# System Design and Optimization of the World's Fastest Hydrogen Fuel Cell Vehicle

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***Abstract*—The Buckeye Bullet 2 is the world's fastest hydrogen fuel cell electric vehicle, with a certified FIA record of 487.433 km/hr (302.877 mi/hr). This paper provides the basic details of the overall vehicle and focuses on the design, testing, and optimization of the propulsion system. A unique fuel cell system was designed, tested, and integrated to produce over 500 kW of power, more than twice of its original rating. A unique pressure control is required to run the cathode system at maximum pressure during the race, and to manage the transient pressure pulses that occur when the race vehicle manual transmission is shifted. This causes rapid changes in the consumption of reactants, leading to severe pressure spikes that were limited with a custom tuned pressure relief system for the anode and cathode.**

## I. Introduction

The year 2010 marks the 16th anniversary of The Ohio State University's involvement in electric racing. Beginning in 1994 with the Formula Lightning series, OSU campaigned their vehicle, The Smokin' Buckeye until 2002. The series was a collegiate open-wheel formula-style race that traveled to major racetracks around the country [1]. As the Formula Lightning series was being phased out, the team decided to take electric racing to a new level, by designing the Buckeye Bullet, a streamliner powered by a NiMH battery. The Buckeye Bullet worked its way up to a top speed of 321 mi/hr, and holds the U.S. record for electric vehicles at 314.958 mi/hr. The Buckeye Bullet was retired after its October 2004 runs, but still holds the U.S. land speed record in the E/III class (Electric power, over 1000 kg) [2].


Figure 1. The Buckeye Bullet 2 and the Development Team

The success of the Buckeye Bullet led the team to look for new propulsion technologies that could be used to set land speed records. The Buckeye Bullet 2 was conceptualized as a hydrogen fuel cell vehicle that aimed to break 300 mi/hr with fuel cell technology. On September 25th, 2009, the Venturi Buckeye Bullet 2 became the first hydrogen fuel-cell vehicle to exceed the 300 mi/hr mark, setting an international speed record of 302.877 mi/hr in the flying mile. The Buckeye Bullet 2 program included over 2 years of initial conceptual design, followed by 3 years of testing, development and racing.

## II. Design of the Buckeye Bullet 2

### A. *Overall Vehicle Layout*

Figure 2 shows an overview of the Buckeye Bullet 2 (BB2) architecture. The vehicle uses four-wheel independent suspension to provide optimum vehicle control over a variety of rough track conditions. The major factors considered in placing the components in the vehicle were safety and aerodynamics. The high pressure hydrogen fuel tanks are at the far rear of the car, with the driver in front of the fuel cells, separated by a firewall from any hydrogen gas systems. The small diameter of the electric motor compared to the height of an internal combustion engine allowed front wheel drive to be considered. With the low profile motor in front of the driver, the drivers head can be lowered, which reduces frontal area.

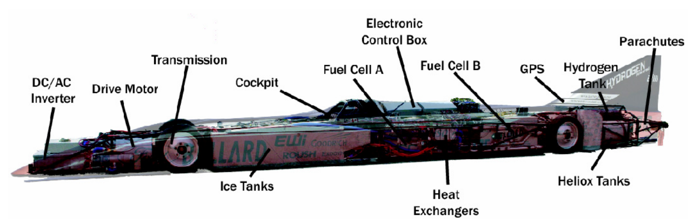


Figure 2. Buvkeye Bullet 2 Vehicle Architecture

The driver is surrounded by a roll cage and carbon fiber safety tub. The primary method to stop the vehicle is with the use of 2 high-speed parachutes. The vehicle also has Lear-jet aircraft

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brakes at all 4 wheels that could stop the vehicle in an emergency situation or parachute failure.

*Powertrain*

The inverter/motor controller, along with the motor, was carried over from the Buckeye Bullet 1 program, where the batteries were the power limiting factor. The inverter/motor controller was designed and programmed by Saminco Electric Traction Drives. Interestingly, this controller was also originally used with the fuel cell system that Ballard Power Systems used in their city bus program, long before being used for land speed racing.

The basic I/O structure of the motor controller is a torque reference and DC power input, and 3 phase AC power output. Internally, there are preset torque limits and other calibration adjustments to tune and optimize the power output from the motor. The DC/AC inversion is performed using variable voltage, variable frequency switching. Ultimately, the electrical power is converted to mechanical energy through the AC induction motor, and is sent to a six-speed transmission and to the ground via special land speed tires.

## III. MAXIMIZING FUEL CELL POWER

### A. Design of the Gas Delivery System

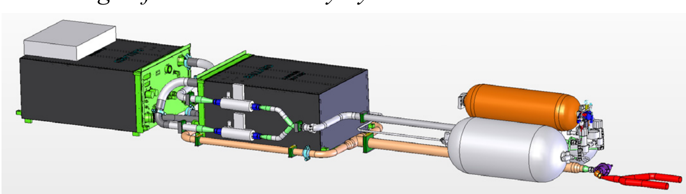

Figure 3. The BB2 Gas Delivery System

#### 1) Hydrogen Supply System

Figure 3 shows a CAD diagram of the vehicle gas delivery system, specifically designed for the Buckeye Bullet 2. A critical challenge was in the design of the hydrogen supply system. In fuel cell systems, hydrogen must be supplied to the anode with sufficiently high partial pressures and concentrations, in order for the reactions to be efficient [3]. For this reason, hydrogen gas must be supplied at higher mass flow rates than the rate it is actually consumed. The unreacted gas exiting the stack is recirculated back to the inlet via a pump.

During normal use, water and other inert gases (Nitrogen, or in the case of the BB2, Helium) can accumulate in the fuel loop, because the seals separating the anode and cathode are never quite perfect. The fuel loop must be periodically purged to clear out these contaminates. Typically, only a small percentage of the total fuel is wasted to satisfy purge cycle conditions.

The fuel is recirculated using a multistage ejector system using the hydrogen pressure at the fuel cell inlet. The multi-stage ejector has a limited turn-down ratio, requiring a smaller jet for low flow rates. Hydrogen fuel pressure and flow rate are otherwise controlled passively using a pressure regulator externally piloted by the air delivery system to balance the air and hydrogen pressures across the fuel cell membrane.

#### 2) Oxidizer Supply System

Much like the hydrogen system, the amount of oxygen needed for the reaction is proportional to the current demand. Typical fuel cell vehicles are designed to use oxygen that is in the air outside the vehicle. A compressor, typically driven by an electric motor, is used to pump air to the desired inlet pressure to flow across the cells. The compressor represents a large parasitic loss, typically absorbing as much as 20% of the total power produced by the fuel cell [3]. For a land speed vehicle, a difference of 20% would severely affect the acceleration and top speed. Furthermore, a special air filtration requirement would also be imposed to the BB2 due to the impurity and salty conditions of the air at the Bonneville Salt Flats, which could eventually lead to stack damage.

For the reasons cited above, the short duty cycle of a speed run enabled other non-traditional automotive oxidizer supply systems to be considered. A high-pressure stored oxidizer supply architecture similar to that of the hydrogen would eliminate the largest parasitic loss. Refilling a pressurized gas cylinder in between runs enabled gas mixtures other than air to be considered. Furthermore, higher oxygen concentrations (partial pressures) allow fuel cells run more efficiently.

The choice of the oxidizer was made as a trade-off between the maximum system performance and safety. For a PEM fuel cell, the best performance would be using pure oxygen instead of air. However, using pure oxygen would be considerably more dangerous [4]. Hence, a mixture of Helium and 40% oxygen was chosen to reduce the flow rate requirements, however still gaining the benefits of oxygen enrichment and maintaining a reasonable level of safety.

The oxidizer loop differs from the hydrogen because it is not recirculated. The oxidizer must also be supplied at a ratio λ higher than needed to support the reaction stoichiometric requirements. The oxidizer mass flow calculation is expressed as follows [3]:

$$\dot{m}_{Ox} = \frac{I}{4F}\frac{M_{O_2}}{pp_{O_2}}(\lambda)(N_{cells}) \qquad (1)$$

where λ is typically of the order of 2.

The oxidizer delivery control system consists of two mass flow controllers that regulate the flow of oxidizer into the fuel cell cathode. The traction drive controller interprets the driver command for torque and given the motor speed computes a total power demand from the fuel cell. This power estimate is converted into an electric current demand using a polarization curve derived from load testing of the fuel cells. The electric current demand is communicated to the fuel cell controller via a CAN network. The fuel cell controller then sends a flow rate requirement to the mass flow controllers based on (1).

#### 3) Pressure Control

Another critical aspect is maintaining the supplied gases at the highest possible pressure to minimize voltage losses [3]. However, the fuel cell stack does have pressure limits, which if exceeded, can result in the costly damage of internal seals.

The BB2 regulates the oxidizer pressure using passive internally piloted back-pressure valves. These valves are adjusted to provide the desired operating pressure at peak temperature and load. On the anode side, hydrogen pressure is regulated through a quick reacting high-flow hydrogen regulator that is referenced to the cathode pressure. The hydrogen regulator tries to maintain a constant anode pressure that is roughly 500 mbar above the cathode pressure.

A unique pressure control challenge faced by the BB2 is the result of the integration of a manual transmission shifting sequence. This provides a very dynamic change in current draw on each shift. The fuel cells can be operating at over 400 amps per module, but on each shift, the current will momentarily drop to 0. On the cathode side under load, the exiting gases are a mix of the unused oxygen, and the product water in liquid and vapor form. When current draw is stopped, the exhaust gases switch from a low density, water droplet rich stream, back to a higher density pure oxidizer stream. The passive back pressure valves cannot maintain a constant pressure with such a drastic change in gas density, and a pressure spike is seen with each shift.

On the hydrogen side, during high current draw, there are pressure losses due to the high hydrogen flow rates in the regulator, this is referred to as regulator drop. When current draw is momentarily cut for a shift, hydrogen is not being consumed, so the pressure losses are removed, and the hydrogen pressure will spike further above the oxidizer pressure.

To allow operation near the pressure limitations of the stack, extensive testing and system modeling was conducted, so that the pressure spikes during shifts would remain below the design limits, while operating pressure is maximized when drawing full load [5].

*a) Cathode Pressure Tuning*

A unique method to limit this pressure was engineered through a pressure relief valve (PRV) system. PRVs were originally installed on the cathode loop between the humidifier and the cathode inlet to prevent emergency overpressure situations. Later, the system design was improved by controlling the PRVs to limit peak pressures on each shift. The PRVs were set slightly above the highest expected operating pressure that occurs near the end of each run. As the operating pressure rises, the PRVs are used to limit the peak cathode pressure, venting the excess flow during each gear shift.

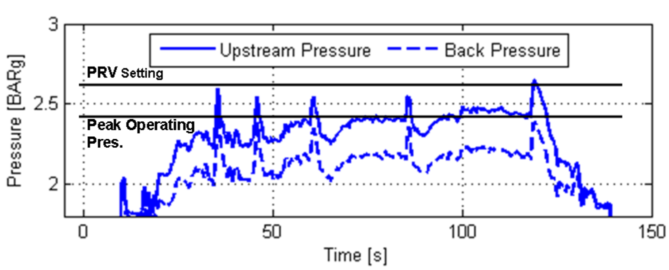


Figure 4. Example of Cathode Pressure Spikes During a Race, with Operating Thresholds for the PRV System.

Figure 4 displays the cathode pressures during a racing test, showing the effects of the PRV when properly tuned to the desired threshold pressure. The PRV is capable of controlling the peak pressure limits of the stack during shift sequences, while allowing the cathode to operate at a higher pressure between shifts. In addition, it was found through simple modeling that the pressure spikes are also reduced if more back pressure valves are used. Packaging allowed the room for an additional back pressure valve to be added to the vehicle, leading a total of 3 back pressure valves.

*b) Maintaining Proper Cross Pressure*

It is critical to maintain a proper cross pressure on the membrane during fuel cell operation. The anode pressure should always be maintained above the cathode pressure. This is because the anode system is a closed system which recirculates the unused fuel, while the cathode is a flow through system that contains the oxidizer. The membrane is never quite a perfect seal, and small amounts of the gases will inevitably flow from the high pressure side to the lower pressure side. In this respect, if the cathode oxidizer gases were to cross over to the anode side, where they were contained and recirculated, it may be possible to build up a combustible mixture of hydrogen and oxygen on the anode side. If there were a problem at the membrane, a hot spot could be developed that could ignite this mixture. In addition to the combustibility of the mixture, maintaining anode positive pressure also aids in keeping the concentration of hydrogen as high as possible at the anode, and reduces the needed number of purge cycles for the anode loop.

While the cross pressure should always favor the anode side, it also has to be controlled to a reasonable limit. Ideally the cross pressure could just be set very high to eliminate any worry, but this can cause a few problems. The largest problem is that the membrane is not able to handle too high of a pressure differential. The membrane is simply a thin film of polymer, and with enough pressure it is possible that it could rupture. This would result in a massive leakage of hydrogen to the cathode and possibly result in a combustible mixture of gases exiting the cathode, and therefore exiting the vehicle. Another concern for limiting the cross pressure is that the membrane could simply deform toward the cathode side, which would increase the flow resistance to the cathode gases. The third concern is that the peak pressure is to be controlled altogether. Therefore the pressure of both the cathode and anode should be maximized, right to the design limit. If the cross pressure is very high, and the anode is set to the operational limit, that will limit how high the cathode pressure can be, and therefore lower performance.

The control of the pressure difference across the membrane is further complicated by the flow design of the stack, as illustrated in Figure 5. The Ballard stacks are set-up in a counter flow layout. Most modern stack designs use this configuration. This means the anode gas enters on one side of the flow channel, and cathode gases enter at the opposite. Due to pressure losses down the length of the channel and the progressive consumption of reactants between inlet and outlet, there is a much larger pressure difference on the side of the anode inlet and cathode exit. If the differential pressure regulator were poorly adjusted, it would be possible for the anode pressure to fall below the cathode pressure on the opposite side of the channel. Thus a delicate balance is required to always maintain positive cross pressure across the entire membrane, without exceeding the pressure limitation of about 700 mbar anywhere on the membrane.

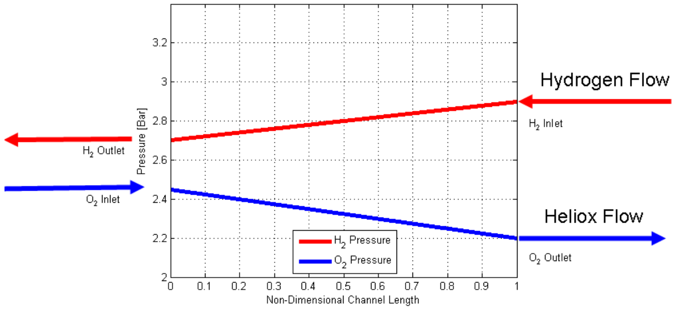


Figure 5. Cross Pressure Under Load for the Counterflow Stack.

### c) *Anode Pressure Tuning*

While much effort was put into controlling the cathode pressure, the previous section indicated it is not actually the limiting pressure in the fuel cell. The real pressure limitation is on the anode side. The Ballard hydrogen delivery system uses a pressure reference regulator that maintains the anode pressure above the cathode pressure. So the total stack pressure limitation comes from the anode pressure. The anode pressure spikes on each shift because it is referencing the cathode pressure.

However the anode pressure actually faces an even higher change between its operating pressure and its pressure spike on each shift. This higher pressure spike is due to the regulator drop of the pressure reference regulator in the anode system. When the regulator is supplying hydrogen gas to match the flow rate required for high current operation, it experiences heavy flow losses, and cannot maintain the same pressure difference as it can in its steady state pressure setting. Then when a shift occurs, hydrogen consumption is momentarily stopped because current draw reaches zero. Thus on each shift the regulator can then reach is its static pressure reference setting. With a simultaneous increase in cathode pressure, this leads to an even higher anode pressure.

A similar solution to the cathode PRV tuning was found to help limit the hydrogen pressure spikes, while maintaining the highest possible hydrogen pressure during normal operation. The Ballard hydrogen supply system already contained a PRV valve. The valve was located downstream of the stack, attached to the same line as the purge valve. The valve is really installed as a marginal safety measure for the stack, as the single valve would not be capable of releasing the full flow rate the hydrogen regulator could provide. In addition, the valve was set fairly close to the design limit, at about 3 bar.

The anode PRV valve did have a variety of springs that were available from its manufacturer. By ordering the spring set that is just below the original one, the cracking pressure of the valve was able to be manually adjusted to be just above the steady state operating pressure of the Anode system under full load. In addition, since the highest pressure on the anode side was up stream of the stack, a second anode PRV was added to the upstream portion of the anode loop, providing two separate PRVs for the anode loop.

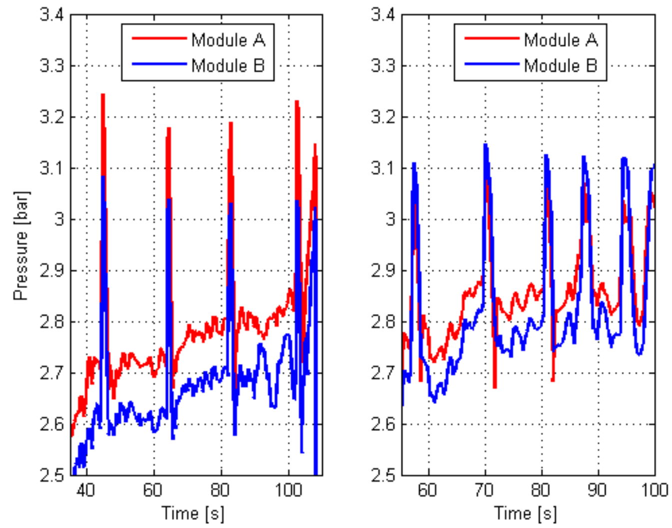


Figure 6. Anode Pressure Tuning Comparison

Figure 6 shows the results of the tuning done to the anode system. The left plot shows a pressure trace before the anode was properly tuned, and the right plot shows the results after all the tuning. The three modifications that were made to the anode system were the installation of the second PRV on the upstream side, properly tuning both the downstream and new upstream PRV, and finally the proper adjustment of the cross pressure regulator. These three adjustments combined resulted in the ability to run the anode at a higher steady state operating pressure under high load, while reducing and controlling the peak pressure obtained during a shift. The adjustments on the anode side were particularly small and sensitive relative to the adjustments for the cathode. The reason for this is likely the significantly smaller volumes in the anode side.

At the conclusion of the pressure testing, adjustments, and design changes that were made to the BB2 fuel cell system, the BB2 fuel cell system was sealed up and shipped to Bonneville for the record setting runs. During the two week period, the fuel cell system performed flawlessly, and zero adjustments were made to any of the pressure regulators, PRVs, or BPVs. During the race event, the vehicle never failed due to any fault of the fuel cell system. As power demand was increased further and further through adjustment to the motor's inverter, the fuel cell supply system was always able to provide the requested power, all while providing clean reliable cell voltages.

## B. *Design of the Cooling System*

One of the challenges for a fuel cell system is in the design of the cooling system for heat removal. A PEM fuel cell stack could theoretically operate above 70% efficiency, but the efficiency decreases with increased current density. The Buckeye Bullet 2 is pushing the current density to nearly the peak power point of the fuel cells, which is a region that operates at approximately 50% efficiency. This means that, for 500kW of electrical power produced, an equal amount of thermal energy must be removed. The use of a traditional liquid-air radiator was quickly eliminated due to the low effectiveness and the aerodynamic drag penalty potentially imposed by the space requirements.

For this reason, a dual-loop cooling system was designed for the BB2, as outlined in Figure 7. The primary loop contains deionized water, and exchanges the heat removed from the fuel cell to the secondary loop through a liquid to liquid heat exchanger. The secondary loop contains regular water, and goes through an ice bath, pump, and the heat exchanger.

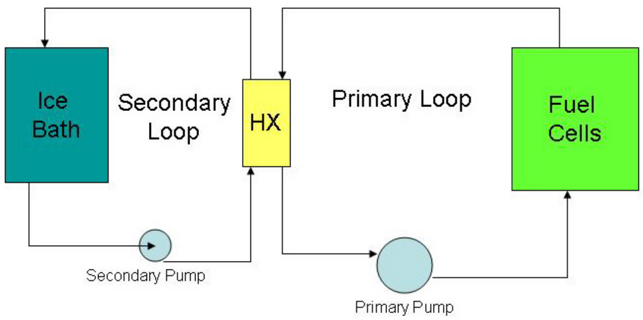


Figure 7. Outline of the Cooling Flow Diagram.

Ideally, the fuel cells would be held at an outlet operating temperature of 80ºC and inlet temperature of 65ºC, thus having a temperature difference across the stack of 15ºC. Since the duty cycle of the fuel cell in this application is well known, the desired thermal cycle is predictable. The stack temperature increases from the initial value until it reaches the desired operating value, and is held constant throughout the rest of the run. If the temperature exceeds 85ºC, the fuel cells are shut down to prevent damage. In this special application, aborting a run is a small price to be paid when compared to the cost of any equipment failures.

There is a good reason, however, to implement closed-loop control of the cooling system. Besides having the fuel cells run at a higher efficiency, closed loop control makes it possible to minimize the mass of the coolant, thus reducing the vehicle weight. As suggested earlier, there are basically three stages of thermal operation for the vehicle. First is the warm-up period, in which the fuel cell outlet temperature is less than 75ºC. Second is the steady state region, where the fuel cell outlet temperature is held at 80ºC. Third is near the end of the run, when the ice bath outlet is greater than 10 ºC.

The first, warm-up stage is when the fuel cells are heating up, beyond the pre-heating temperature (typically 40ºC) that they are brought to prior to running. In this mode, the primary loop flow rate is run proportionally to the current being drawn, in order to maintain the correct temperature gradient across the fuel cell stack, and the secondary loop is inactive. Once the designated temperature has been reached, the controller switches to a setpoint mode, in which it holds the outlet and inlet temperatures constant. Maintaining operating temperature is done using a PID control of the flow rate in the primary and secondary loops. When operating in this mode, the heat is absorbed by the large latent heat of fusion of the ice, and the ΔT across the secondary loop is nearly 80ºC. Finally, once the outlet temperature in the ice bath has exceeded 10ºC (an indication that the ice has nearly run out), the secondary pump needs to ramp up flow rate because the ΔT at the heat exchanger is decreasing as the remaining water heats since the energy is absorbed into heat capacity, rather than heat of fusion.

This strategy is implemented using a PID controller with a feed-forward element, defined as

$$\dot{V}_{FC} = f_{feedforward}\left(T_{FC,out}\right) + K_{P,IB}\int\left(80 - T_{FC,out}\right) + K_{I,IB}\left(80 - T_{FC,out}\right) \quad (2)$$

where $f_{feedforward}$ is an empirical lookup table, $K_P$ and $K_I$ are the proportional and integral gains, respectively. The desired operating temperature of the fuel cells in this equation is 80ºC.

## IV. VEHICLE SIMULATION AND CONTROL

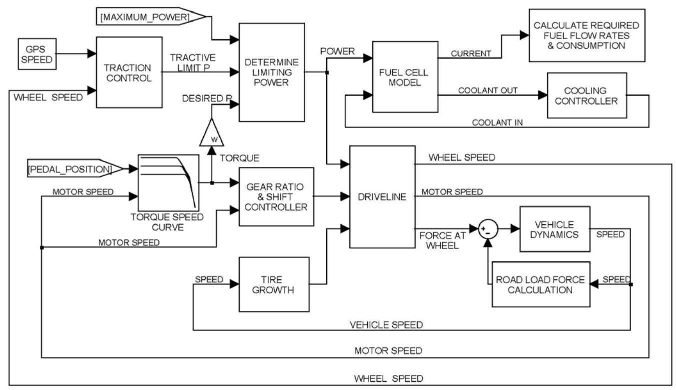


Figure 8. Block Diagram of the Vehicle Simulator.

In order to facilitate optimization and control studies, a forward-oriented vehicle simulator was built. Figure 8 shows the flow of information in the model.

The simulated driver is modeled so as to demand the maximum available power at all times except during a gear shift. Based on known models of the motor, the requested power is compared to the theoretical peak tractive force of the tire and sent through the drive line. The actual power demand is then sent to the fuel cells, where the theoretical gas flow rates are computed. The cooling controller manages the heat generation in the stack and maintains the optimal temperature. The traction force at the wheel is then computed by accounting for the various power losses in the drive line. The resulting vehicle acceleration is ultimately computed by applying Newton's second law to the longitudinal dynamics of the vehicle, and by accounting for the road loads [7]. The shift controller monitors output power and predicts when output power is better in the next gear. The simulation is terminated when the vehicle has traversed the length of the race course [6].

The supervisory controller represents the top level of control and arbitration for the vehicle. This controller handles a variety of alarms such as those from the fuel cells, temperature limits, and fuel starvation and tank pressures, and also monitors the driver's torque requests and moderates the power between the fuel cells and inverter based on these requests. As seen in Figure 9 the supervisory controller provides the primary inputs to each of the main controllers, from the input of driver throttle. This controller uses the cooling temperatures, driver torque requests, available fuel cell current, and motor speed to provide to the various subsystems fuel cell outlet temperature, ice bath outlet temperature, requested fuel cell current, and requested motor torque. This is implemented as rule-based control, using techniques learned through years of land speed racing [8].

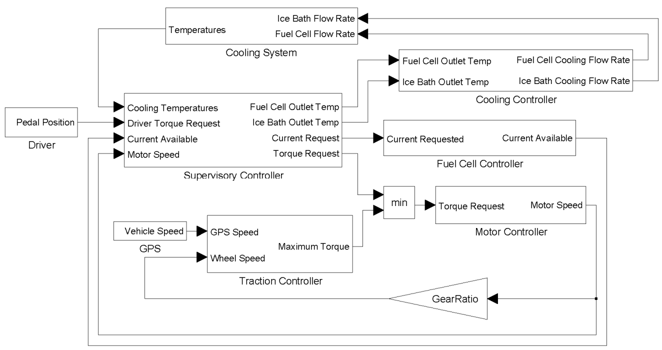


Figure 9. Block Diagram of the Supervisory Control Architecture

One of the main tasks for the supervisory controller is safety. Since it has the highest level of information of the vehicle, it can make split-second decisions regarding the vehicle. One big role is to ensure that the motor controller does not draw more power than the fuel cells have ready. Drawing power too early can cause fuel or oxidizer starvation, so the balance of power draw between the motor and the fuel cells must be carefully managed.

The simulator and supervisory controller were extensively validated during the BB2 vehicle design. Initially, experimental data were acquired on the individual vehicle components (electric motor, inverter, fuel cell, etc…), to characterize each submodel. Then, validation of the models and control algorithms was performed using laboratory and race data.

## V. Race Results

The results of the simulation, testing and design work are here summarized in Figures 10 and 11, which report experimental results during the record setting vehicle race.

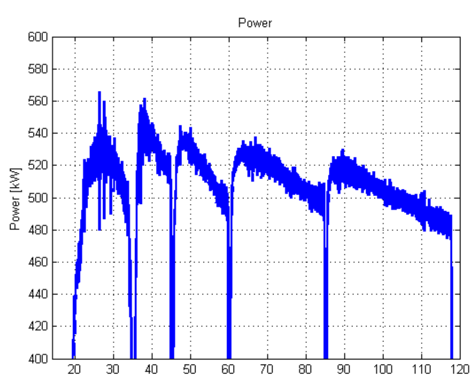


Figure 10. Fuel Cell Power Produced During The Record Setting Run.

Figure 10 shows the fuel cell power profile during the course of the race, while Figure 11 shows the vehicle speed as a function of the distance. It is worth observing that the design of the propulsion system allowed the two fuel cells to deliver a peak power of over 540 kW to the inverter, more than twice of the original power rating.

Figure 11 shows the vehicle velocity profile during the race. The record speed was achieved through the average of two runs in opposite directions, within one hour.

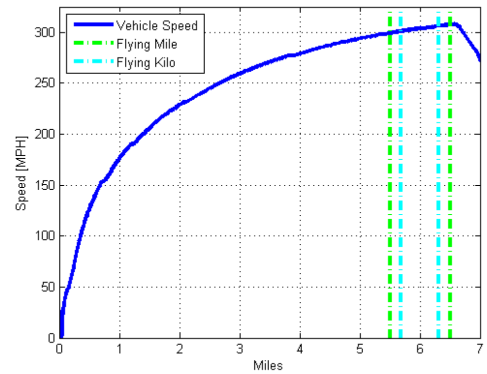


Figure 11. Vehicle Speed vs. Distance for Record Setting Run.

## VI. Conclusion

The design of the Buckeye Bullet 2, the world's fastest hydrogen fuel cell electric vehicle, is described in this paper. The focus of the paper is on the engineering challenges that were solved during the design of the propulsion system. This required a combined effort in modeling, simulation, control and integration that led the Buckeye Bullet 2 team to the achievement of a certified FIA record of 487.433 km/hr (302.877 mi/hr).

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