FINAL REPORT

Connected Vehicle Technologies for Efficient Urban Transportation

Date: Sep 2016

Prof. Ajay Prasad (UD) prasad@udel.edu
Prof. Suresh Advani (UD) advani@udel.edu
Prof. Hyeon-Shic Shin (MSU) hyeonshic.shin@morgan.edu

Prepared by:
Prof. Ajay Prasad
Department of Mechanical Engineering
University of Delaware
Newark, DE 19716-3140

Prepared for:
Virginia Center for Transportation Innovation and Research
530 Edgemont Road
Charlottesville, VA 22903

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Connected Vehicle Technologies for Efficient Urban Transportation		5. Report Date 10/24/2016
		6. Performing Organization Code
7. Author(s) Prof. Ajay Prasad (UD) Prof. Suresh Advani (UD) Prof. Hyeon-Shic Shin (MSU)		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Delaware Department of Mechanical Engineering Newark, DE 19716-3140		10. Work Unit No. (TRAIS
		11. Contract or Grant No. DTRT13-G-UTC33
12. Sponsoring Agency Name and Address US Department of Transportation Office of the Secretary-Research UTC Program, RDT-30 1200 New Jersey Ave., SE Washington, DC 20590		13. Type of Report and Period Covered Final 1/1/15 – 8/31/16
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Connected vehicle technology is employed to optimize the vehicle's control system in real-time to reduce congestion, improve fuel economy, and reduce emissions. This project's goal was to develop a two-way communication system to upload vehicle data to a server at the Traffic Management Center (TMC) or to other servers in real-time, and download traffic information from TMC or other sources to the vehicle. To pursue this task, a computational optimization model was developed in order to send the optimal control strategies to the vehicle. The model's results were analyzed to evaluate reductions in traffic congestion and improvements in vehicle efficiency and fuel economy. The optimization module was integrated with an on-board control system to maximize fuel efficiency based on real-time traffic inputs and navigational guidance. Durability was also added to the optimization model to improve the lifetime of fuel cell system. The ultimate goal is to implement an intelligent power management system to optimize fuel consumption, emission and durability all at the same time leveraging real-time traffic information.

17. Key Words	18. Distribution Statement
Connected Vehicle Technology, Fuel Cells, Transit Bus, Battery, Durability	No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	23	

Acknowledgments

We are grateful to MATS-UTC which provided the funding to make this work possible.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the U.S. Department of Transportation's University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Contents

List of Figures

List of Tables

Background

Like most of the nation, the urban transportation system in the mid-Atlantic region suffers from severe congestion. This results in reduced traffic capacity, longer travel times, reduced fuel economy, higher rates of vehicle emissions, and higher vehicle and roadway wear and tear. A solution is urgently needed to increase traffic capacity and reduce congestion.

Connected vehicle technology represents a powerful tool to create a solution for current urban transportation systems which have become increasingly congested over the years. The development of these technologies would enable real-time vehicle-to-vehicle and vehicle-to-infrastructure communication that can be leveraged in many useful ways. The real-time availability of various data, such as location and velocity of vehicles, and road and weather conditions give rise to numerous possibilities to improve fuel efficiency such as adaptive cruise control, signal timing control, and eco-navigation systems. In conjunction with the development of hybrid electric vehicles, these data can also be exploited to optimize on-board control systems to maximize fuel economy and vehicle durability.

Historical traffic data have provided strategic inputs for roadway planning, and general guidance for traffic control and vehicle navigation. While this has proven very useful for traditional traffic management, it cannot account for local fluctuations in real-time traffic due to traffic incidents or weather-related factors. Also, there does not currently exist a robust algorithm to calculate the most economical route for individual vehicles in real-time due to the inherent complexity of this problem and the lack of real time traffic data. New developments in connected vehicle technology enable vehicles to communicate information such as position and velocity with other nearby vehicles as well as with associated infrastructure. This technology provides the most accurate real-time traffic data to date and can become the foundation for various strategies to improve the overall efficiency of traffic systems. For example, vehicles within a given proximity of each other with similar routes could group together to form a 'platoon' which would not only reduce the gap between vehicles while maintaining high speed and increase the overall capacity of a given roadway, but also improve aerodynamics and save significant amount of fuel. Real-time traffic data could also be used to provide fuel-economic routes to individual drivers especially in situations involving traffic incidents or severe weather. Systematic route optimization can also be very useful to reduce congestion caused by massive traffic flux during rush hours. The same data will also be beneficial for electric drivetrain vehicles (including all-electric, hybrid, plug-in hybrid, and fuel cell vehicles) to predict system load and optimize the on-board power management system intelligently to achieve the highest fuel economy and system longevity.

The Center for Fuel Cell Research (CFCR) at the University of Delaware (UD) has been operating two 22-ft fuel-cell/battery hybrid buses as student shuttles since 2007. The drivetrain of the buses is schematically depicted in Figure 1. A system called Universal Data Acquisition and Control, or UDAC, has been developed to record all vehicle data using a host of on-board sensors and to automatically transmit it to a central laboratory server in real-time. The computer is also equipped with a cellular modem that provides internet connectivity. This system serves the needs of multiple user communities:

- It compiles an operational history of the bus with important information about each run, which is available for research purposes as well as for public web access.
- It sends immediate warnings of vehicle faults to the staff responsible for maintenance.

- It provides detailed data to researchers at the Fuel Cell Research Lab who wish to analyze the buses' performance.

These data are then used to assess traffic patterns along the bus route which enables the on-board control system to operate in an intelligent manner to maximize fuel economy and system durability (a fluctuating power demand and frequent startup/shutdown can reduce the lifetime of the fuel cell stack).

Second, we have previously developed a powerful vehicle simulation software tool called LFM (Light, Fast and Modifiable) that allows us to simulate the fuel cell bus system under any desired driving schedule. The whole platform can be readily modified for connected vehicle technologies and incorporated into an intelligent transportation system to provide data collection, analysis and control system optimization.

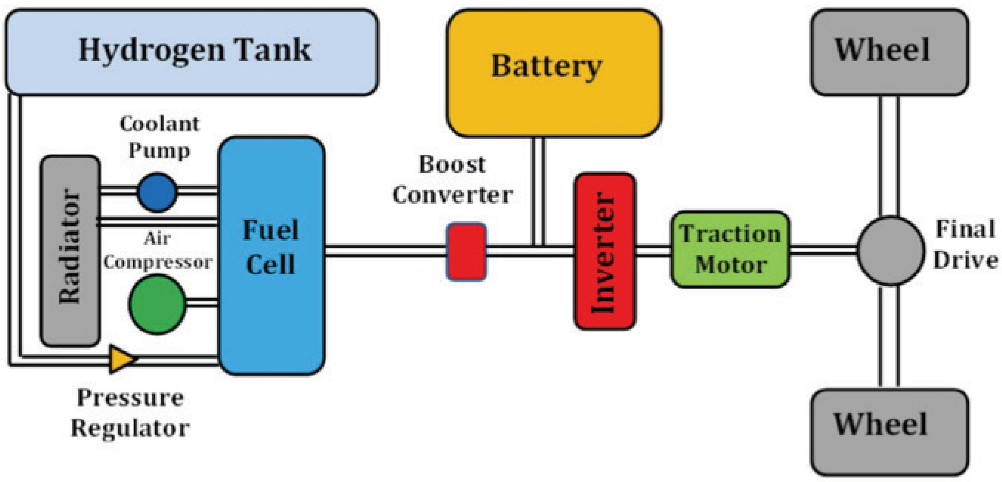

Figure 1 Schematic drivetrain for UD's hybrid fuel cell/battery bus.

Our previous research has involved collecting historical work load data for the buses with the goal of modifying its control strategy using our LFM simulation tool to maximize fuel economy and fuel cell stack life [1-4]. We have previously shown that an intelligently optimized control system can generate up to 10% saving in fuel consumption while maintaining a steady power demand from the fuel cell which improves its durability. The LFM model has also been used to optimize the control strategy for a fuel cell/battery hybrid forklift, which has become very popular for material handling [5] owing to its zero-emission nature. LFM can be easily modified to simulate any type of hybrid vehicle such as the most popular internal combustion engine (ICE)/electric hybrid vehicle such as the Toyota Prius.

The future transportation system has to solve two major problems, congestion and environmentally-friendly transportation, which basically demand improving the efficiency of both the roadways and the vehicle. Our research will optimize both traffic flux and vehicle fuel economy which will lead to a solution to both of these problems. Our proposed transportation system will consist of multiple components intelligently integrated to operate at their optimal condition. The outcome from this project will be a more efficient transportation system that responds to routine as well as atypical traffic situations in an intelligent and efficient manner. Results from this effort will provide key insights as we progress toward a future with fully connected vehicle systems.

Research Objectives and Approach

We proposed a solution based on *connected vehicle technology* to optimize the vehicle's control system in real-time to reduce congestion, improve fuel economy, and reduce emissions. The goal is to develop a two-way communication system to upload vehicle data to a server at the Traffic Management Center (TMC) or to other servers in real-time, and download traffic information from TMC or other sources to the vehicle. To pursue this task, a computational optimization model will first be developed and the optimal control strategies will be sent to the vehicle. The model's results can be analyzed to evaluate reductions in traffic congestion and improvements in vehicle efficiency and fuel economy. The optimization module will be integrated with an on-board control system to maximize fuel efficiency based on real-time traffic inputs and navigational guidance. Durability will also be added to the optimization model to improve the lifetime of fuel cell system. The ultimate goal is to implement an intelligent power management system to optimize fuel consumption, emission and durability all at the same time leveraging real-time traffic information.

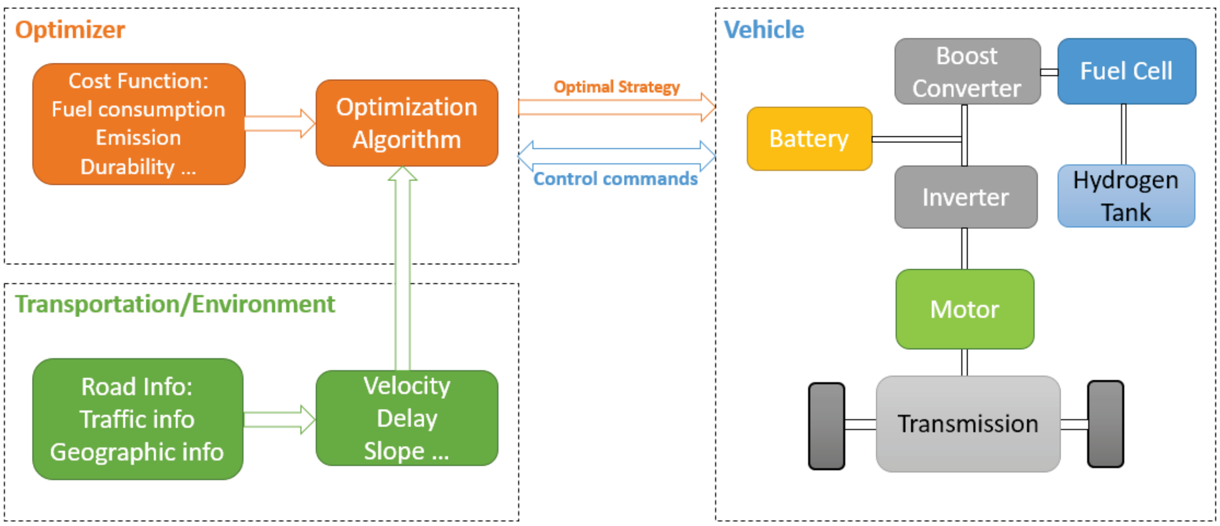

Figure 2 Connected vehicle technologies for efficiency power management of hybrid vehicles.

Approach

The University of Delaware has been conducting a very successful Fuel Cell Hybrid Bus Program since 2005 to research, build and demonstrate fuel cell powered buses and hydrogen refueling stations in Delaware. Under funding from the Federal Transit Administration we have successfully demonstrated two 22-ft fuel cell buses with a 140-mile range on our campus since 2007. The buses transport students across campus as part of the UD shuttle bus system. One larger 40-ft advanced fuel cell hybrid bus was added to the University of Delaware's fleet in December 2015. We have also successfully demonstrated a hydrogen refueling station for our bus program since 2007. The buses have been shown to be reliable, safe, and efficient while producing zero emissions.

Several tangible benefits from the UD Fuel Cell Bus Program can be leveraged for the proposed work. First, we have developed a powerful Matlab/Simulink based simulation tool called LFM to simulate the performance of our buses on a variety of driving schedules. This in-house software has been validated against actual data acquired from the buses and it has been confirmed that its key outputs such as hydrogen consumption, battery state-of-charge, and fuel economy are accurate. Second, we have already developed a one-way cellular link between our buses and a server in the lab. Data is continuously recorded by on-board computers and relayed to the lab server for real-time analysis and fault-detection. We propose to convert this one-way communication into a two-way communication to optimize both the transportation system and the vehicle's control system in real-time. Hence, we intend to leverage all of our accumulated experience with the UD Fuel Cell Bus Program to make rapid progress with the proposed tasks.

Our intent was to use our fleet of fuel cell hybrid buses and our LFM simulation tool to analyze and solve many problems related to urban transportation system. A two-way communication system between sever and bus was developed to exchange vehicle data, traffic and other information. Finally, the optimization model was developed to generate the optimal power control strategy for the hybrid bus to improve fuel economy and fuel cell durability under a variety of traffic and weather conditions.

After successful validations of the real time two-way communication system and optimization control system developed and implemented under this program with our UD fuel cell hybrid bus fleet, the on board control and communication system was integrated into a single portable device which was installed on our fuel cell bus3. The modules can be expanded in the future for real time eco-routing system for local traffic as well as for programming the arterial network to reduce congestion and improve fuel efficiency based on information gathered from individual optimal power management systems in a crowd-intelligent way. The regional demonstration of this system can be easily adapted and combined with future nationwide connected vehicle system to form the intelligent transportation system.

Tasks Completed

1. **Modeling of hybrid fuel cell bus**: A platform to develop optimization algorithms to improve fuel cell economy and vehicle durability was created in Matlab.
2. **A new optimization model with dynamic programming:** A new approach based on dynamic programming (DP) was developed to optimize power management system.
3. **Collection of trip data with fuel cell hybrid bus2**: An interface was created to extract various metrics for the analysis of bus performance and efficiency under (1) the rule-based power management system, and (2) the optimization-based power management system.
4. **Optimization based power management of hybrid vehicle with known velocity profile**: Using dynamic programming, new algorithms were formulated and the results for fuel economy were compared with the original rule-based power management system.
5. **Sizing study with different cost functions**: An EPA drive cycle (UDDS) was employed as a benchmark to determine the optimal sizing of fuel cell hybrid buses under different traffic conditions. Different cost functions were used in the optimization process to account for fuel economy and durability.
6. **Two-way communication system**: A two-way communication system was built based on our current one-way communication system on the hybrid bus. The system consisted of a web server and a cellular communication system.

Below we summarize the details of the tasks completed.

1. Modeling of hybrid fuel cell bus

The power management system of a hybrid fuel cell bus can be viewed as a simplified energy balance equation shown below:

$$\eta_{fc}P_{fc} + \eta_{batt}P_{batt} = P_{trac} + P_{aux}$$

where:

P_{fc} : is the gross power from fuel cell stack
η_{fc} : is the efficiency of fuel cell stack depending on gross power
P_{batt} : is the battery gross power
η_{batt} : is the efficiency of battery system depending on SOC
P_{trac} : is the power demand of traction system
P_{aux} : is the auxiliary power of other on-board accessories

The efficiency of the fuel cell stack and battery pack was obtained from experimental data provided by the manufacturer of the corresponding components. Auxiliary power is relatively small compared to the traction power required to drive the heavy bus and thus is normally treated as a constant. The traction power can be modeled as:

$$P_{trac} = (ma + mg\sin\theta + (C_{r1} + C_{r2}v)mg\cos\theta + \frac{1}{2}\rho A C_d v^2) * v/(\eta_{trans}\eta_{motor})$$

which includes the acceleration force, gravity, rolling resistance and aerodynamic resistance. Efficiency of the transmission and motor were also obtained from experimental data provided by the manufacturer.

A Simulink model called LFM was developed as a numerical simulation platform to evaluate various aspects of the performance of current bus2. The model consists of the battery system, fuel cell system, and traction system as shown below:

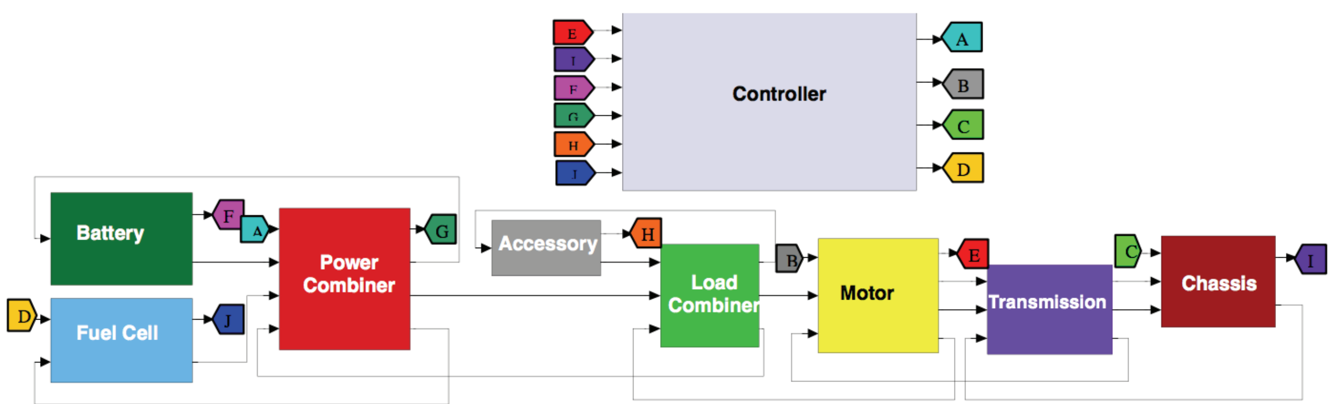

Figure 3 Different subsystems of the LFM Simulink model.

The original LFM model employed a rule-based power management system, which determines the fuel cell power by calculating the running average traction power consumption and desired battery end-state-of-charge (SOC). Any velocity profile can be fed in to the Simulink model, and a sample result is shown below. The result consists of input velocity profile, battery SOC, running average power consumption, fuel cell power output, motor power demand, battery power output and fuel consumption. In the sample results shown in Figure 4, the drive cycle is much too short for the fuel cell to turn on, and hence the vehicle drives purely on battery power, due to which the battery SOC declines steadily from 0.75 to 0.66.

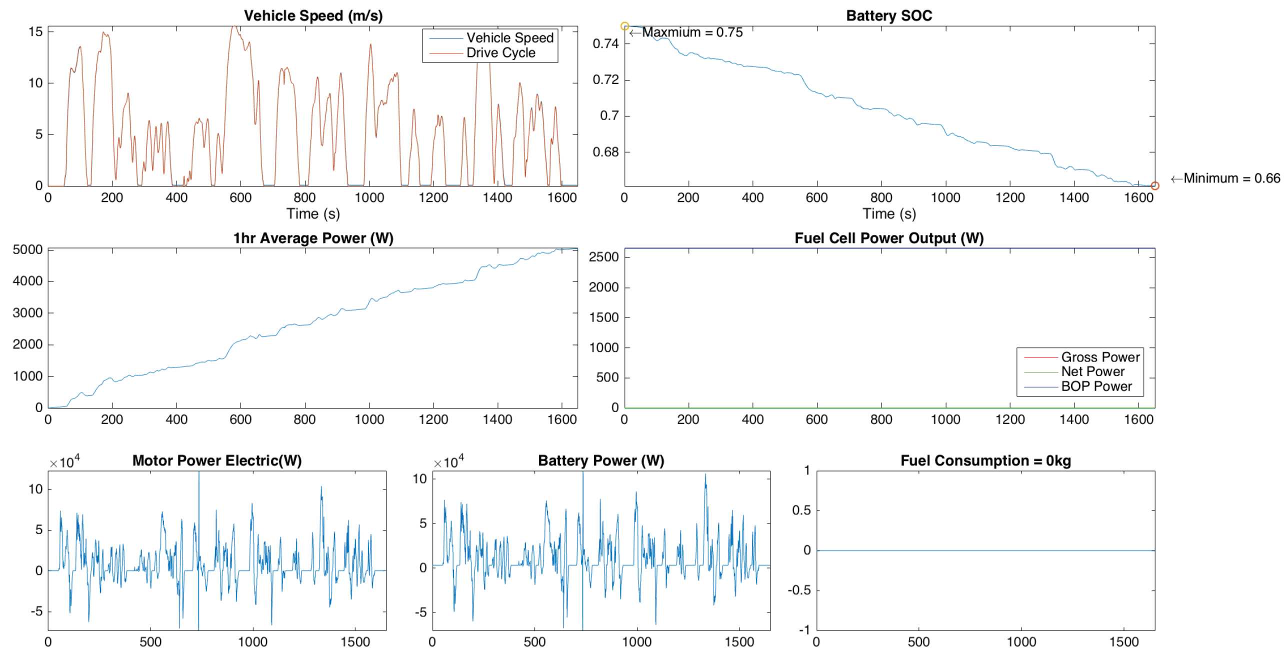

Figure 4 Sample results from LFM for bus2 operating on a typical UD shuttle bus drive cycle.

2. Optimization model with dynamic programming

A new optimization model was developed in Matlab because the existing Simulink model usually carries a lot of block-to-block overhead which makes it very slow; this situation will become worse considering the high computational demand of the dynamic programming (DP) method. So the original LFM vehicle model was modified and coded directly into Matlab to improve performance.

The cost function of the optimization algorithm and its form in DP is shown in *Eqn. 1* which includes fuel consumption and the number of on/off cycles (N) of the fuel cell stack for a specific drive cycle. The purpose of including the number of on/off cycles is to prevent the fuel cell system from turning on/off too frequently which has been shown accelerate degradation and compromise the durability of the fuel cell stack (the platinum catalyst in the fuel cell electrodes tends to dissolve rapidly when cell voltage transitions from low to high state during startup/shutdown) [6]. The state variable x_k only contains SOC assuming the ramp rate of fuel cell power is relatively high for commercial fuel cell stacks. The control variable u_k is the fuel cell power $P_{fc.}$

$$J = \int_0^T \dot{m}_{H2}(t)\, dt + \sum_0^T \alpha N$$

$$\begin{aligned} min: \quad & J = \sum_{k=0}^{N} c(x_k, u_k) \\ subject\ to: \quad & x_k = SOC \end{aligned}$$

Eqn. 1 DP with fuel consumption and on/off cycles as cost function

3. Collection of trip data for analysis with fuel cell hybrid bus2

All historical running data of bus2 had been previously collected and archived on our lab server. Organized information regarding all the trips can be found in Google calendar on our website: http://fcrl.me.udel.edu/. A typical UD shuttle bus route is shown in Figure 5 which circles around the main campus. The availability of realtime traffic data depends on the reception quality of campus Wi-Fi network. Bus2 transmits all its collected data to the server whenever the network is available and can serve as a realtime traffic probe in the framework of connected vehicle technologies.

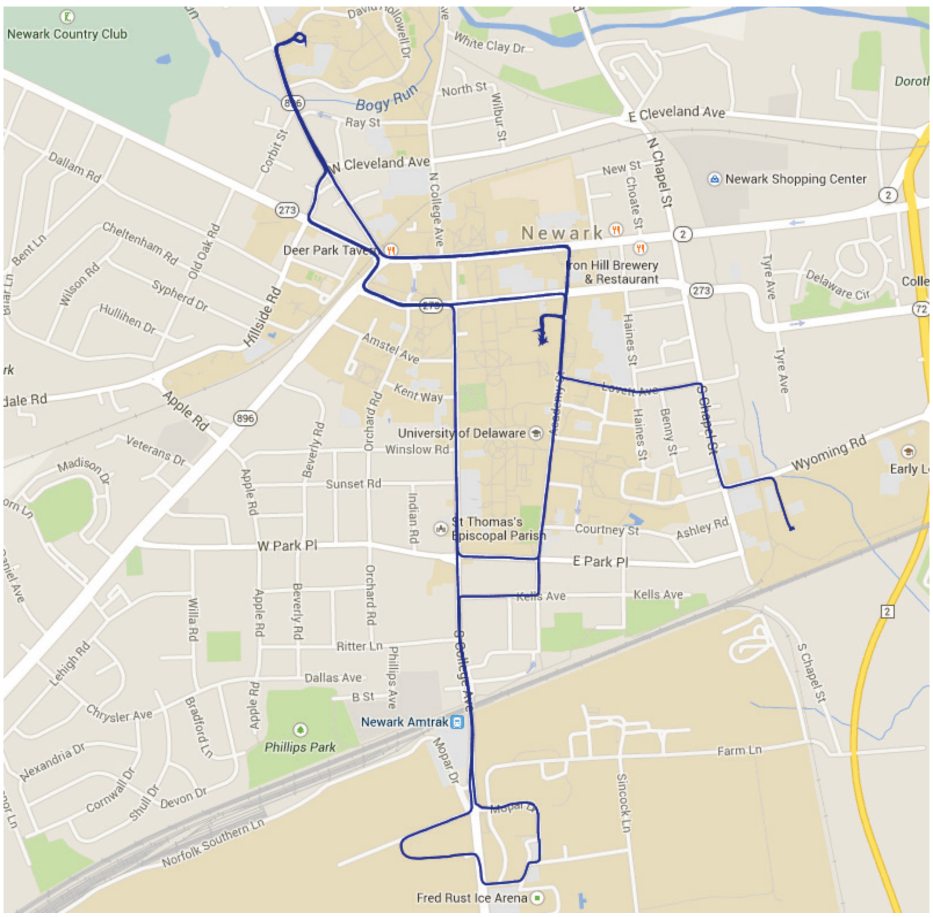

Figure 5 One of the UD student shuttle bus route.

Summarized trip information is calculated from data collected from on-board sensors. A typical trip is shown in *Table 1*. Information like energy to traction system and regenerated energy are important in designing a rule-based power management system which often relies on prediction of the average running power to determine when to turn on the fuel cell system to charge the battery and the corresponding demanded power.

Distance	**57.3 km**
Stop ratio	**0.338**
Fuel consumed	**2.250 kg**
Energy from battery	**2.017 kWh**
Net energy to traction	**24.266 kWh**
Regenerated energy	**9.516 kWh**
Energy to auxiliaries	**9.270 kWh**
Starting battery SOC	**85.0 %**
Ending battery SOC	**53.4 %**
Total vehicle energy use	**33.536 kWh**
Hybrid on time	**1.760 hr**
Gross energy from fuel cell	**40.699 kWh**
Net energy from fuel cell	**31.519 kWh**

Table 1 Summarized trip information of bus2.

The bus route is not always fixed depending on the schedule of UD shuttle bus fleet, but the trip data can be extracted and summarized for a specific segment of the road often taken by the hybrid bus as shown in Figure 6. Each line indicates a different trip passing through this segment and the velocity profile in the figure shows the location of fixed bus stops as well as random stop-and-go's in between bus stops.

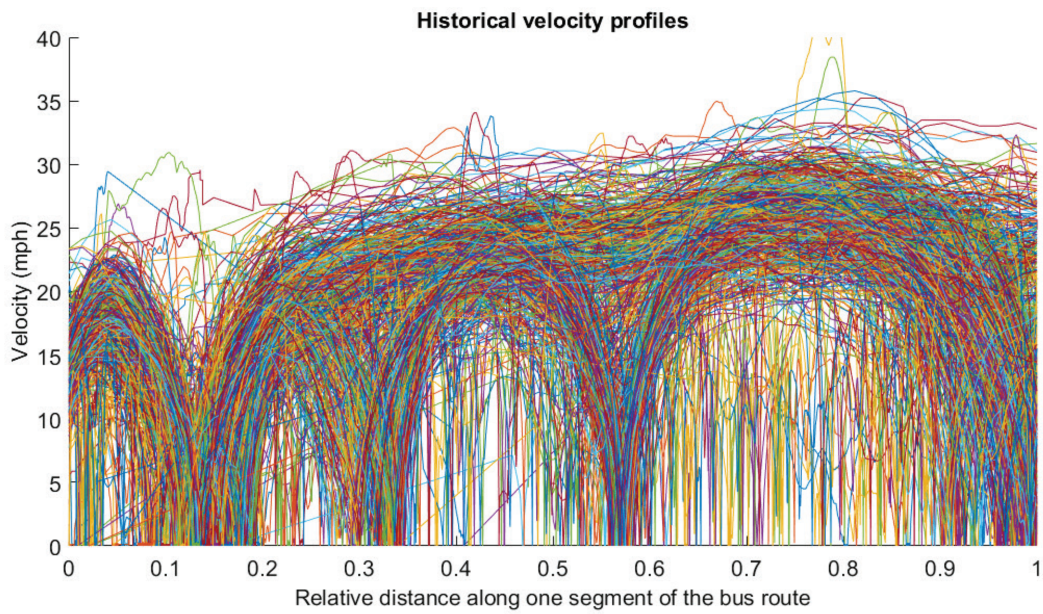

Figure 6 Historical trip data of bus2 along a segment of bus route.

Figure 7 shows a less dense trip velocity profile separated by the day of the week. The velocity profiles indicate a traffic intersection rather than a bus stop because there are many trips where the bus does not stop at all when passing through it.

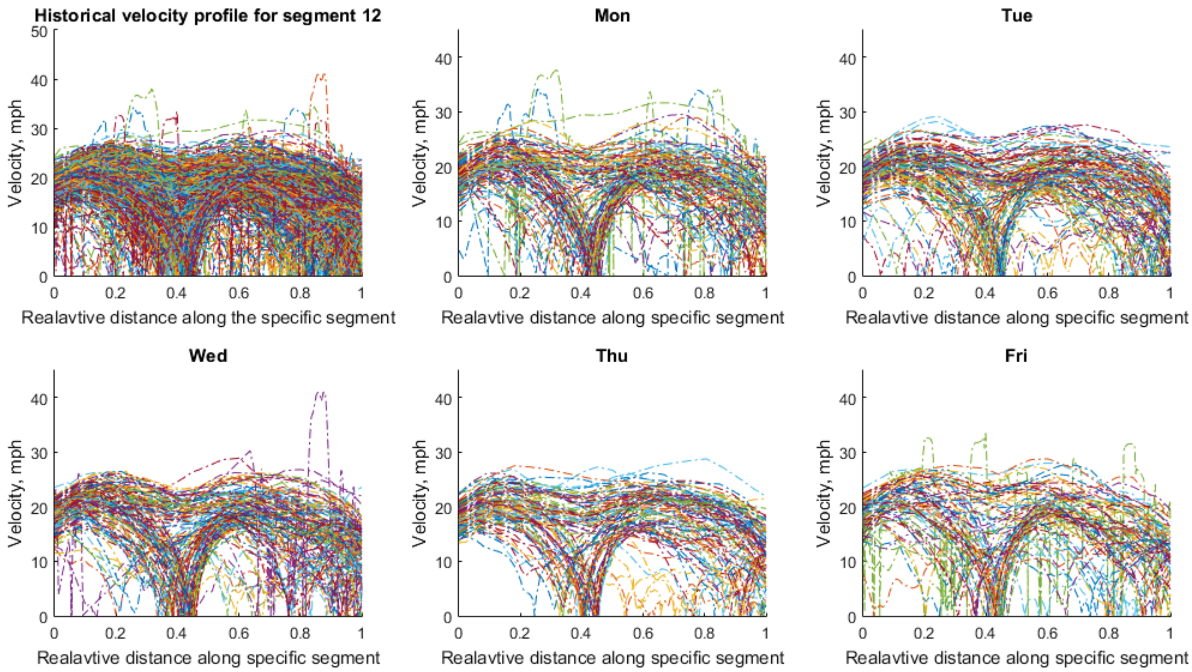

Figure 7 Historical trip data of bus2 along a segment of bus route over weekdays.

Although the trip velocity graphs show a strong pattern, they are also highly stochastic which makes it harder to utilize them for power management purposes. There have been many efforts in the literature [7] to build a stochastic model of the velocity profile, but they mostly capture the driving behavior rather than traffic information. More accurate realtime traffic information is needed to develop a better practical power management system.

4. Optimization based power management of hybrid vehicle with known velocity profile

An EPA UDDS drive cycle was used as a benchmark to develop an optimization-based power management system. The original LFM Simulink model was used as a reference for developing a new vehicle model in Matlab which was then validated against the original model. A dynamic programming (DP) optimization algorithm was also developed in Matlab with the cost function, state variable and control variable as shown in *Eqn. 1*. Initial and end-SOC were both set to 70% to ensure a continuous routine drive cycle which is typical for bus operation. A comparison between the SOC trajectory from the DP model and the original LFM model is plotted at the top in Figure 8 which shows excellent agreement. The middle panel shows the optimal fuel cell net power command calculated from the DP. The DP has a 2s time-step to save computational time, and so the fuel cell power is filled to have a 1s time step at the end and is then fed into the original model to validate the DP model. Traction power shown in the bottom panel also matches very well with the original model.

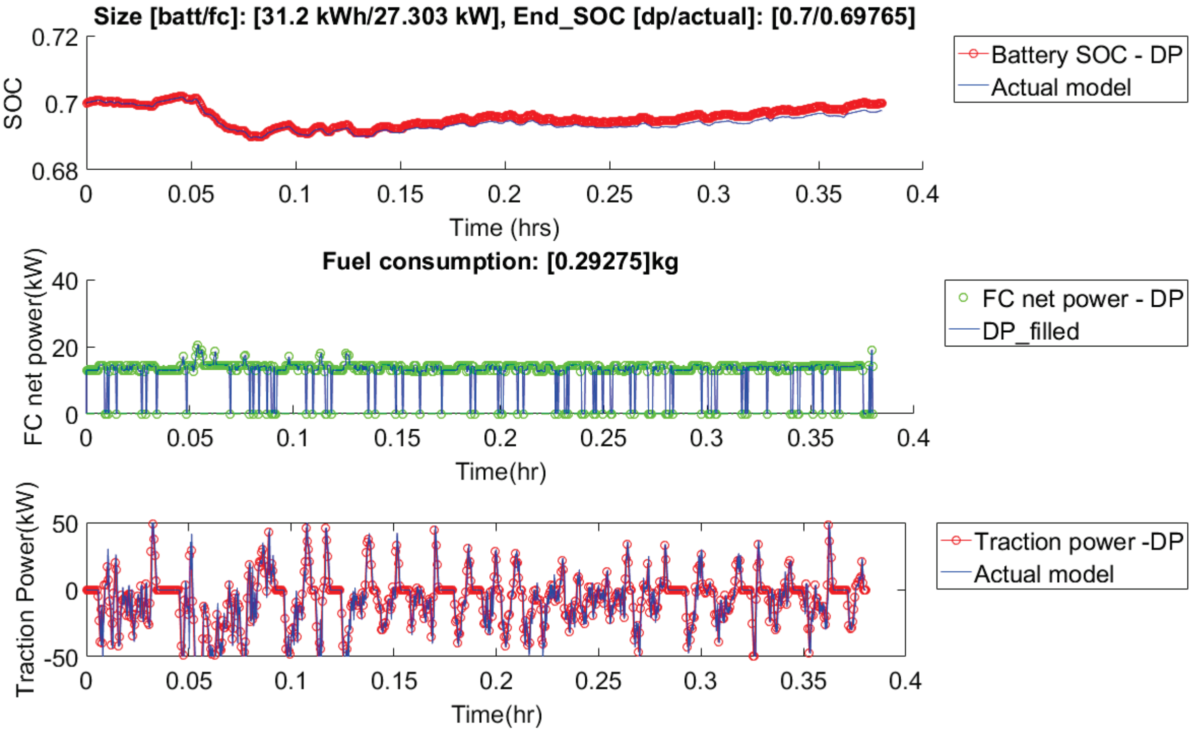

Figure 8. Optimal control without on/off penalty.

Figure 8 is the simulation result with α in *Eqn. 1* set to 0 which means there is no penalty for on/off cycles. It is obvious that the fuel cell system experiences a high frequency of on/off cycles which is not good for the durability of fuel cell system. A comparison of the DP optimization-based power management and the original rule-based power management system is shown in Figure 9. It shows that DP optimization-based power management reduces fuel consumption by 3.1% from 0.30205kg to 0.29275kg compared to the rule-based strategy. This is a significant saving when extrapolated to the entire fleet. Also, it should be noted that the fuel cell power profile from the DP model exhibits an excessive number of on/off cycles compared to the rule-based model which only uses average running power consumption as input.

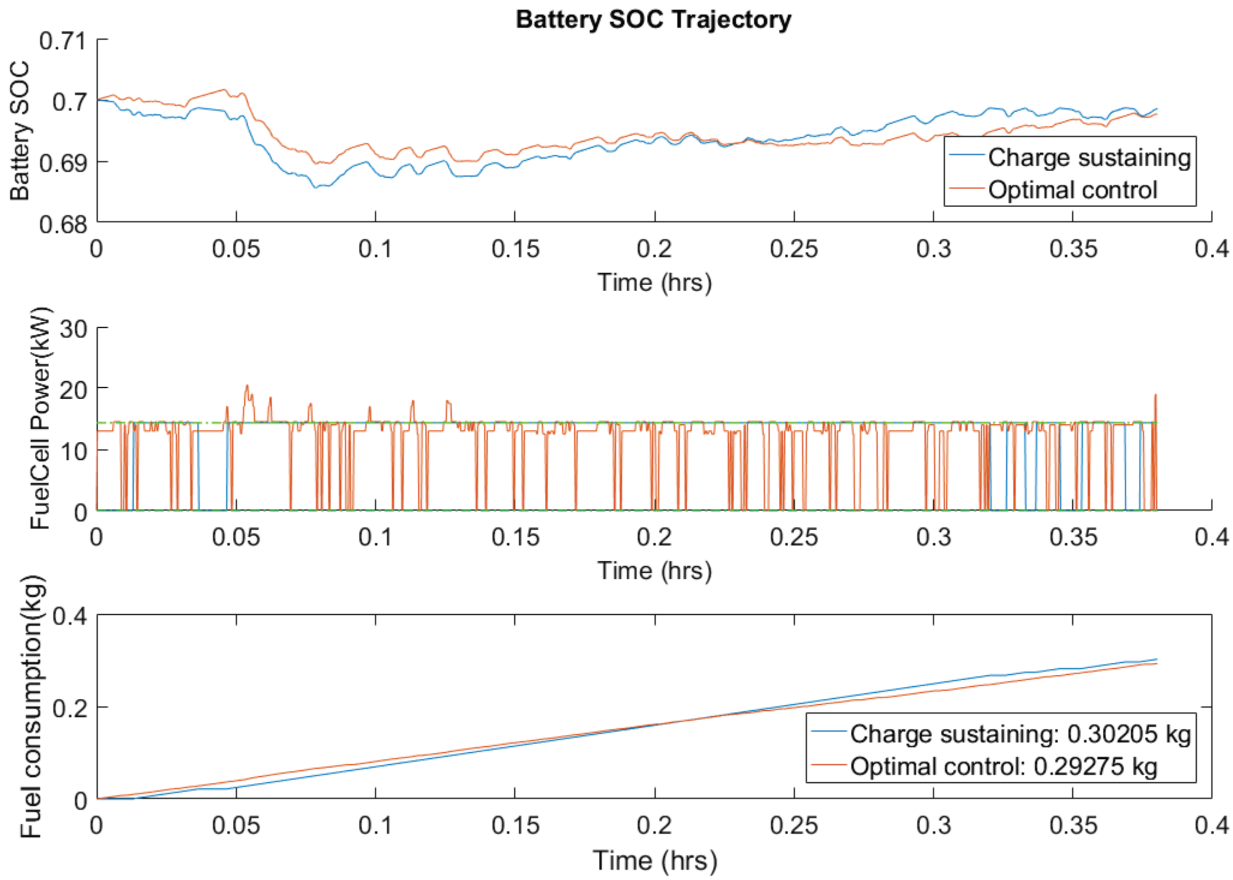

Figure 9 Rule-based control vs DP-based optimal control without on/off penalty.

Frequent on/off cycling is not desirable in a real power management system. Hence, next we added a penalty for on/off cycling to the cost function to mitigate this issue. Accordingly, the exact same drive cycle was simulated again with α set to 0.001 which adds a small penalty to on/off cycling of the fuel cell system. The DP results are shown in Figure 10. The added penalty term immediately suppressed the frequent on/off cycling seen in Figure 8, which is desirable from a durability viewpoint of the fuel cell stack.

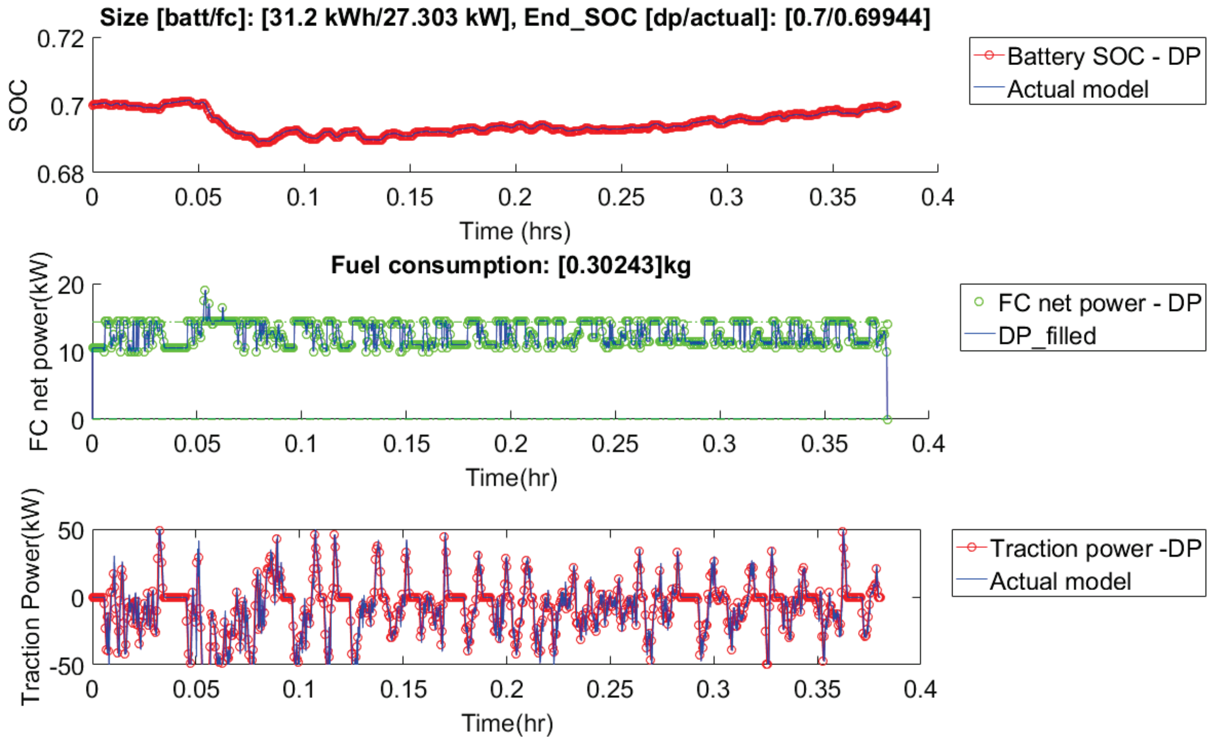

Figure 10. Optimal control with on/off penalty.

A comparison of the DP optimization-based power management and rule-based power management system in Figure 11 shows that the optimization-based power management reduces fuel consumption by 2.4% from 0.30953kg to 0.30233kg if both fuel consumption and stack durability are optimized. This is not as good as 3.1% when only fuel consumption is optimized, but it may be an acceptable outcome considering it completely suppressed the frequent on/off cycling of the fuel cell system. Adding a penalty for on/off cycling to the objective function ensures a smoother workload for the fuel cell stack and thus extends its lifetime.

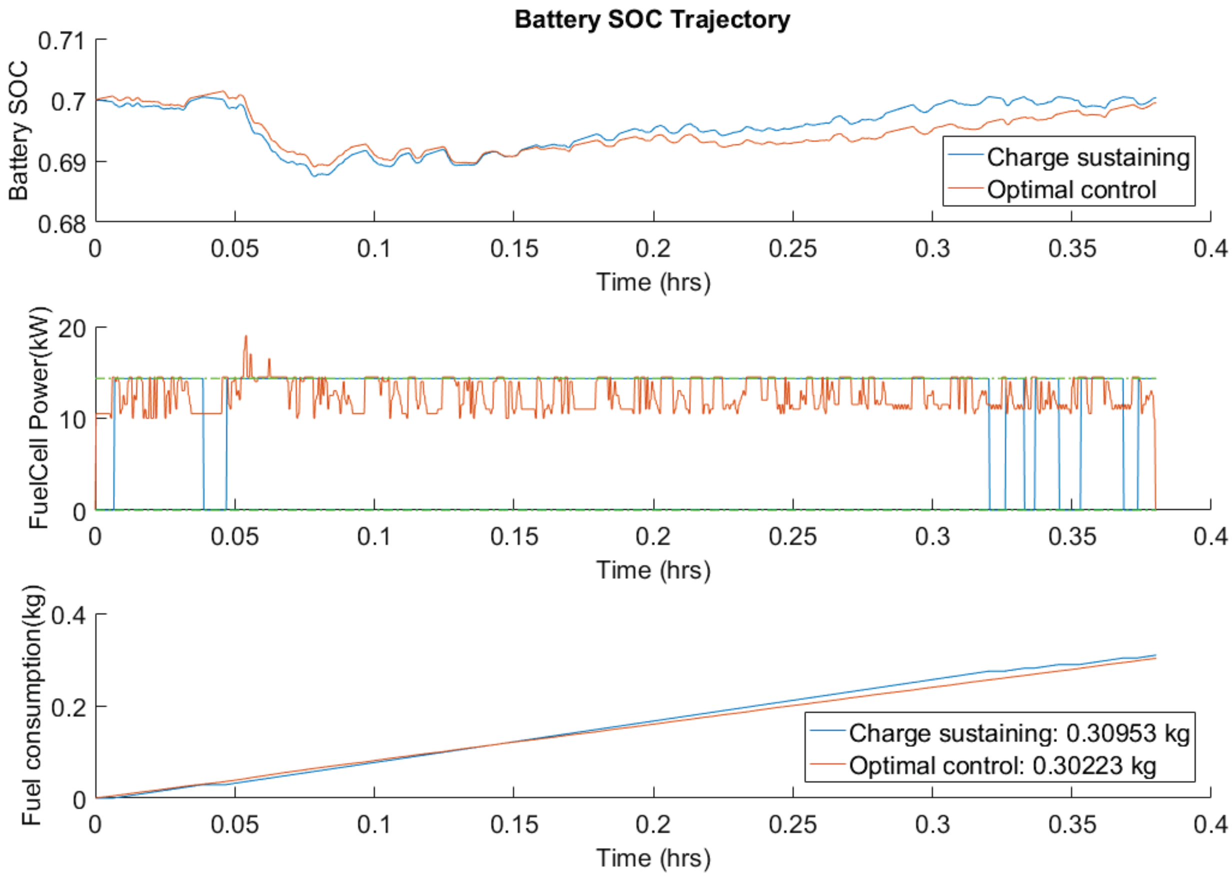

Figure 11 Rule based control vs optimal control with on/off penalty.

Figure 11 also shows that although the added penalty effectively suppressed on/off cycling, there is still quite a bit power fluctuation. Realizing that bus2 has a hybrid configuration with a relatively small fuel cell system and large battery pack, this means the fuel cell system on bus2 works as a range extender whose role is to charge the battery to sustain its SOC. In the future, as fuel cell prices fall, the hybrid configuration will change accordingly. If the bus has a relatively larger fuel cell system and smaller battery pack, the fuel cell system will have to directly supply the transient power demand from traction system, leading to large power fluctuations and hence compromised durability. Thus, an extra penalty on the transient fluctuation of the fuel cell power is added to the cost function as described next.

5. Sizing study with different cost functions

The original cost function for optimization with a penalty for on/off cycling was shown to effectively suppress frequent on/off cycles of the fuel cell system in the hybrid bus. But this penalty, by itself, could not eliminate frequent fluctuations in the produced fuel cell power. Considering that this case represents a battery-dominant hybrid configuration with a small fuel cell system, we expect an even higher power fluctuation with a larger fuel cell system that directly supplies most of the transient power with a smaller battery to serve as a backup and an energy reservoir for regenerated power from braking. Considering all these factors, we decided to conduct a sizing study of fuel cell hybrid buses based on our DP optimization model which accounts for both the fuel consumption and durability.

The new cost function is shown in *Eqn. 2*.

$$J = \int_0^T (\dot{m}_{H2}(t) + \alpha \dot{P}_{fc}^2(t))\, dt$$

$$\begin{aligned} min: \quad & J = \sum_{k=0}^{N} c(x_k, u_k) \\ subject\ to: \quad & x_k = (SOC, P_{fc}) \end{aligned}$$

Eqn. 2 DP with fuel consumption and fuel cell power fluctuation as cost functions; state variables are SOC and fuel cell power.

The power fluctuation term $\dot{P}_{fc}$ is added to the cost function to get a smoother workload for the fuel cell system. The state variable is also expanded to include SOC and fuel cell power. Adding fuel cell power as a state variable is more rigorous and makes the DP algorithm mathematically complete. It also makes it possible to directly constrain the power fluctuation at each time step by limiting the admissible states of each previous state, which means that one can directly limit the ramp rate of fuel cell power at any time for any SOC and previous P_{fc} state.

Adding one more state variable usually introduces a significant amount of extra computational burden and demands much more simulation time. Pre-calculating the admissible states is a good practice to dramatically eliminate the side effects of having an extra state variable. From an implementation point of view, the DP algorithm demands more careful treatment due to the added complexity of cost-function interpolation. This effort is currently ongoing to complete the sizing study of the battery and fuel cell stack in a fuel cell hybrid bus.

6. Two-way communication system

The power management system of the newly delivered bus3 can be controlled remotely. We exploited this capability for the purpose of advancing connected vehicle technologies by implementing a two-way communication system using a Raspberry Pi computer, a GPS unit, and a CAN-bus interface unit. The setup is shown in Figure 12. The firewall computer is responsible for collecting all the data from another controller computer, as well as GPS data, and sending them to the server residing in our laboratory. The Pi computer is connected to the vehicle CAN-bus network through a CAN-bus interface. In the current setting, the Pi communicates with the cellular network and is designed to receive traffic information ahead of the current route, then calculate the optimal fuel cell power based on the current SOC, and output a fuel cell power control command to the bus through the CAN-bus network. The entire system can be easily adapted for other vehicles given that all vehicles nowadays have a CAN-bus interface. The control program implemented on the Pi for a fuel cell hybrid vehicle can also be easily adapted for a more general application on other types of hybrid vehicles.

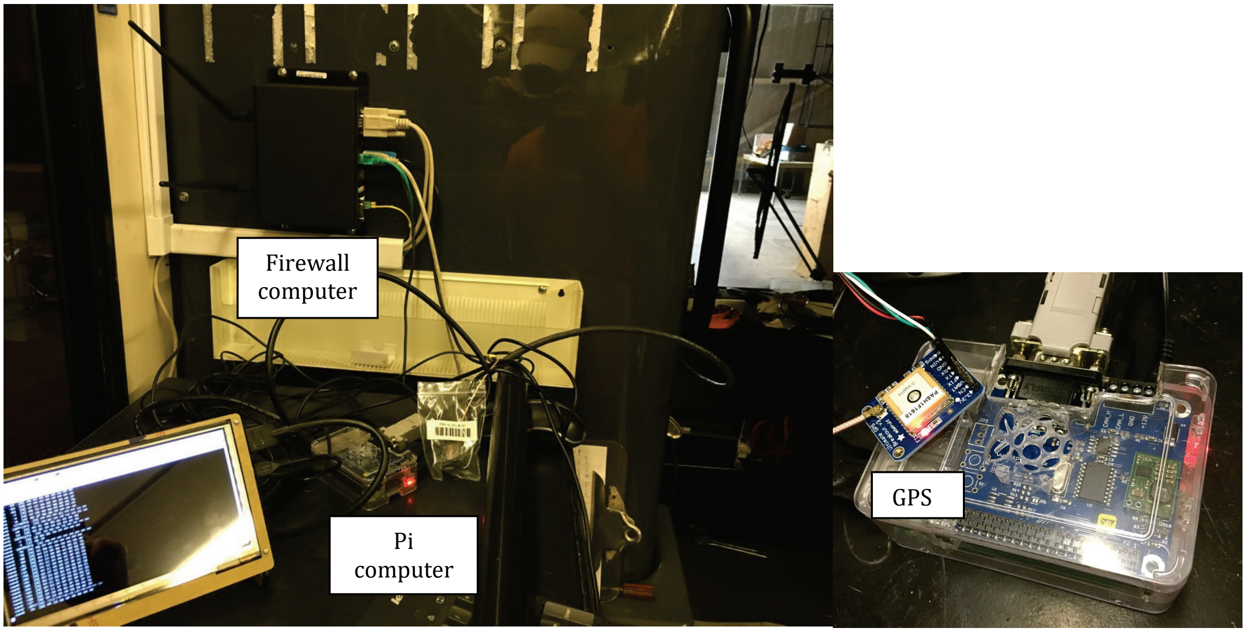

Figure 12 Communication system: Raspberry Pi, GPS unit and CAN-Bus interface to control fuel cell power.

Bus3 is currently undergoing regular test drives to fix any remaining mechanical problems within the bus, as well as to test the reliability of new communication system and CAN-bus control program. Summarized data from a recent bus3 trip is shown in *Table 2*.

Trip distance	43.07 km
Battery SOC	0.297 to 0.485
Total battery energy	10.04 kWh
Fuel cell net energy	52.86 kWh
Fuel cell gross energy	58.03 kWh
Traction energy	40.03 kWh
Auxiliary energy	2.79 kWh
Regenerated energy	10.44 kWh
Total energy consumption	42.82 kWh
Average energy consumption	0.99 kWh/km

Table 2 Summarized trip information of bus3.

The test drive route is shown in *Figure 13* and the corresponding velocity profile in *Figure 14*.

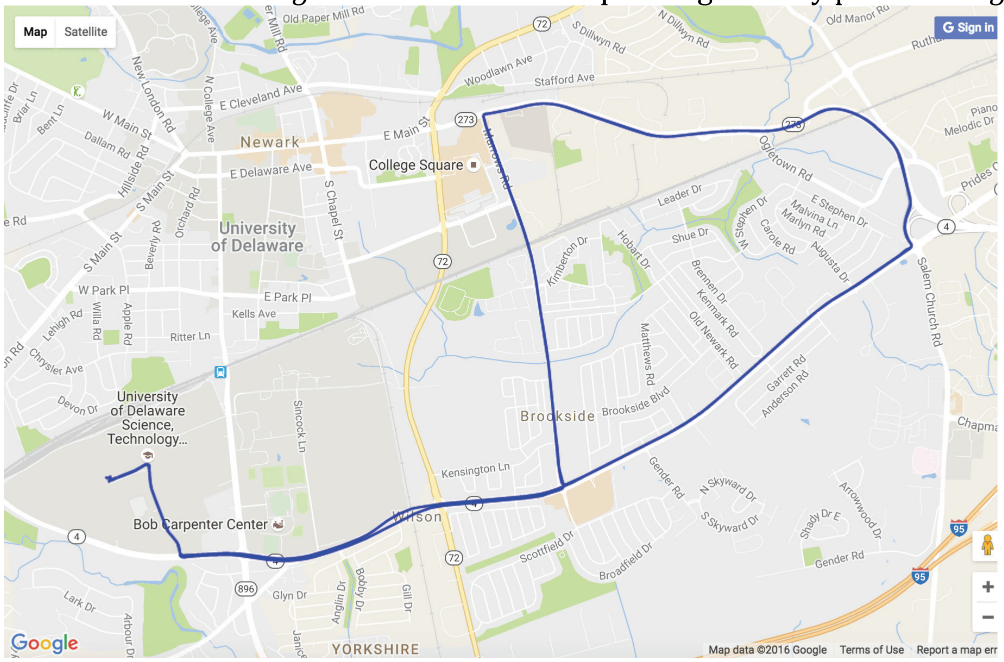

Figure 13 Test drive route of bus3.

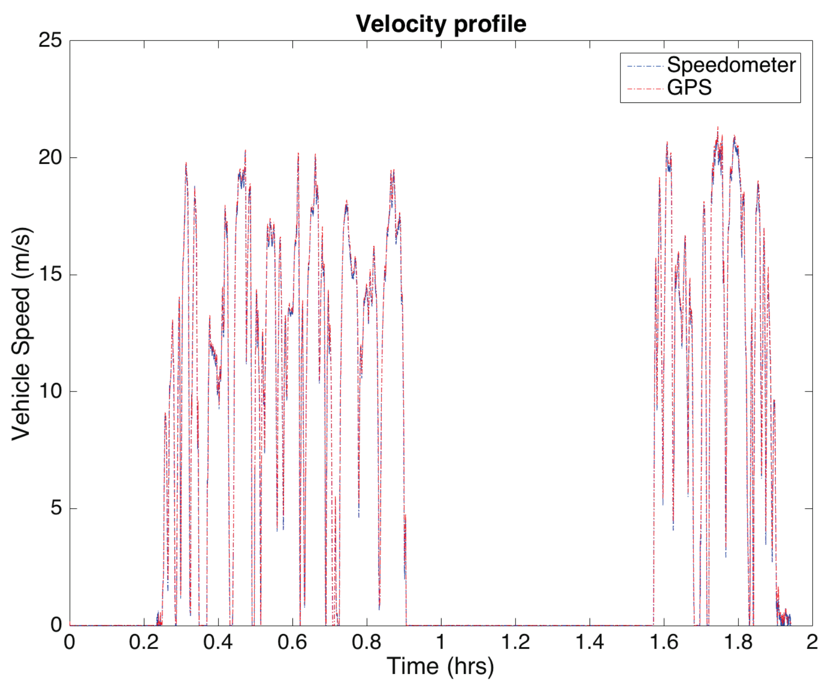

Figure 14 Velocity profile of bus3 for the route shown in Figure 13.

The data collected on bus3 are slightly different from bus2, but they still include all the essential data needed for the power management system. Similar to bus2, all the data are sent to the server in realtime and are saved on the server. Figure 15 shows the power demand, energy consumption, battery SOC, and hydrogen consumption for this specific route.

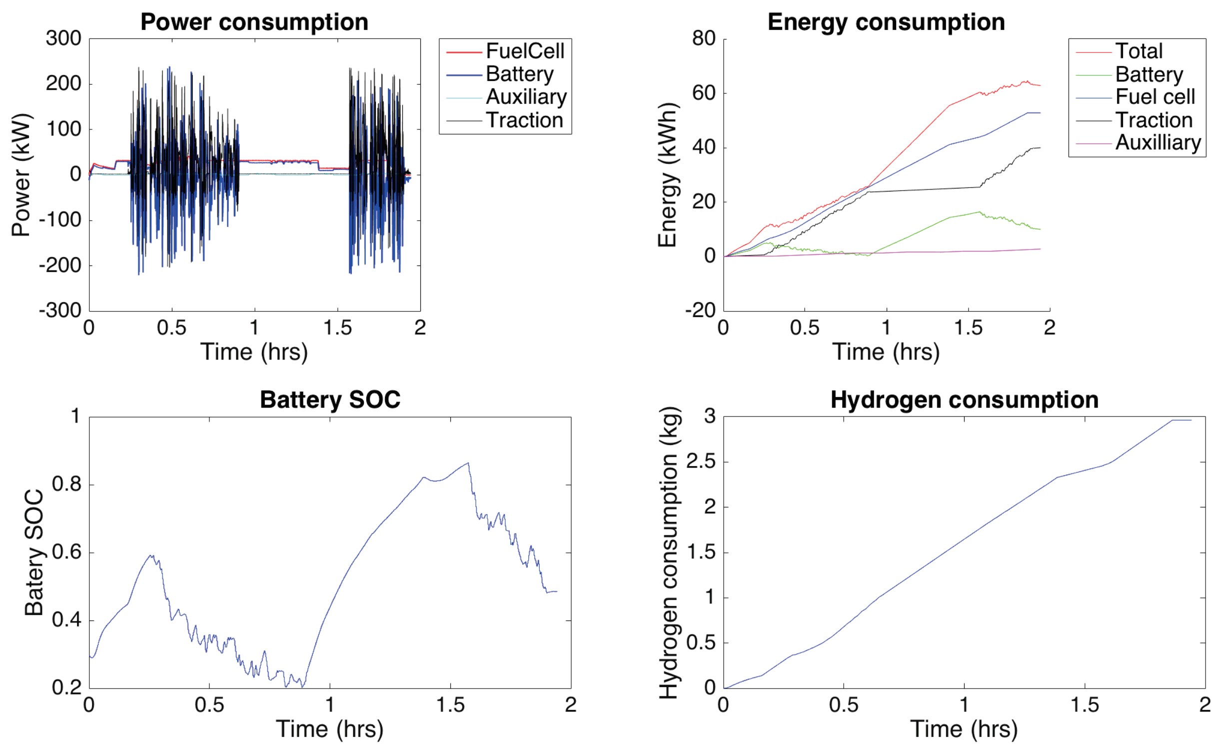

Figure 15 Plots of trip information for bus3.

The communication system implemented on bus3 will be tested in real time after rigorous reliability tests and improvement.

Work Allocated to Morgan State University

Conjoint Survey of Drivers: This portion of the work was awarded to Dr. Hyeon-Shic Shin at Morgan State University. His goal was to survey a small set (up to 100) of voluntary drivers for their willingness to pay for CV technology. The survey was to be conducted using an online-based adaptive conjoint analysis survey tool that can imitate people's purchasing behavior. The survey would collect information for estimating drivers' preference structure and reactions to different price/product bundles. Unfortunately, difficulties in allocating funds to Dr. Shin caused significant delays in executing this portion of the work. Hence, the final report from Dr. Shin will be filed separately at a later date. The expected results from Dr. Shin's work are:

1. <u>Drivers' Preferences on New Technology Bundles and Willingness-To-Pay</u>
   The relative importance is evaluated as part-worth utility scores that measure the contribution of a specific attribute to the total utility of an alternative extracted by a hierarchical Bayesian (HB) method at the aggregated and individual levels. This method is appropriate for estimating preferences and WTP for new products or products not yet on the market.

2. <u>Policy Suggestions</u>
   The study will provide preferences and WTP by various socio-economic characteristics. This will inform the characteristics of early adopters who should be targeted first for a faster diffusion of new vehicle technology and generate contagion effect. Also, identified will be late adopters and concerns of drivers, which need to be addressed to increase adoption rates.

These findings will have valuable policy implications to develop a carefully designed roadmap, not just driven by technology interest groups.

Summary and Conclusions

This work has shown that although historical trip data show a strong pattern, they are still very stochastic in nature. Thus accurate realtime traffic information is essential to improve the power management system of the fuel cell hybrid bus, either for fuel efficiency or for durability. A two-way onboard communication system has been developed to transmit or retrieve traffic information. The onboard control system will use the traffic data to optimize the power control strategy for the hybrid vehicle and maximize its fuel economy and durability in realtime. This project has successfully explored the idea of using connected vehicle technologies to benefit the transportation system and maximize its overall efficiency.

This research conducted through this project has helped to advance the mid-Atlantic region to the forefront of connected vehicle technologies. DelDOT/TMC has made great progress in providing a sophisticated infrastructure for future transit technologies. Our software tools for vehicle system management and optimization represent an ideal platform for traffic data communication and analysis to reduce congestion and save fuel. Such a program can help to propel mid-Atlantic region to the forefront as a test bed for implementing future connected vehicle technologies.

References:

1. Brown D, Alexander M, Brunner D, Advani SG, and Prasad AK, "Drive-Train Simulator for a Fuel Cell Hybrid Vehicle," *Journal of Power Sources*, 183:275-281, 2008.
2. Bubna P, Brunner D, Gangloff JJ, Advani SG, and Prasad AK, "Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications," *Journal of Power Sources*, 195:3939-3949, 2010.
3. Bubna P, Brunner D, Advani SG, and Prasad AK, "Prediction-based optimal power management in a fuel cell/battery plug-in hybrid vehicle," *Journal of Power Sources*, 095:6699-6708, 2010.
4. Bubna P, Advani SG, and Prasad AK, "Integration of batteries with ultracapacitors for a fuel cell hybrid transit bus," *Journal of Power Sources*, 199:360-366, 2012.
5. Hosseinzadeh E, Rokni M, Advani SG, and Prasad AK, "Performance simulation and analysis of a fuel cell/battery hybrid forklift truck," *International Journal of Hydrogen Energy*, 38:4241-4249, 2013.
6. Rod B, Jeremy M, "Scientific Aspects of Polymer Electrolyte Fuel Cell Durability and Degradation", *Chem. Rev.*, 2007, *107* (10), pp 3904–3951.
7. Scott M, Hosam K, Duncan S, Jeffrey L, "A Stochastic Optimal Control Approach for Power Management in Plug-In Hybrid Electric Vehicles", *IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, VOL. 19, NO. 3, MAY 2011.*