we converting everything to gallons of milk? Well it's a reasonably understood unit, and while the density difference should be taken to account in the conversion, the size is a good indication of the space we will need. A gallon jug is like 6"x6"x11" so let's say we need 16 of them

Hydrogen Tank Storage:



Calculated System Parameters

Hydrogen Capacity Calculations

Fuel Storage Raw	26.6134615384615	kWh
Mass of Hydrogen	0.798403846153845	kg
Mass of Hydrogen	396.033653846153	mols

PV = nRT —> ideal gas law

Plotting Pressure vs Required Volume

Pressure (bar)	Volume for H2 storage (m^3)
100	0.0981201891826921
200	0.049060094591346
300	0.032706729727564
400	0.024530047295673
500	0.0196240378365384
600	0.016353364863782

Notes

—> of just hydrogen gas

AVERAGE TANK PRESSURE IS AROUND 350bar

—> assume 298K

—> 350bar seems to have been chosen because post that the increase in tank thickness required would likely increase cost too significantly

Graph 1—Volume of H2 storage vs pressure in bar for 27kWh worth of H2 gas storage.

stacked in 2 tall, 2 wide, and 8 long configuration. That's a size of around 12"x48"x22."

Now that seems really large, but this is completely based on the 0.659kWh/person-mile number which is an average of *all motorcycle on the road in the US*. And we also know that that number is likely a function of bike mass, rider mass, aerodynamics, wheel size, so on and so forth—there's many variables. So this number serves as an argument that for a lighter, sport bike and for city commuting, it's possible this could be feasible.

Additionally, this calculation assumes the fuel cell provides all of the energy to charge the battery, and in electric vehicles in reality this is not true. Regenerative braking is a significant source of power that captures much of the energy being used during the acceleration process of getting the mass up to speed. Studies have shown regenerative braking can reduce vehicle energy requirements by as much as 20% [9].

All this is to say yes, these estimates seem large but not TOO large. Which means a next-step of analysis should be conducted before the idea is ruled out. It's possible we can solve some of the issues with optimization of engineering design. It's also important to note that some larger bikes could fit this size a power train if we include things like the fuel tank as available space, which mean *at a first-pass,* this is feasible.

III. Motor/Battery + More Detailed Analysis

Now we have to model the motor, the gearbox, and the battery. We model these components of the system together because they are inherently coupled. The voltage of the battery and the gearbox determines there size of the motor required to achieve certain performance requirements, and the current the motors draws in-turn has some say on the requirements on battery sizing.

III.1.0 Modeling the System using Torque/Speed Curves. A motor torque-speed curve is basically a limit line of what a motor can do [10].

The torque-speed curve has a few key characteristics. First, is the saturation torque. Since Torque is proportional to the magnetic field generated by electric motors, there comes a point where we physically cannot shove more magnetic field through the material of the motor's stator core. The magnetic domains are all fully oriented in the direction of the field so more magnetic field, or more torque, is not possible.

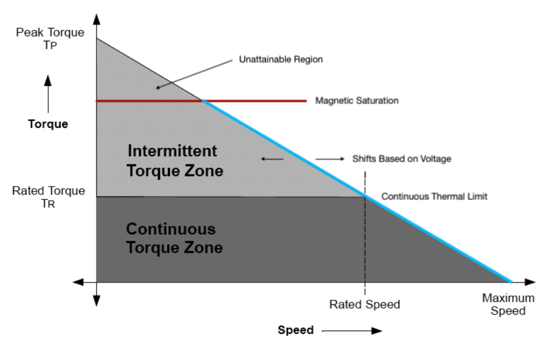


Figure 4—Modified torque/speed curve diagram from both [10] and [13].

This is a physical material limit and is shown on the torque-speed curve as a hard saturation.

Second, is the "Maximum Speed" or free-speed of the motor. This is the fastest speed a motor will spin under no external loads. Since motor speed is proportional to voltage applied, this is dependent on the voltage of the battery.

Third is a physics limit defined by the fact that a motor is a constant power device. It can only supply a certain max power dependent on physics, so for some time as the motor speeds up, we can still apply max torque until we reach the power limit of the motor where the following holds.

$$P_{max} = T_{sat}\omega_{peak-power} \tag{3}$$

After that, the Torque roughly linearly falls off with increasing speed. A motor can achieve any T/S combination *under* it's torque-speed curve but not over. The gear ratio and the voltage affects on the torque-speed curve are shown in Figures 6 and 7.

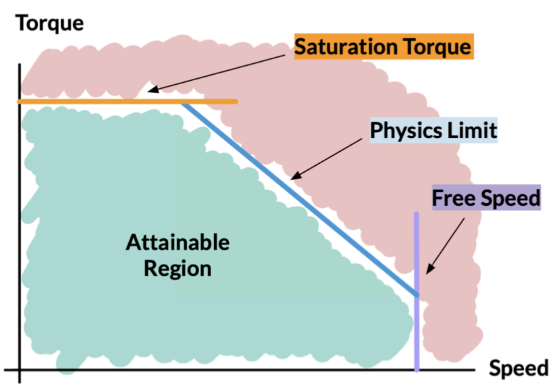


Figure 5—Torque/speed curve with labels from [10].

III.2.0 Strategy for Motor + Battery Sizing. So what we can do now, is estimate the amount of torque our motor needs to apply under certain desired conditions of the bike's operation and the speed at which it needs to achieve those torques. Then we can plot these points on a torque-speed plane and ensure they fall under the motor limits defined by the torque-speed curve. We can then play with the gear ratio and voltage to compare the effectiveness of different motors.

We compared two motors, the 10kW Golden Motor which was purpose designed for motorcycles, and the T-Motor U15 which was designed for drones. We decided we would use either one Golden Motor or *two* T-Motor U15s. The specifications for both of these motors are shown in the tables below. It's also important to note that we had two T-Motor U15s on hand so

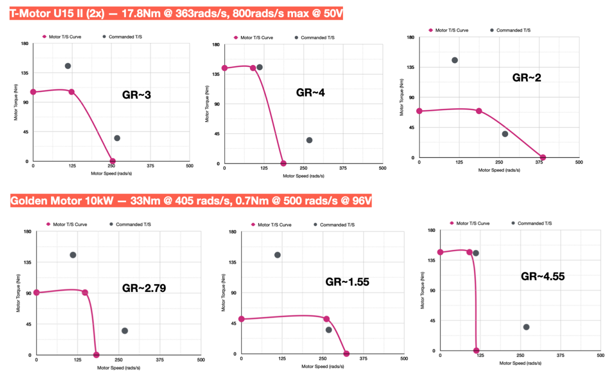


Figure 6—Gear ratio affect on the torque/speed curve. The magnitude of peak power of a motor does not change with gear ratio rather it shifts towards higher torque and lower speed or lower speed and higher torque based on gear ratio. The free-speed and saturation torque also move depending on the ratio.

Motor Parameters

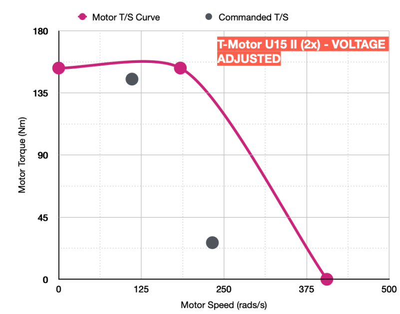
Motor Speed (rads/s)	Motor Torque (Nm)
0.0	35.6
791.34	35.6
1744	0.0

Motor Geared Parameters (2 MOTORS)

Motor Speed (rads/s)	Motor Torque (Nm)
0.0	153.08
184.032558139535	153.08
405.581395348837	0

Desired Parameters from Math

Requested Speed	Requested Torque
232.4608	26.5280386064
110.86592	145.055



Motor Parameters

Motor Speed (rads/s)	Motor Torque (Nm)
0.0	35.6
529.98	35.6
1168	0.0

Motor Geared Parameters (2 MOTORS)

Motor Speed (rads/s)	Motor Torque (Nm)
0.0	153.08
123.251162790698	153.08
271.627906976744	0

Desired Parameters from Math

Requested Speed	Requested Torque
232.4608	26.5280386064
110.86592	145.055

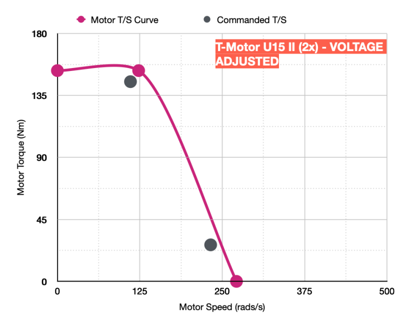


Figure 7 a (top) + b (bottom)—Voltage affect on the torque/speed curve. The voltage affects only the speed, not torque of a motor. This means increase in motor performance can be achieved by supplying the motor with an increased nominal voltage.

this was really more to understand how two of them compared to using a purpose-designed motorcycle motor, and what performance we might be able to expect when using the materials we had on-hand.

Table 2: T-Motor U15 vs. Golden Motor 10kW

Motor Parameter	T-Motor U15	Golden Motor 10kW
Stall Torque	17 Nm	33Nm
Velocity @ Peak-Power	363 rads/s	405 rads/s
Velocity Max @ 50V	800 rads/s	500 rads/s
Peak Power	6.2 kW	13 kW

Comparing motor parameters yields that (2x) T-Motor U15 motors is almost equivalent in power to a Golden Motor 10kW, however the Golden motor has a much sharper derate after the peak-power point.

Based on the above table, we can see that (2X) T-Motor U15s in terms of peak power. We would likely see similar acceleration performance between two bikes that used both these motor setups. But due to the significantly higher max velocity of the U15 motors, we likely get much better top-speed performance with the T-Motors.

III.2.1 Estimating Motor Requirements from Bike Performance Requirements. We know we will see maximum electrical system load in two cases: maximum acceleration, and top speed. This is true because the vehicle's top speed is limited by motor power and the vehicle's acceleration is also limited by the motor power (and the rest of the electrical system).

$$F_{drag} = \frac{\rho C_d A v^2}{2} \tag{4}$$

$$F_{accel} = m a \tag{5}$$

In the case of top-speed, we know the motor through the wheel only needs to overcome air resistance and that all forces on the bike are balanced. Knowing the force of air resistance based on Equation 4, estimates of C_d and A from [7], the gear ratio, and an estimate of wheel radius from Table 1, we can calculate the motor torque requirement and motor speed.

*F_drag = 1/2 * p * C_d * A * v^2*

*T_motor * R = F_road * r_wheel*

*T_motor * R / r_wheel = 1/2 * p * C_d * A *v^2*

$$T_{motor} = \frac{\rho C_d A v^2 r_{wheel}}{2R} \tag{6}$$

w_motor / R = w_wheel (6a)

*v_wheel = r_wheel * w_wheel*

$$\omega_{motor} = \frac{R v_{wheel}}{r_{wheel}} \tag{7}$$

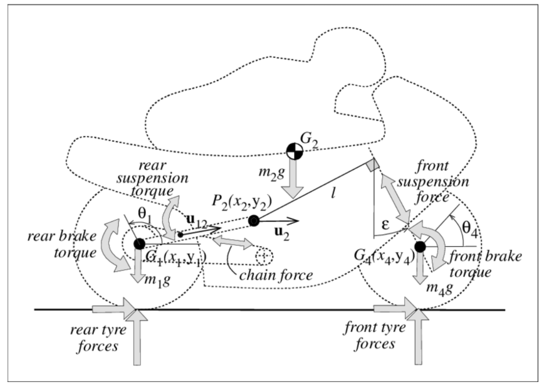


Figure 8—Basic motorcycle FBD from [14]. Also consider Air Resistance as a force pointing towards the rear of the bike acting at the center of pressure (CoP).

In the case of maximum acceleration we know the motor simply needs to apply maximum torque until we achieve a certain speed. After this maximum speed, the motor torque will de-rate according to the torque, speed curve. This is the reason motors like the Golden Motor 10Kw have a sharp de-rate of velocity, the system can be designed so the bike has more uniform acceleration across its entire speed range.

*F_bike = m_bike * a_bike*

*T_motor * R = F_road * r_wheel*

*T_motor * R / r_wheel = m_bike * a_bike*

$$T_{motor} = \frac{m_{bike} a_{bike} r_{wheel}}{R} \tag{8}$$

Now, of course, the maximum bike speed before the acceleration starts to de-rate due to motor performance occurs at the peak-power-point of the torque speed curve which is dependent on voltage. If you know you want a constant acceleration up to a desired speed V_max, you can use equation (6a) to determine w_motor at the peak-power-point and equation (8) to determine the torque required.

This gives us two points to plot, the speed performance limit point (SPLP) and the acceleration performance limit point (APLP). For our bike, we assumed we wanted maximum acceleration up to 31mph before de-ration and a top speed of 70mph. Figure 7 shows these points as grey dots under the torque-speed curve. When then played with the voltage and gear ratio parameters until we found a roughly optimal gear ratio of 4.3 and a voltage requirement of around 70V minimum. The final parameters are summarized in the table below.

Table 3: Final Selected Drive-System Parameters

0.02	f_r (est.)
65	v_max (mph)
70	voltage (est.)
4.33	m/s^2 (accel.)
6.35	m/s^2 (deccel.)
4.3	gear ratio

NOTE: All values in this table are represented as parameter sliders for analysis.

Summary of final selected parameters for the bike, f_r refers to the coefficient of rolling resistance which was also accounted for and described in the linked spreadsheets.

Also note that in this case, 'optimal' is defined as the voltage-gearing combination that allowed both the SPLP and the APLP to lie exactly on the limits of the torque speed curve meaning the system would be operating at its limits at top speed and maximum acceleration with no safety factor.

IV. System Layout + Integrating the HFC

So far in our system, we have selected the motors, gear ratio of the drivetrain, and the system voltage, but haven't determined the battery sizing or the integration of the fuel cell. We have two realistic options for the method of fuel cell integration and energy storage for the bike as described in Figure 9 below. One relies on the use of a large battery as the main power source for propulsion, and the other relies on a small battery or capacitor bank for handling burst currents as well as regenerative braking. Fuel cells do not accept regenerative braking currents. Technologies such as regenerative fuel cells may be used in the future to use the power generated from regenerative braking to split water into hydrogen generating more gaseous H2 fuel for the vehicle [15]. But we suspect that the low efficiency of H2 generation and the efficiency of the fuel cell itself cannot compete with the efficiency of capturing regenerative braking power with a battery or capacitor bank which is estimated to be over 60% according to [9], and as high as 70-90% in direct-drive systems according to [16].

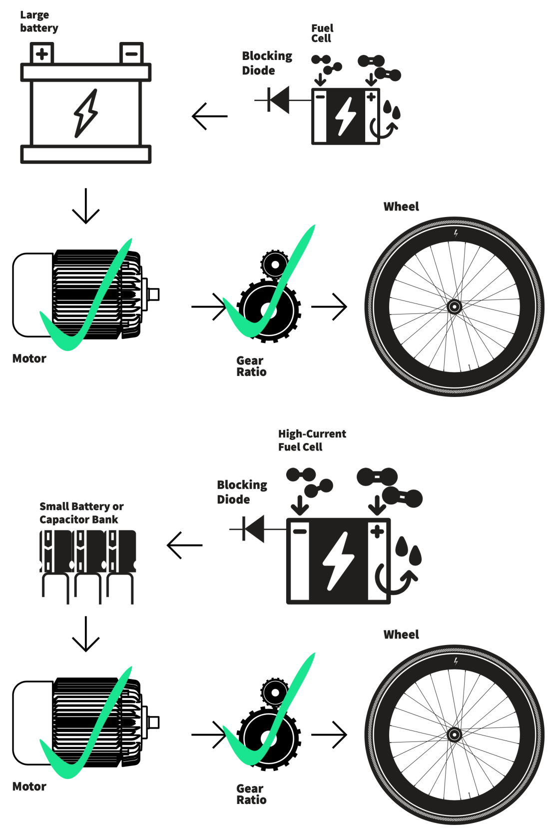


Figure 9 a (top) + b (bottom)—Either have a large battery that serves as the main power source which is trickle-charged by a fuel cell (a), or have a large fuel cell that serves as the main power source for the motor and any regenerative power is sent to a series of capacitors or a small battery. The blocking diode is a protection diode that helps protect the fuel cell from regenerative braking currents.

IV.1.0 Sizing the Fuel Cell. There are many types of fuel cells including Alkaline Fuel Cells, and Solid Oxide Fuel Cells. A comparison from [17] indicated PEM fuel cells don't require CO2 scrubbing, have short startup times, operate at lower temperatures than solid-oxide fuel cells, and don't have known issues related to limits on power cycling. Newer fuel-cell vehicles such as the Toyota Mirai generally tend to use PEM fuel cells [18]. Based on this, we chose to only analyze a PEM fuel cell as the chosen technology, at least for now.

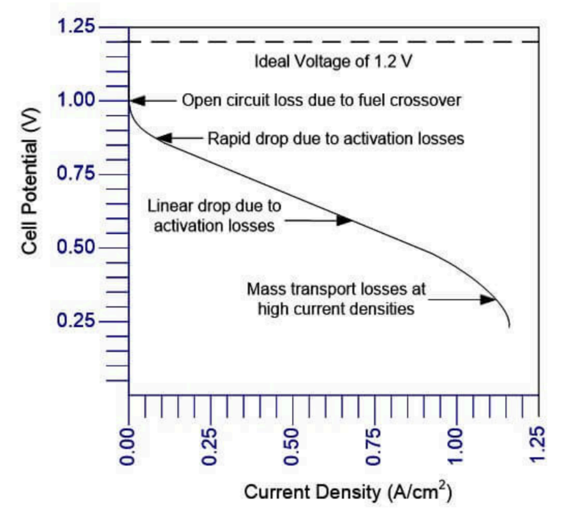


Figure 10—PEMFC Polarization Curves show the potential of a single hydrogen cell as a function of surface current flowing across the cell [19].

We can predict the performance of a fuel cell based on its size using a sample PEM fuel cell polarization curve from [19].

We can use PEMFC Polarization Curves, like the one shown in Figure 10, to perform preliminary design on a fuel cell stack based on the desired voltage and current we need from the stack. For our calculations, we will use the curve in Figure 10 as a general estimate for PEM fuel cell performance, and we will stick to the middle of the curve between 0.5-0.75A/cm^2 current density at a cell potential of 0.5-0.75V. Each curve is for a single element of the fuel cell stack. We will assume all elements of the stack are in series, therefor each cell must be rated to provide the full desired current, and the number of cells will directly determine the stack voltage.

We determined in section III, the desired system voltage would be around 70V minimum. At 70V, and based on the power draw of the motors at top speed and max acceleration, we can estimate a 200A fuel cell would comfortable supply the system with adequate power. These current requirement calculations are shown in the attached design sheets, and some simple

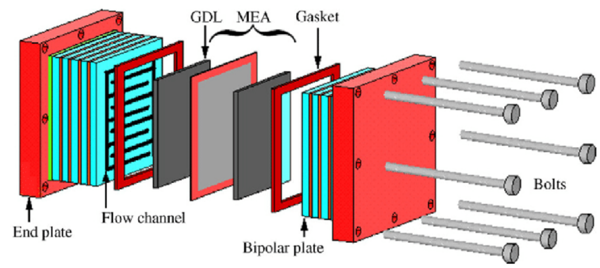


Figure 11—Fuel cell stack construction schematic from [20]. Each combination of a GDL, MEA, gasket, and Bipolar plate is a single cell or element of the fuel cell. Cells are electrically connected in series and gas can flow from each cell to cell so all elements of the stack receive the supply of oxygen and hydrogen.

calculations follow to size the fuel cell assuming the earlier noted operating range.

N_cells = V_stack / 0.6V/cell = 70V / 0.6V/cell ~= 100 cells

A_cell = A_stack / 0.5A/cm^2 ~= 380cm^2 cell area

Assuming the fuel cells are square in shape… that's about a 100 unit stack of 19cmx19xcm cross-section fuel cells.

If we assume a cell thickness of around 7mm (which is not unreasonable) that gives us a total fuel cell length of around 0.6m—very doable for fitting inside a motorcycle, however, likely very expensive.

Cost is the highest barrier to PEM fuel cell production today, studies from [21] indicate battery vehicles (BEVs) are much more cost effective than FCEVs as of 2004. But studies from [22] around the same time period indicate the cost for FCEV power units in mass production could potentially match internal combustion. Very recent news indicates the large car manufacturer Toyota is unveiling a hydrogen fuel cell pickup truck, and FCEV version of their popular corolla in addition to the Miari FCEV they already sell. This indicates the potential for fuel cells to be cost competitive at higher production volumes. Toyota also recently open sourced all its FCEV patents, indicating potential for collaboration in terms of driving down the cost of fuel cell production [24].

V. Hardware Platform

For the hardware platform, we chose to go with the system presented in Figure 9a, a large battery trickle charged by the fuel cell, purely for cost and sourcing reasons. This system will also allow us to analyze the performance of a fuel cell to verify the earlier theories presented in section II. The system can be changed in the future if we wish to implement the system presented in Figure 9b, or an alternative system. We will modify an existing Ducati 900ss motorcycle (shown in Figure 1), and attempt to build this system at a low-cost from parts we can find before spending the time developing new hardware. The goal for this initial system is a proof of concept.

V.1.0 Battery. The battery system is a re-configuration of the modules of the Nimbus solar powered vehicle developed by the MIT Solar Car team for the 2021 American Solar Challenge [32]. The vehicle had (4x) Lithium-Ion battery modules in a 8s13p configuration. In the solar vehicle, the modules were wired in series for a 32s13p configuration that ran nominally at 130V and stored 5kWh of energy.

For our system, we grouped the modules into pairs and wired those pairs in parallel, then we wired the groups in series for a nominal voltage of 65V and an energy capacity of 5kWh. This is shown in Figure 12.

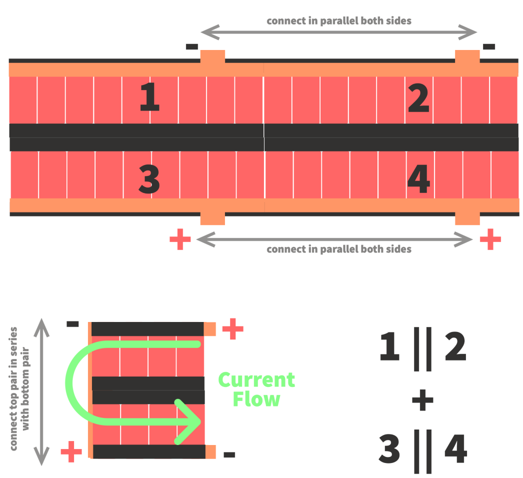


Figure 12—Connecting the (4x) solar car battery modules in parallel pairs and then in series.

To connect the modules together we designed (3x) copper bus bars. One large bus bar connects the negatives of modules 1 and 2, and the positives of modules 3 and 4 all together. Two smaller bus bars connect the positives of

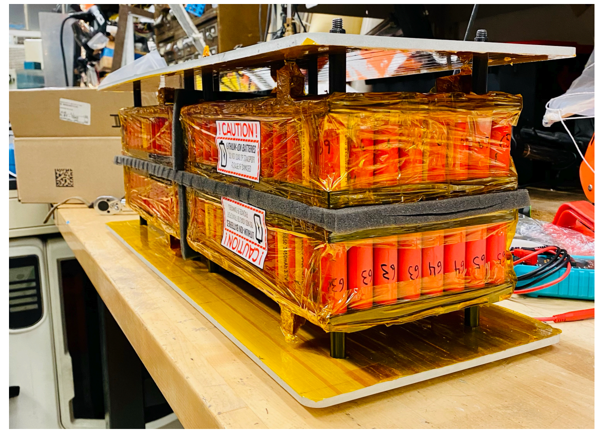


Figure 13—Progress on the battery unit so far. The (4x) modules have been mechanically mounted to an aluminum frame. The bus bars have been manufactured but are not mounted to the modules yet.

modules 1 and 2 together, and the negatives of modules 3 and 4 together. The main battery cables attach to the two smaller bus bars and current flows through the modules as shown in Figure 12.

Using this new battery, the calculations presented in section III, and data presented in [7], we estimated the range of our motorcycle system at 64.4kph highway, and at a 44.4kph average speed in city driving. These calculations are shown in the attached design sheets, but we can estimate a range of roughly 172km highway, and 92km city at these respective speeds. These both fulfill our original design requirements.

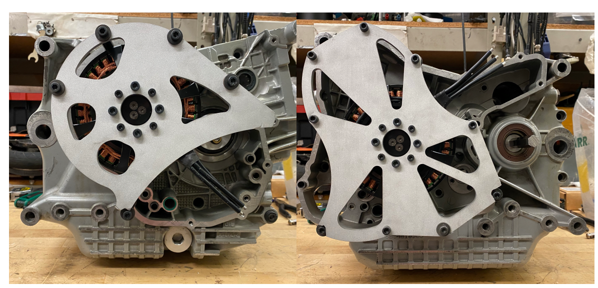


Figure 14—Images of the assembled drivetrain from the outside including the mounts for the two T-Motor U15 motors. motor 1 is on the right, motor 2 is on the left.

V.2.0 Drivetrain. The drivetrain consists of a modified gearbox from the original bike. We chose to stick with the original gearbox casing as the gearbox of a Ducati 900ss is structural, and the rear swing-arm suspension mounts to the gearbox. To avoid the added complexity of having to design a suspension mount in addition to the drivetrain, we stripped out the components from an original gearbox and used that as a base for development.

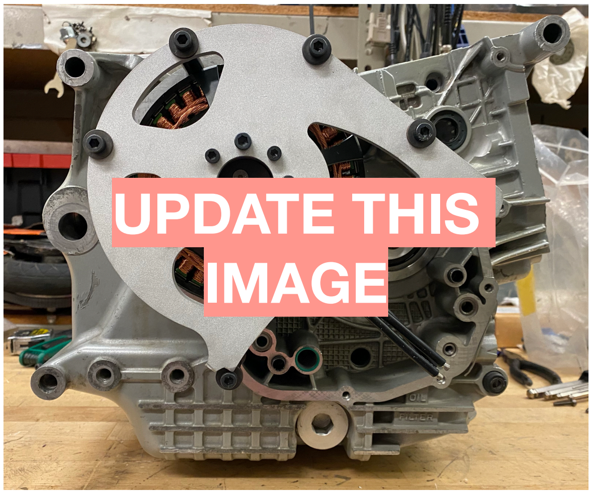


Figure 15—A view of the belt drive system which includes a 1:1 reduction between the two motors and a 1.4:1 reduction from the motors to the main output shaft. The rest of the required 4:1 reduction comes from the chain drive itself.

We mounted the two T-Motor U15 motors to the gearbox using water-jet aluminum plates. One motor was placed where the clutch assembly used to be, and the other was placed where the alternator/stator used to be. The motors are belted to each other through a 1:1 reduction and then the shaft of motor 1 is belted to the main output shaft with a 1.4:1 reduction. The motor mounts are shown in Figure 14 and the belt system is shown in Figure 15. Belt tension for the belt between the motors is achieved with a tensioner assembly, belt tension between the motor 1 shaft and main output shaft is achieved by stretching the belt onto the assembly. The main output shaft connects to the sprocket that drives the chain of the bike.

For now, the belts used were VexPro HTD 5mm pitch by 15mm width timing belts used in FRC robot drivetrains due to availability. In the future, we plan to use either Breco drive belts or Gates Polychain GT Carbon belts because of their larger pitch, increased stiffness, and higher force capabilities. We used the standard bearings that came with the transmission, the bearings are additionally lubricated with white lithium grease as this was a readily available lubrication compound.

V.3.0 Fuel Cell. For this initial system, we're working to acquire a small size fuel cell in the range of 1-2kW. If we cannot acquire a fuel cell, we can simulate the performance of a fuel cell with a current-limited power supply. The goal of the fuel cell or simulated fuel cell in this initial system will be for the experiments presented in section VI and verification of the design methodology presented in the previous sections.

VI. Future Work

Our goal with this project is to develop a platform to analyze the performance and potential of Hydrogen Fuel Cell that can serve as a robust test bed for future development towards alternatives to BEVs. What we really want to create is a open-source knowledge base. A base that others can use to develop this technology even further to implementation. The open-source community has solved many of the world's challenges in the past by sharing knowledge and collaborating on difficult problems—we believe this is necessary right now for the realization of FCEVs.

We plan to run the following experiments using the hardware platform described above—and publish the data open-source.

- Verification of the claim "we never need to charge the battery off the wall, we only need to fill the tank with hydrogen" for a set of practical scenarios.
- Verification of the performance of the bike system as compared to the predicted performance in III as a test of the design methodology.
- Test of the bike's regenerative braking capabilities to recover energy used for acceleration during braking, and a test of the speed at which the fuel cell could continuously power the bike at steady-state.

We plan to look into the following alternatives to make hydrogen fuel cell more accessible as an alternative to BEVs—and publish the results open-source.

- The use of a bank of super-capacitors and associated power electronics instead of a large lithium battery in a system similar to Figure 9a. This may help with the long

charging times and negative environmental impact of Lithium [25].
- Large-scale manufacturing cost of FCEV power units and PEM membranes, technologies for manufacturing, and alternatives to PEM cells [22].
- Higher efficiency motor and motor control designs for equivalent power output at lower power draw [26].

We also plan to look at the following technologies to address some concerns regarding FCEVs—and publish the results open-source.

- Sustainable, green production of hydrogen gas. Hydrogen gas accessibility and cost [27].
- Safety precautions related to hydrogen gas and fueling.
- Hydrogen storage technology [28].

This preliminary report started from high-level design requirements and used fundamental physics to determine the feasibility of a hydrogen fuel-cell motorcycle. It provided a design methodology for selection of key drivetrain components, and outlined a potential preliminary hardware platform for future tests that can answer more detailed questions regarding the design of an FCEV. Finally, it identified key experiments to be conducted in future work. We determined that such a system, the assembly of the platform, and its experimental verification is feasible. We hope to continue this work with the end goal of developing an open-source hydrogen fuel cell power unit, a knowledge base for fuel cell technology, and a community focused on the development of FCEVs to build a cleaner future.

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PLEASE NOTE—for some of these citations we are citing the link to a website or blog post, for a conference paper we would cite the actual academic source linked to these listed sources and re-phrase the paper.

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