FINAL REPORT

Hydrogen Internal Combustion Engine (ICE) Vehicles and Fueling Infrastructure

Alternative Fuels & Life-Cycle Engineering Program

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Center for Integrated Manufacturing Studies
Rochester Institute of Technology
133 Lomb Memorial Drive
Rochester, New York 14623

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1. Executive Summary

This report presents the results of the successful RIT-CIMS Hydrogen Internal Combustion Engine (ICE) demonstration program conducted from September 2007 to September 2010. The program was jointly funded by U.S. DOT and NYSERDA. It includes details of the infrastructure construction and coverage of activities of the hydrogen ICE vehicle operation. During this period, CIMS constructed a hydrogen fueling station and operated a fleet of three gaseous-hydrogen-powered ICE vehicles. The vehicles operated on the RIT campus and in the surrounding Rochester metropolitan area from July 2008 to September 2010.

The construction of a hydrogen station on the RIT campus took approximately one year and involved a significant amount of safety and code reviews. The basic station design was changed to accommodate upgraded capability and additional cosmetic enhancements. Hydrogen dispensing capability was provided by a tube skid storage system, piped through a Quantum B70 fueling unit. This unit can service both ICE and fuel cell vehicles. The station was formally opened for operations in January 2009. During the station operational period, a number of durability and mechanical problems were encountered. Causes for these were divided almost equally between design shortfalls and cold weather operation. Most of the deficiencies have been corrected, but there is significant room for improvement in the fueler design.

The ICE vehicles were operated by a wide range of users. In particular, two of the vehicles were dedicated full time to RIT Public Safety patrol. The third vehicle was a rotational staff car and demonstration platform used at CIMS. Although the vehicles performed adequately on the road, there were a number of durability and reliability problems. Primary failures were in the fuel injectors, but there were also a number of other failures in mufflers, fittings, lines and electrical connectors. All these led to significant down time on the vehicles. All though most drivers were impressed with the implementation of the hydrogen technology, the reliability problems cast a negative shadow over the vehicles. In addition, most of the negative driver impressions of the hydrogen ICE vehicle operation centered around the excessive noise from the Continuously Variable Transmission (CVT)[1] The short range of the vehicles (approximately 100 miles on a full tank) prevented wider usage and public exposure. Another final drawback was the refueling time (20 to 25 minutes) which was excessive compared to gasoline vehicles.

Working within the vehicle and station constraints, CIMS executed an aggressive and comprehensive public outreach and education program. The vehicle was featured at a number of high profile events and highlighted the implementation of hydrogen fuel technology, which is a unique feature of the Rochester region. CIMS accomplished all the program tasks and objectives established at the beginning of the DOT program. In spite of the problems and issues with the

[1] A continuously variable transmission (CVT) is a type of automatic transmission that is advertised to provide more useable power, better fuel economy and a smoother driving experience than an automatic. CVTs work with a heavy-duty chain belt. The reinforced belt runs between two cone-shaped pulleys. One pulley is hooked to the engine and the other is hooked to the drive train. As the engine turns the pulley hooked to it, the belt transfers power to the other pulley that is hooked to the drive shaft, which powers the wheels. The CVT's biggest problem has been user acceptance. Because the CVT allows the engine to rev at any speed, the noises coming from under the hood sound odd to ears accustomed to conventional manual and automatic transmissions. Such was the case with our Ford Escape.

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vehicles and fueling station, we consider this a successful vehicle demonstration program. We look forward to engaging in future hydrogen projects and vehicle demonstration programs.

2. Program Summary/Research Goals

Introduction

The introduction of any new transportation technology will be measured against the 246 million examples of existing technology – the number of light duty vehicles in the U.S. fleet. As researchers, it does not matter whether that is an appropriate criteria or not, the fact is we are dealing with a long-established consumer product and as long as Americans still have disposable income, they will buy what they want, not necessarily what is "better" for them. The auto industry group Edmunds predicts that although they have been available for many years, only 3.2% of 2010 auto sales of 11.5 million light duty vehicles will be hybrids.[i] That amounts to only 368,000 vehicles, which is only 0.15% of the U.S. light duty vehicle fleet.

Before these technologies such as flex-fuel, hybrids hydrogen ICE or fuel cell vehicles can be introduced to the mass market, they must be to some degree "ready" for consumer operation. In order for them to be adopted and successful, they must be usable by a wide range of drivers with different driving skills and experience levels. In order for them to be bought, they must be able to be operated. Designing a product that can be used (and maintained) by hundreds of millions of different users results in some compromises in technology insertion. Just as aircraft are not designed to be flown only by test pilots, automobiles must be designed for use by average consumers, not Formula 1 drivers.

Hand in hand with development of the vehicles must be development and deployment of fueling stations, maintenance and repair centers and even disposal methodologies. Alternative fuel vehicles are at a level of development that is analogous to the development of the airplane a century ago – expensive, specialized technology that requires special support structures but only offers limited range and servicing locations.

Just as the airplane required construction of flying fields and maintenance stations to allow increased operation, so too do alternative fuel vehicles. However, as aircraft offered a revolution in transportation due to increased speed and flexibility which incentivized their development, alternative fuel vehicles only offer a simple replacement for existing vehicles. Thus the "pull" of technology is not sufficient to spur significant investment in the infrastructure needed to support them. Consumers only get a substitute for what they have now, and what they are comfortable with. They get no increase in speed, extra parking spaces or reduced Thruway tolls for alternative fuel vehicles. They may even face higher total cost of ownership at this stage in development. So again, the significant hurdle of institutional inertia works against their adoption.

In addition, as our final report was being formulated, the U.S. Government announced significantly stricter Corporate Average Fuel Economy (CAFÉ) standards and Greenhouse Gas Emissions levels. The new standards, covering model years 2012-2016, and ultimately requiring an average fuel economy standard of 35.5 mpg in 2016, are projected to save 1.8 billion barrels of oil over the life

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of the program with a fuel economy gain averaging more than 5 percent per year and a reduction of approximately 900 million metric tons in greenhouse gas emissions. This would surpass the CAFE law passed by Congress in 2007 (which) required an average fuel economy of 35 mpg in 2020.[ii] Because of this aggressive mandate, auto manufacturers are now bound to devote their limited research resources to improving the existing internal combustion engine vehicles, at the expense of striking out on new pathways for alternative fuels.

One promising alternative to fossil fuels is hydrogen because, through its reaction with oxygen, hydrogen releases energy explosively in heat engines. It is "clean" and abundant. However, the gap between the present state of art in hydrogen production, storage, and use and a competitive hydrogen economy is great. One way to bridge this gap is to have hydrogen demonstration projects which showcase the hydrogen internal combustion engine (HICE) vehicles and fueling stations. Hydrogen ICE is seen as that "bridge" technology between conventional vehicles and fuel cells.

CIMS Program Summary

The CIMS Hydrogen Vehicle Program was a project funded jointly by the New York State Energy Research and Development Authority (NYSERDA) under Program Opportunity Notice (PON) 1082 "*Hydrogen Transportation Development Program*" and by the U.S. DOT Alternative Fuel and Life Cycle Engineering Program. The specific NYSERDA award to RIT was for "*Deploying Hydrogen Internal Combustion Engine (ICE) Vehicles and Demonstrating Hydrogen as a Viable Transportation Fuel*." The contract was awarded to RIT CIMS for a three-year program, running from September 12, 2007 to September 11, 2010.

The NYSDERA contract with RIT was valued at $999,964. This amount was to be matched at 33% by cost-sharing from RIT. CIMS used additional funding from the four-year DOT Program as the cost match for this amount (approximately $330,000). The NYSERDA funding was used primarily to purchase and modify the vehicles and to construct the hydrogen fueling station. The U.S. DOT funding was used to purchase the hydrogen fuel, lease the hydrogen storage equipment and perform vehicle maintenance, data collection and program management tasks as outlined in the NYSERDA Statement of Work.

The broad objectives of the overall NYSDERA PON 1082 were: 1) to support the development of efficient hydrogen-fueled transportation technologies in commercially promising applications, and 2) to help support hydrogen transportation demonstration projects involving hydrogen internal combustion engine (HICE) vehicles and the development of hydrogen fueling stations. NYSERDA was seeking as many efficient HICE vehicles and as much refueling capacity as possible.

Specifically, NYSERDA's goals were:

1. Showcasing the scope and role of hydrogen as a viable transportation fuel to meet New York's energy needs.
2. Capitalizing on the opportunities presented by moving to a hydrogen-based economy.
3. Helping NYSERDA best apply its limited resources to the maximum benefit of the State in fostering hydrogen as a transportation fuel.

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NYSERDA felt that expanded use of hydrogen as an energy carrier could enhance fuel diversity, help address concerns about global oil depletion and energy security, reduce global climate change, and enhance local air quality. They realized that developing hydrogen as a major transportation fuel, however, will require significant investment in both the vehicle and fueling station infrastructure.

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3. RIT CIMS NYSERDA Program Task Summary

Against this background, the specific NYSERDA statement of work for RIT contained the following tasks. These are included as information to our DOT sponsor.

Project Management and Reporting (SOW Task 1)

CIMS would prepare a "refueling protocol" (training instructions) for refueling our vehicles and provide this to the other sites in the program. Monthly progress reporting was required on vehicle and fueling station operations. Technology Transfer was required which consisted of showcasing the hydrogen technology through demonstrations, tours of the application of hydrogen to the educational community and the general public. Metrics reporting data on numbers of events and education and outreach opportunities was also collected.

Obtaining HICE Vehicles (SOW Task 2)

CIMS would acquire and arrange for the conversion of three gasoline-powered ICE hybrid vehicles to run on hydrogen. The selected vehicle platform to be converted was the 2008 Ford Escape Hybrid. These three vehicles were then converted by Quantum Technologies into HICE-hybrid vehicles. The hybrid drive system was retained, but the gasoline fuel system was replaced by a hydrogen fuel distribution system. Once the vehicles were converted by Quantum in California, they were shipped to RIT and arrived in June 2008. Cost to acquire the three vehicles was approximately $85,120 and cost of the three conversion kits and installation from Quantum was $262,230.

RIT Public Safety HICE Vehicle (left) and CIMS Demonstration Vehicle (right)

Fueling Infrastructure Development (SOW Task 3)

RIT would construct an on-campus hydrogen fueling station to operate the three vehicles. The proposed fueling equipment consisted of a hydrogen tube trailer for storage and a Quantum hydrogen booster-refueling unit (B70 type). This would enable fueling with 350 bar vehicles (HICE) or 700 bar vehicles (hydrogen fuel cell-type.) Construction on the fueling station behind the CIMS Building 78 was completed in December 2008 and after operator and safety training was declared "operational" in January 2009. The fueling station option of a tube trailer plus booster

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was selected because CIMS believed that the technology for the current hydrogen fueling stations or the individual fueling station that produces its own hydrogen (electrolyzer) was not mature enough for our application. The original tube trailer design for fuel storage was later switched to a tube-skid arrangement to reduce the program cost. Overall cost to construct the fueling station was $543,657. This included $375,000 for the Quantum refueler system equipment. This funding was all provided through the NYSERDA portion of the program. However, this cost did not include the hydrogen storage skid, which was leased at $1100 per month from December 2008 to December 2010 and was paid for from the DOT funding.

Performance Testing of Hydrogen Technologies (SOW Task 4)

The objective of this task is to operate the three HICE vehicles and monitor their performance for a minimum of two years. The plan for the vehicles was to issue two of them to RIT Public Safety for campus patrol duties and the third would be used by CIMS as a rotational "staff car" and also for outreach and education events such as vehicle exhibits, parades and media events. This vehicle would also be integrated into various RIT curricula dealing with alternative fuels. The Public Safety application was chosen because there was an opportunity to operate the vehicles 24/7 and with a range of different drivers. CIMS would monitor the performance of these vehicles as they progressed through the demonstration program. To assist in this task, CIMS purchased three commercial Networkfleet vehicle monitoring units and installed them on the three vehicles. They provide GPS location information, engine health monitoring and performance reporting information that is very useful in evaluating the vehicle performance.

Hydrogen Infrastructure Management (SOW Task 5)

CIMS would operate the hydrogen fueling station and document any ongoing issues with reliability, cold weather operation, safety and human factors. Under our DOT grant, we have also examined life cycle issues with hydrogen infrastructure on a national scale. These have been reported previously. At the same time as RIT was constructing its station, Monroe County government was building a similar facility three miles away, and we were able to share "lessons learned" with the county on these issues.

Dissemination of Project Results (SOW Task 6)

This task had two objectives. The first was to create an awareness at the Rochester community level of the hydrogen infrastructure and vehicle usage. This was to be accomplished by demonstrations at schools, faculty demos at RIT and incorporating the vehicle into RIT classes in engineering and alternative energies. The second objective was to support the NYSERDA Hydrogen Transportation Development Program by aggregating and analyzing vehicle and site level project data and information from all of NYSERDA's demonstration projects funded under PON 1082. Ultimately, there are only two other sites in NY operating under this PON. The Albany airport site is operational and supports four vehicles (two converted Toyota Prius HICE and two converted Chevy Silverado HICE). The Hempstead, L.I. site is operational and will support a HICE shuttle bus for the town of Hempstead. Under this second task, CIMS was to collect vehicle and fueling performance data from all three sites and report this to NYSERDA on a monthly basis. However, as the overall NYSERDA program did not fully develop as intended, this data collection

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task was revised to an evaluation of the differences in fuel economy between HICE and fuel cell vehicles. The results of that analysis are presented in Appendix C.

4. Fueling Infrastructure Development and Management

Hydrogen Station Construction

The first task in this program was construction of the infrastructure necessary to fuel hydrogen vehicles on the RIT campus. Under this project, CIMS constructed a hydrogen refueling station consisting of a skid storage and booster delivery system. The RIT campus station was designed to provide hydrogen gas at the necessary pressures for both current HICE and potential future fuel cell vehicles. The RIT station is one of only a handful of stations in New York, and so the development and construction process is not yet "standardized" or by-the-book. No "turn-key" station designs were available for us to use on campus or within our budget. This section will document the work accomplished to complete the station, which became fully operational at the end of calendar year 2008. Below is a summary of the station project that took approximately a year to complete.

Developing RIT's hydrogen fuel infrastructure started with creating specifications for the fuel itself. This was done with careful review of our intended use in the HICE Ford Escape vehicles converted by Quantum Technologies (California). With this information in hand, CIMS research and priced out several fueling station options. The original concept was onsite production via an electrolysis system. After further review, price, time and simplicity turned us in favor of a hydrogen station based instead on a high-pressure tank storage system. CIMS chose Airgas from among two other companies as the contract hydrogen supplier, due primarily to the lower cost of the equipment lease. At their suggestion, a skid-pack storage system designed for high-pressure DOT gas storage was selected. The modular system consists of twenty-seven storage tubes, a fill stanchion for easy tanker truck refilling, and features a total volume of 55,756 standard cubic feet. CIMS chose to lease this skid pack through Airgas at a cost of $1100 per month for a period of twenty-four months. Initially, Airgas offered a hydrogen cost of $3.45 per hundred cubic feet, but this was contingent upon a three-year service contract. When we informed them that we could only accept a two-agreement, they immediately raised the hydrogen charge to $3.65 per hundred cubic feet. These costs remained in effect for the duration of the program.

The booster delivery system to provide the stored hydrogen gas at the necessary pressures for the HICE Ford Escapes was also sourced from Quantum Technologies. Again, CIMS evaluated several models, but in the end preferred a Quantum refueler for the obvious relationship and successful demonstration with the retrofit Quantum vehicles. Using a single supplier offered ease of maintenance and troubleshooting. The initial Quantum refueler system, which is 350 bar (5000 psi) capable, was priced at $325,000. Following discussions with General Motors Fuel Cell Research and Development Center in nearby Honeoye Falls, NY, CIMS decided to upgrade to the B70 type refueler, adding a 700 bar (10,000 psi) capability as required by fuel cell vehicles. The fueler upgrade added $50,000 to the system cost and provides a dual-capable system with no change to the fueling infrastructure. Under the total $375,000 fueler contract with Quantum, a cost share arrangement was established entitling CIMS to approximately $25,000 of Quantum's labor for on-site start up, commissioning, troubleshooting and training. Overall, this portion of the

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project which included initial hydrogen research, refining the station options, and choosing hydrogen suppliers through competitive bid spanned approximately three months.

With the skid storage and booster delivery system selected, deciding on a site location and developing a layout followed. CIMS enlisted the campus Facilities Management Service (FMS), who subsequently contracted with LeChase Construction Services LLC for this process. A lawn area off the parking lot behind CIMS building 78 was selected as the site location. This area was chosen based on available space, tanker truck access requirements, distance from buildings and wetlands areas. All Town of Henrietta, Monroe County and NYS building codes were applied to the project. Additionally, in NYS, the National Fire Protection Association requires compliance with Code 50, "*Standards for Bulk Oxygen Systems at Consumer Sites*" and Code 50A, "*Standards for Gaseous Hydrogen Systems at Consumer Sites*." In addition, the hydrogen supplier Airgas, desired additional safety factors by requiring NFPA Code 55, "*Standard for the Storage, Use and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders and Tanks*." As guidance for the design, a report published by the Fire Protection Research Foundation, titled "*Site Requirements for Hydrogen Supplies Serving Fuel Cells in Non-Combustible Enclosures*," was also consulted. Adherence to all these codes and standards was necessary to obtain building permits but also to obtain a certificate of operation once the station was complete. Once design was complete and the permits obtained, construction began. It took approximately five months for this design, approval and preparation work before ground breaking.

The construction contract with LeChase started with the parking lot cut in, excavation and site work for pouring of a large concrete pad to hold both the skid storage tank and the refueling equipment. The safety codes called for the storage tanks to be located a minimum distance of fifty feet from the walls of adjacent structures. In addition, the refueler had to be located at least fifteen feet from the storage tanks and fill stanchions. The pad thickness under the refueler was subsequently increased during the project to allow for the heavier upgraded dual capable B70 refueler system. Also, it provides the potential for growth capability for an improved storage system later if that is desired. Once the concrete was installed, the entire pad was surrounded by a perimeter fence. The roof of the facility is left open to allow hydrogen gas to easily escape in the event of a mishap. The perimeter fence that was ultimately installed is an upgraded cosmetic design required by RIT. A conventional chain-link type fence was all that was required for safety and access restrictions. This improved fencing added almost $39K to the cost of the project.

The solid fence features an gate/door at the refueler, the fill stanchion, one emergency exit and an opening for placement/removal of the skid storage system. The fence is further surrounded by concrete safety bollards on the parking lot side to protect the facility from vehicle collisions. High voltage electricity (480V, 60 amp, 3-phase power) was run to the site to power the refueler. Safety codes required that the power hook up for the refueler connector must also be at least fifteen feet from the device, and all electrical connectors and switches had to be explosion-resistant. Both the refueler booster system and the storage tank required redundant grounding rods to mitigate electrostatic discharges. Data cables for future data collection equipment and standard 110V electrical power was also provided at the station site. A streetlight pole added near the station to assist fueling operations and security became the location for these extra data and power hookups. Finally, a security camera focused on the hydrogen station was added to the RIT Public Safety Security Network. The total cost for the construction from LeChase was $142,257. This cost

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includes engineering, design, construction management, insurance and permits. The entire construction phase of the project took three months. A summary of all the project costs is provided in Table 4-1.

Once station construction was complete, the final step before operation was inspection from the local fire agency. As part of the NFPA codes, the responsibility of creating an emergency plan falls on CIMS, the operator of the station. CIMS held general safety meetings with local fire companies and emergency first responders. The training classes took place at the fueling station and covered station operations, emergency procedures and contact information. The final approval and training classes lasted another month. With this complete, the CIMS hydrogen station became officially operational and received its certificate of operation from the Town of Henrietta.

Total cost of the refueling infrastructure project was $543,657. In addition to this, approximately 350 hour of labor from CIMS and other RIT employees was required during construction.

Hydrogen Refueler System		
	Quantum 350 bar system	$325,000
	Upgrade for 700 bar capability	$50,000
Skid Storage System		
(Airgas contractor)	27 Tube storage skid and stanchion ($1100/mo. x 24 mo.)	$26,400
Original Construction Budget		
	General mgmt, insurance, permit fees	$8,000
	Chain link fencing	$9,091
	Electrical work and lighting	$22,507
	Concrete pad work	$19,186
	Safety Bollards (22)	$8095
	Security camera installation	$6,813
	Site prep work, excavation	$20,213
	Design fees and drawings	$5,462
Additions and Change Orders		
	Fencing Upgrade	$38,924
	Increase concrete pad thickness	$2,442
	Grounding changes	$294
	Placement of fueler on pad	$1,230
Total Cost of Project		**$543,657**

Table 4-1. Hydrogen Fueling Station Cost Breakdown

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Figure 4-1. RIT station under construction, showing storage tube skid and fueler but prior to installation of fencing.

Figure 4-2. Completed station storage skid and manifold

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Figure 4-2 Quantum B70 Refueler exterior (L) and interior (R) showing dual 350 and 700 bar fueling equipment

Figure 4.3 Completed hydrogen station

Hydrogen Station Operation

Once the station construction was completed, there was a short delay for station operation due to the requirement for CIMS to train all potential vehicle operators and first-responders in hydrogen operations. When the required training and orientation was complete, the station was officially "open for business" in January 2009. During the two-year period of station operation, both RIT HICE vehicles and GM Equinox Fuel Cell Vehicles were fueled there.

Day-to-day operation of the station was not trouble-free. In particular, several components in the B70 equipment experienced problems particularly during cold-weather operation.

When the refueler went on-line in January 2009, it would not operate at temperatures below 30°F because the air compressor valve was malfunctioning. Quantum provided a software solution that cycled the air compressor valve at specific time intervals to keep it functioning. CIMS also switched out two programmable logic controller (PLC) modules to incorporate the software

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solution into the refueler. Unfortunately, this repair did not work and the workaround was to thaw the compressor out each day with a heat gun.

Melting snow periodically leaked into the refueler, so CIMS replaced the weather stripping around the refueler. The new weather stripping cured this defect in the Quantum design.

Some drivers and operators experienced a situation where the fueler would activate, but would then immediately switch off before dispensing any hydrogen. CIMS investigated this and discovered that it was possible to attach and lock the fueling nozzle onto the vehicle even if it was not fully opening the tank valve. All operators were advised to fully seat the nozzle on the tank valve so it would complete the interlock system. Fig 4-4 shows vehicle-nozzle hookup.

Figure 4-4 Vehicle fueling hookup

During the two year operational period, there were also additional problems with the refueler system. A hydrogen sensor periodically failed and would shut down power to the refueler during fueling operations. Quantum replaced the sensor and the problem did not reappear. In addition, a water flow sensor and boost pressure sensors failed. Quantum also replaced these sensors.

In July 2009, the fueling station experienced high pressure (5000 psi) boost pump start-up problems. During a fill, the high pressure boost pump needs to engage after the low pressure pump achieves a specific gas pressure. If the high pressure pump does not start, the fill is aborted. This boost pump problem was isolated to a temperature monitoring problem. CIMS and Quantum worked together for two months implement corrective action. Also while installing the repair, CIMS discovered a cracked thermocouple control circuit board and several broken thermocouples inside the refueler.

In September 2009, another problem of the hydrogen fill ending prior to the vehicle tank being completely filled occurred. This was caused by the failure of a coolant temperature switch which

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caused the temperature control circuit board to fail. Three temperature control circuit boards failed before the problem could be properly identified and corrected.

To prevent the recurring problem of air compressor freezing during low temperature operations, Quantum installed their B70 X11 Hydrogen Refueler Cold Weather Package in October 2009. This ensured uninterrupted operation when the temperature fell below 32°F for extended periods.

In December 2009, the refueler began to "abort" during a fill start-up cycle, preventing the vehicles from being refueled. The problem was traced to ice buildup in the air compressor lines. Once the ice was removed from the lines, the refueler resumed normal operations. The station was down for approximately one month due to this problem.

In March 2010, the refuel shut down before the vehicles were completely filled. This problem was traced to the electrical umbilical that attaches to the vehicles. Examination of the electrical cable that plugs into the vehicle communications port (to ground the vehicle and communicate with the refueler) showed significant corrosion on both connectors of the cannon plugs. Quantum subsequently replaced the cables to resolve the problem.

The final significant problem occurred in June 2010. The unit was inoperable for most of the month because of a failure of the touch-screen/operator interface module. CIMS attempted several component replacements and repairs but none was successful. The only alternative was to procure a replacement touch screen module from Quantum. Cost of this replacement module was $1,400 as it was not covered under the Quantum warranty.

Below is a complete log (Table 4-2) of the issues and repairs on the station and refueler.

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Date	Event
1/14/2009	Compressor frozen. Quantum developed a software change to help prevent freezing, but it was not effective. Compressor must be thawed before using.
1/14/2009	Replaced coolant temperature switch 701 because it was damaging thermocouple card. Replaced touchscreen due to slow reaction time. Replaced pressure switch 102.
1/23/2009	Replaced weather stripping to eliminate water seepage. Replaced PLC with updated cold weather version. PLC cycled the compressor at times to try to keep heat in it. Compressor still freezes
5/11/2009	Installed data collection system and computer to monitor fill ups.
6/7/2009	Air line leak detected. Line replaced.
7/6/2009	Replaced hydrogen sensor board due to sensor going out of calibration and shutting unit down.
7/23/2009	Replaced thermocouple card due to data errors
7/28/2009	Had to bypass pressure switch 102 because of low inlet pressure. Problem still exists.
7/29/2009	Replaced PLC backplane due to repeated thermocouple failures.
8/6/2009	Replaced 3 HIP Valves. Replaced PLC. Replaced 1 thermocouple.
8/31/2009	Air powered HIP valve replaced. Replaced ethernet hub to repair data communication. Replaced thermocouple card. Cleaned valve seat contamination out of the system.
10/13/2009	Oil fitting for compressor cracked and leaked some oil onto the ground. Replaced fitting to repair oil leak.
10/16/2009	PDC Compressor repaired a 1st head leak on the compressor.
10/26/2009	Installed Quantum cold weather package to air compressor so compressor no longer had to be thawed out before use.
10/28/2009	Air compressor hose melted due to cold weather package. Had to replace hose and fitting and reroute heat tape.
11/10/2009	Replaced check valve because system was venting for too long
1/4/2010	Air line froze due to condensation in the lines. Had to remove all air lines, thaw them and then dry them out. Lines had to be reassembled after blockage was removed.
2/2/2010	Bypass pressure switch 102, low inlet pressure failure.
3/30/2010	Replaced electrical cable that connects vehicle to refueler due to corrosion on cannon plugs.
6/7/2010	Touch Screen went down and station could not be operated because we could not input the PIN code. Station was down for 22 days and was fixed on 6/29/10 with new touch screen.

Table 4-2. Summary of hydrogen station maintenance issues.

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Hydrogen Fueling Data Collection

Initially, all fueling data collection was done by hand. Once the drivers had fueled the vehicle, they would note the information, including fuel dispensed, onto a comment card which was kept at the fueling station, and then the data was manually entered into a database. There were no provisions in the Quantum system for automatic data collection, and once the refueler had completed the fill, the data was cleared from the buffer memory and was no longer available.

In March 2009, CIMS upgraded the system to capture the data automatically. This was accomplished by connecting the fueler to a stand-alone computer (used as a relay) and then installing specialized software to allow the data to be fed into a database where all of our alternative fuel data was collected. After this change, the fueling data on each fueling event was transmitted immediately into the database. This method allowed for rapid collection of much more accurate fueling data than was available from the driver's comment card. Cost of this upgrade to the system was approximately $1500, not including the use of a spare computer. A sample driver comment card is provided at Appendix A.

Refueling Protocols

Prior to station operation, CIMS prepared a detailed refueling protocol for both the HICE vehicles (350 bar) and fuel cell vehicles (700 bar). These protocols were used for training CIMS and RIT Public Safety personnel on vehicle fueling procedures. A copy of these protocols is provided at Appendix B.

5. Acquisition and Operation of HICE Vehicles

The other key task in the program was acquisition of an appropriate hydrogen ICE vehicle. As no production HICE vehicles were available on the market at the time of contract award, the only other option was conversion of a conventional ICE vehicle to hydrogen propulsion. The selected vehicle platform to be converted was the 2008 Ford Escape Hybrid. Three of these vehicles were converted for CIMS by Quantum Technologies to HICE-hybrid vehicles beginning in November 2007. The hybrid drive system was retained, but the gasoline fuel system was replaced by a gaseous hydrogen fuel distribution system. Once the vehicles were converted by Quantum in California, they were shipped to RIT and arrived on 23 June, 2008. The cost to acquire the three vehicles was approximately $85,120 and the cost of the three conversion kits and installation from Quantum was $262,230.

Ford Escape HICE Vehicle System

The hydrogen propulsion modification package for the installation by Quantum included:

1. Removing and replacing the gasoline tanks with four, 5000 psi hydrogen storage tanks. These tanks were estimated to provide an operating range of approximately 120 miles per fill-up.
2. Replacing the fuel lines that ran from the fuel storage tanks to the engine.
3. Adding an intercooler and turbocharger,

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4. Increasing the size of the air filter,
5. Modifying the engine control unit (ECU) to enable the engine to run using hydrogen as a fuel.

This modification package was tailored specifically for the Ford Escape Hybrid platform. To accommodate the four gaseous hydrogen storage tanks, the original Ford rear suspension was cut and modified by Quantum (Figures 5-1 and 5-2 below). A finite element analysis performed by Quantum showed that this change did not have a significant effect on the strength of the rear suspension. This allowed the modified Escapes to pass a DOT front, side and rear-end 30 mph crash test. The new hydrogen fuel lines were run beneath the car to the engine compartment in the same locations as the original gasoline lines.

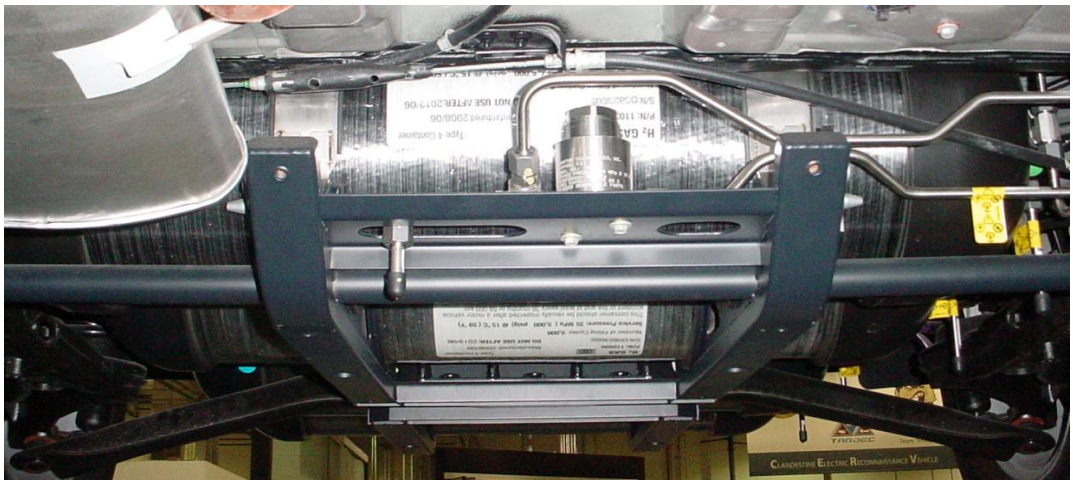
In the fuel deliver system, the hydrogen pressure is stepped down as it moves closer to the engine. The 5000 psi hydrogen pressure in the storage tank system is stepped down with a regulator to 200 psi before entry into the fuel delivery lines that run from the fuel tanks to the engine compartment firewall. Another regulator at the engine compartment firewall steps the hydrogen pressure to 50 psi. Finally, at 50 psi the hydrogen flows through the common fuel rail into the specially-designed hydrogen fuel injectors into the cylinder for subsequent combustion similar to gasoline. Since the hydrogen is under pressure no fuel pump is required for a HICE.

The ECU had to be modified to account for the difference in fuel properties between gasoline and hydrogen.

Two additional modifications made by Quantum to the Escapes were:

- Addition of a turbocharger and intercooler
- Larger air filter and modified filter installation.

Since hydrogen has less energy than gasoline, these changes were required to increase the horsepower of the modified engine back to the levels of the gasoline powered Escapes (turbo charger) and to reduce combustion temperature to prevent NO_x emissions (intercooler). Figure 5-3 shows these modifications.



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Figures 5-1, 5-2 Hydrogen storage tank installation in vehicles

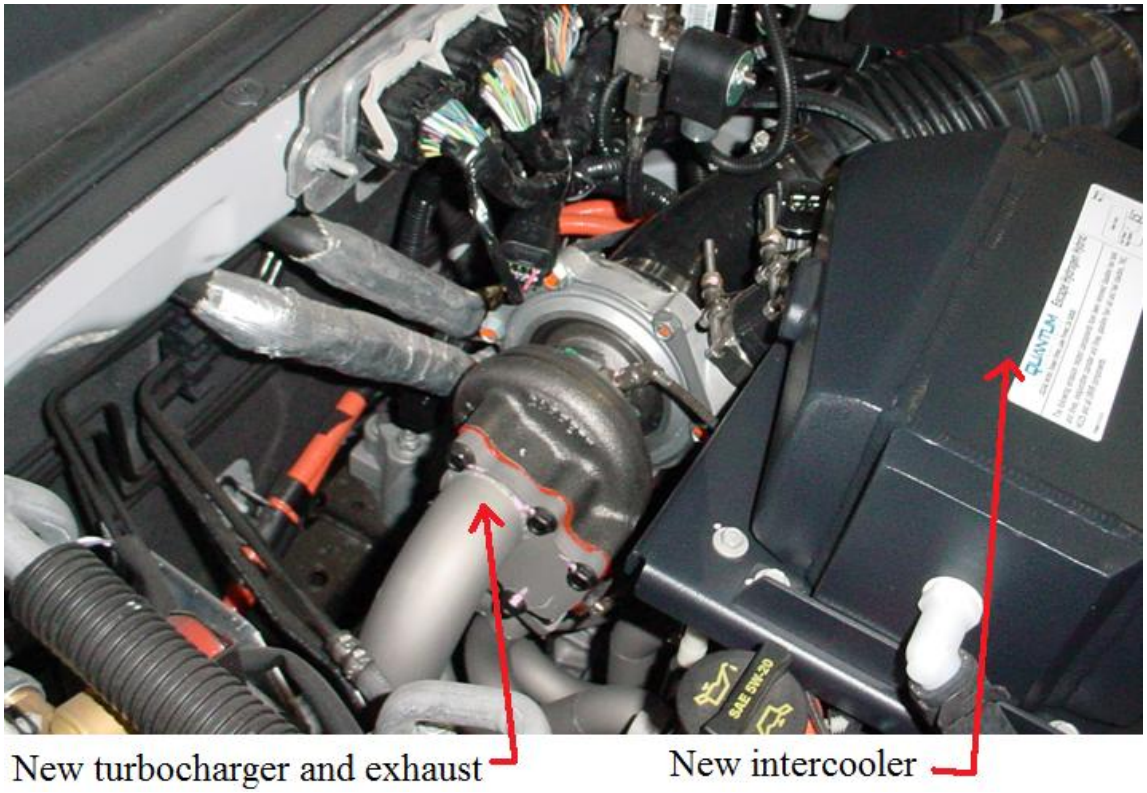

Figure 5-3 Engine modifications for performance compensation

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Vehicle Operations and Data Collection

Once the vehicles were received, inspected to NYS requirements, titled and licensed, two of the three were turned over to the RIT Public Safety Department who installed emergency lights, sirens, radio equipment and laptop docking station for their public safety mission.

Operation of the hydrogen vehicles began intermittently in July 2008 when CIMS was granted access to the hydrogen fueling station at the nearby General Motors Fuel Cell Division facility in Honeoye Falls, NY. This access allowed the vehicles to be operated in a limited way until the RIT hydrogen station was completed. RIT also had limited access to the Monroe County hydrogen station at the Rochester Airport for temporary fueling requirements when our equipment was off-line for maintenance and repair. The vehicles were able to be used at full capacity by January 2009 when the RIT station became operational.

For tracking purposes, the vehicles were identified as RIT 1 & RIT 2 (Public Safety vehicles) and RIT 3 (CIMS vehicle). The vehicles were identical other than the public safety police package.

In January 2009, RIT 1 immediately experienced problems. It became difficult to start and once started, ran very rough for one or two minutes until the engine shut down. The problem was traced to an improperly functioning fuel pressure sensor (circled area in Figure 5-4). Quantum sent a new sensor which was installed on RIT 1. Once the sensor was replaced, the vehicle performed normally.

Figure 5-4 Fuel pressure sensor

Figure 5-5 Replacement pressure transducer

Several problems were encountered with the HICE vehicles in February 2009. First, the fuel gauge in RIT 1 began working improperly. Quantum supplied a new pressure transducer which was installed on RIT 1 (Figure 5-5).

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After this installation the fuel gauge worked properly. Then an air filter modification was required on all three of the Hydrogen ICE vehicles to prevent water degradation of the air filter. Figure 5.-6 shows the air filter degradation that occurred with the original design. This degradation was caused by snow on the battery melting and flowing into the air filter. The fix was to install a smaller battery to increase the clearance between the air filter and the battery and to modify the plastic air filter housing (Figure 5-7). New batteries were also installed in all vehicles. After switching to the new deep-cycle marine battery, the need to constantly jump-start the HICE vehicles was eliminated, which was another problem experienced at the same time.

Figures 5-6, 5-7 Damaged air filter and replacement

Next, RIT 2 began to run rough, specifically it experienced problems accelerating and the check engine (MIL) and maintenance required warning lights were illuminated on the dashboard display. When diagnosing the problem, CIMS personnel discovered that the plastic cap from the throttle body assembly had fractured at the screws holding it in place (See arrow in Figure 5-8). With that failure, it was then hanging underneath the vehicle, attached by only electrical connector. The failure of the cap was likely caused by the shock from the engine backfiring. Quantum provided replacement parts and the new throttle body assembly and sensor was installed by CIMS.

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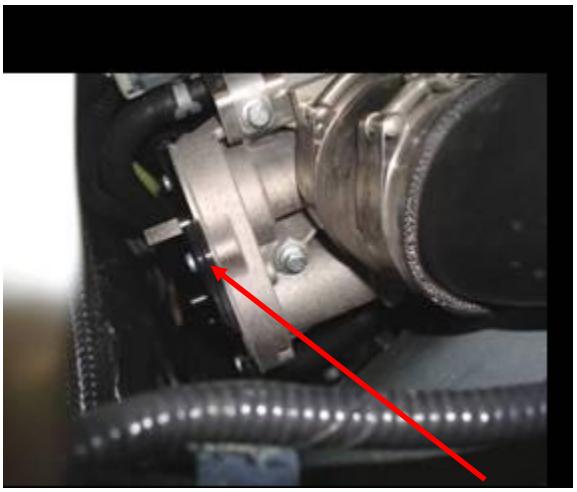

Figure 5-8 Throttle body showing attachment screws

Figure 5-9 Spark plug corrosion

After replacing these components, RIT 2 continued to run rough and backfire. Quantum's follow on recommendation suggested that CIMS replace the fuel pressure sensor and all four spark plugs. Replacing these parts did not fix the problem.

Figure 5-9 shows that the old spark plugs removed from RIT2 were covered with rust. This rust was likely caused by corrosion from the water vapor that formed during the hydrogen combustion. Next CIMS performed a cylinder pressure and leak down test. This test showed a 175 psi cylinder pressure for each cylinder and that all the cylinders held pressure during the leak down test. These values all were within the specifications for the Ford Escapes. Finally, Quantum recommended changing all the spark plugs, ignition coils, and fuel injectors. Once these components were replaced, the backfiring and rough idling on RIT 2 ceased.

Figure 5-10 shows the used hydrogen fuel injectors and fuel rail after removal from RIT 2 and the reason for the backfiring and rough idling. Injectors from cylinders 1 and 2 were discolored and were coated with oil (circled area in Figure 5-10). The improper operating fuel injectors in cylinders 1 and 2 caused the pressure in the fuel rail to become unbalanced, caused the fuel rail pressure sensor to fail. Without a properly operating fuel rail sensor the engine would backfire.

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Figure 5-10 Fuel rail with hydrogen injectors from RIT 2 vehicle

RIT 1 experienced two problems during the May 2009. The first problem was the hydrogen leak detection light on RIT 1 illuminated. Illumination of this light typically indicates a hydrogen leak. However, after examination of the car no hydrogen leaks were detected. Replacing a pressure transducer on one of the fuel tanks solved this problem.

In May 2009, RIT 1 began to lose power after running for approximately fifteen minutes. This problem was traced to the hybrid drive system and for that reason was then taken to a local Ford Dealer for warranty work. The problem was diagnosed by Ford as lack of charge in the air condition system. The air conditioning system is used to cool the hybrid batteries (a fact unknown to us at the time.) This failure to charge the system occurred at the Ford assembly plant before the vehicle was delivered. Once the air conditioning system was charged, RIT 2 operated properly.

RIT 2 struck a deer on campus in November 2009. While there was extensive damage to the driver side front quarter section of the car, the hydrogen fuel system or storage tanks were not damaged. RIT 2 was sent to a body shop for repairs and was received back at the end of November.

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Figure 5-11 Front end collision damage on RIT 2

With the onset of the cold weather in January 2010, the fill nozzles on both RIT 1 and RIT 2 began to leak hydrogen. Although this is not a critical failure because there is another check valve in the system, only a small amount of hydrogen was able to leak out. Still, both fill valves had to be replaced. It should be noted that this is the second time the fill valve was replaced on RIT 1. Also, because of additional hydrogen leaking at a fitting, the fill line was also replaced on RIT 1 (Figure 5-12).

Figure 5-12 Damaged hydrogen fill line

The fuel injectors were replaced on RIT 1 in January 2010 because the engine was backfiring during start-up. This was a repeat of the earlier problems.

The muffler was also replaced on RIT 1 in January 2010 (Figure 5-13). Quantum believed that the muffler failed because of corrosion from the water, the byproduct of the hydrogen combustion process. However, a failure analysis performed on the muffler at CIMS showed no corrosion on the

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inside of the muffler. Instead, the failure analysis showed that the rusting progressed from the outside in. This corrosion was caused by the road salt used in the Northeast to keep ice off the roads, not from by-products from the hydrogen combustion process. The muffler ultimately failed at a point where the engine backfired, blowing a hole in the weakened muffler wall. The mufflers delivered with the Escapes were steel with an aluminum coating which should have been more corrosion resistant than the steel by itself. We have recommended a stainless steel muffler.

Figure 5-13 Failed muffler on RIT 1

In January 2010, RIT 1 was not able to be filled completely, which severely reduced the distance the vehicle could travel between fill-ups. Upon examination, it was found that the connectors on the vehicle hydrogen fuel tank #4 valve were severely corroded. The corrosion on the connectors prevented transmission of an electrical signal to open a solenoid and fill tank #4. For this reason, Quantum provided a new connector which CIMS installed. The new connector resolved the fill-up problem.

In February 2010, RIT 1 again experienced problems with corroded connectors on the fuel tanks (Figure 5-14). As before, the corroded connectors prevented the fuel tanks from being filled completely. This time, the corroded connectors sent a signal to the hydrogen fill controller on the refueler indicating that the tanks were full, when in fact they were empty. As a result, RIT 1 was only able to be driven approximately 15 miles between fills. After checking all four connectors on RIT1, CIMS discovered that the connector for tank #2 was now badly corroded. Once this connector was replaced and RIT1 was able to get approximately 40 to 60 miles between fill-ups.

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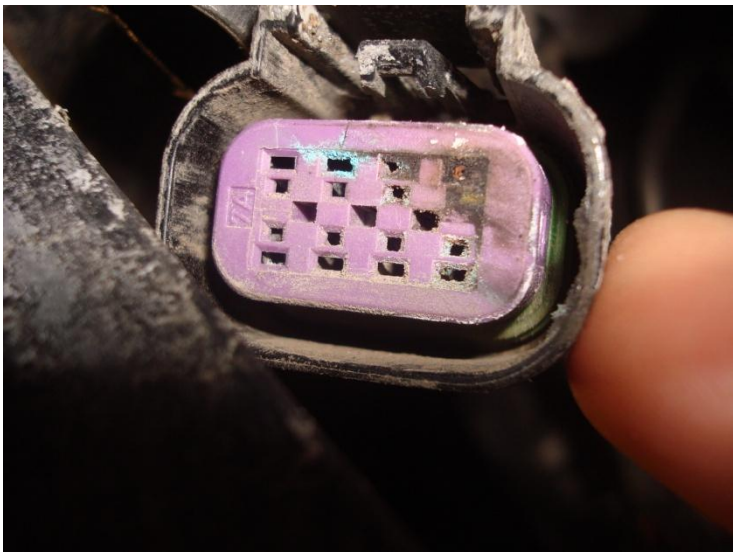

Figure 5-14 Typical corroded hydrogen tank connector

Because of the second corroded connector on RIT1, all the connectors on RIT2 and RIT3 were inspected for corrosion and replaced when required. The results of this inspection were:

- For RIT2 the connectors for tanks #2 and #4 were found to be corroded and replaced,
- For RIT3 the connector for tank #2 was found to be corroded and replaced.

We noted the fact that all the failed connectors were those that were not sealed properly by Quantum during the vehicle conversion. This is a problem specific to the hydrogen conversion.

During February 2010, RIT 2 began to backfire due to the recurring fuel injectors problem. However, before the injectors could be replaced RIT 2 blew a hole in its muffler (Figure 5-15). This was a similar scenario to the earlier failure on RIT 1. Both the injectors and muffler were replaced.

Figure 5-15 Failed muffler on RIT 2

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There was significant down time for RIT1 in March due to a starting problem. RIT 1 failed to start because the fuel pump fuse was tripping during vehicle startup because an electrical short developed on several wires that were cut during the conversion of the RIT 1 from gasoline to hydrogen. The electrical short developed because of corrosion on these wires (Figure 5-16). After isolating the cut wires with electrical tape, RIT1 did not encounter any more starting problems.

Figure 5-16 Area under fuel tank where wires were cut during manufacturing

During March 2010, RIT 2 ran rough, lost acceleration, and the engine RPM would not go above 3000 RPM. In addition, the engine also began to backfire. This backfiring blew a hole in the new muffler that was recently installed in RIT 2. The cause of this backfiring was traced to a faulty injector control module. The injector control module as well as all four fuel injectors was replaced.

In April 2010, RIT 2 again began to randomly lose power and shut down. Then when the vehicle was able to be restarted, it would only drive in a "degraded" mode and would not exceed 8 MPH. This problem was traced to the 12 volt battery system dropping below a critical voltage value. Replacing the vehicle's 12 volt battery corrected this problem.

In May 2010, RIT 2 experienced an electric motor coolant pump failure in the hybrid electric drive system. This failure caused the vehicle to shut down if the vehicle overheated. The Ford Motor Company replaced the electric motor coolant pump as a warranty item.

One result of the problems encountered with RIT 2 between March and May 2010 was Public Safety lost confidence on the ability of the car to perform its function. As a result, Public Safety essentially "grounded" RIT 2, using it only sparingly during the remainder of the program. They continued to use RIT 1 only.

RIT 1 then had a lock-off hydrogen gas solenoid failure in May 2010. This solenoid failed in the closed position and for this reason it would not allow any hydrogen to flow from the tank to the fuel

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injectors. As a result the vehicle would not start. Quantum sent a replacement solenoid, which CIMS installed, enabling RIT 1 to start.

Table 5.1 contains a summary of each HICE vehicle's uptime since February 2009.

Table 5.1 HICE Vehicle Uptime

Month	RIT 1 Uptime	RIT 2 Uptime	RIT 3 Uptime
Feb 2009	100 Percent	27 Percent	100 Percent
Mar 2009	100 Percent	66 Percent	100 Percent
Apr 2009	43 Percent	100 Percent	100 Percent
May 2009	36 Percent	81 Percent	100 Percent
Jun 2009	100 Percent	100 Percent	100 Percent
Jul 2009	100 Percent	100 Percent	100 Percent
Aug 2009	85 percent	100 Percent	100 Percent
Sep 2009	100 Percent	90 percent	100 Percent
Oct 2009	100 Percent	100 Percent	100 Percent
Nov 2009	100 Percent	40 Percent **	100 Percent
Dec 2009	100 Percent	100 Percent	100 Percent
Jan 2010	94 Percent	98 Percent	100 Percent
Feb 2010	89 Percent	54 Percent	100 Percent
Mar 2010	90 Percent	29 Percent	100 Percent
Apr 2010	100 Percent	90 Percent	100 Percent
May 2010	94 Percent	94 Percent	100 Percent
Jun 2010	100 Percent	100 Percent	100 Percent
Jul 2010	100 Percent	100 Percent	100 Percent

** Downtime due to collision damage, not mechanical problems

Vehicle Failure Analysis

As described above, one of the largest challenges encountered during this project was with the fuel injectors experiencing premature wear and failing after only 300 to 400 miles, causing a rough running engine and engine backfiring. Failure analyses performed by Quantum Technologies on the fuel injectors removed from the HICE Escapes identified two different failure modes:

1. Main seat pitting/sealing—Quantum uses a hardened disk for the main seat and they found that during the manufacturing process much (or in some cases all) of the hardened material was removed from the surface of the seat to achieve the flatness required. Removing all or part of the hardened material from the main seat caused accelerated seat wear and premature failure of the injector. Quantum made a physical change to the seat that required significantly less material to be removed during the flattening process, ensuring that the hardened surface remained intact.

2. Retainer Weld Failure– In order to keep the main injector seat in the proper position Quantum's design requires a retainer to be welded to the main seat. However, during the

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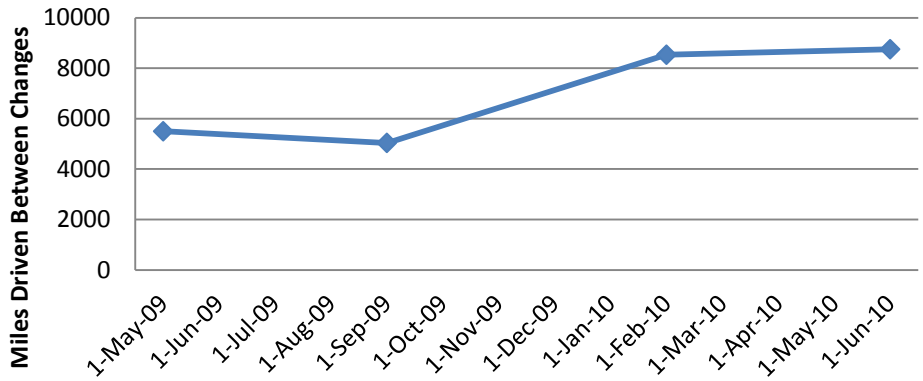
welding operation the material around the retainer welds became brittle. During vehicle operation/injector cycling, the brittle material around the welds fractured allowing the seat to move. Quantum has made changes in the welding procedure to improve both the weld quality and material durability.

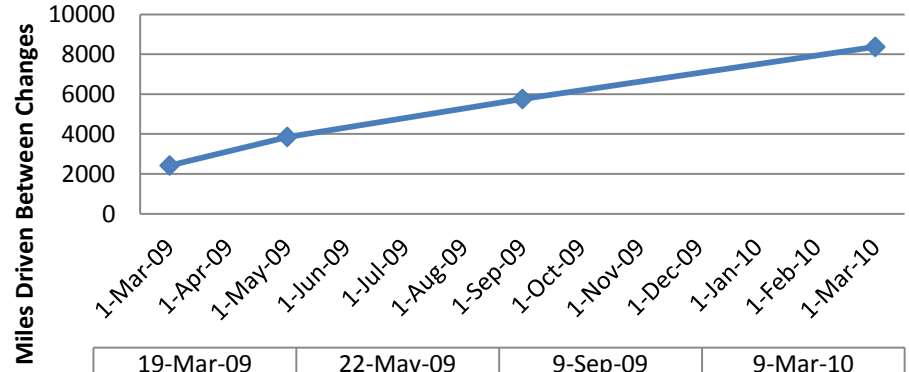
Figures 5-17 and 5-18 show that the changes made by Quantum improved the life of the hydrogen fuel injectors from 5000 to 8000 miles between replacements. However, even with this double improvement, the fuel injector durability is still not acceptable for commercialization, since gasoline fuel injectors have at least a 150,000 mile service life.

Figure 5-17
Fuel Injector Changes for RIT 1



	1-May-09	1-Sep-09	2-Feb-10	1-Jun-10
Series1	5500	5039	8537	8755

Figure 5-18
Fuel Injector Changes for RIT 2



	19-Mar-09	22-May-09	9-Sep-09	9-Mar-10
Series1	2419	3853	5757	8371

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Oil Analysis Program

After each scheduled oil change for the vehicles, oil samples were analyzed for potential problems. In particular, the water content in the oil was crucial to determining if there was hydrogen blow-by in the cylinders.

One part of the oil analysis, Elemental Analysis, or Spectroscopy, identified the type and amount of wear particles, contamination, and oil additives. Understanding the amount and type metal content in the used oil can identify the type and severity of any wear occurring in the engine. These measurements are expressed in parts per million (ppm). Additional tests performed on the used oil samples were viscosity testing at 100°C and Water content by Karl Fisher % (ASTM D1744). The viscosity testing measures the lubricating properties of the oil. Low viscosities can be caused by overheating the oil or water contamination.

During the power stroke of an internal combustion engine, blow-by around the piston rings occurs allowing some of the combustion gasses into the crankcase. Since the combustion product of the hydrogen combustion is water vapor, any blow-by will allow water vapor to get into and condense in the crankcase. Mixing of the water with the crankcase oil will reduce the viscosity of the engine oil and degrade its lubricating ability and increase engine wear. For this reason, the amount of water in each oil sample, after the initial oil change, was determined by a Karl Fisher method. The Karl Fisher % method uses a titration to determine the amount of water in the oil. Results are reported as either % water or ppm (1% = 10,000ppm).

Two of the HICE vehicles, designated RIT 1, and RIT 2 were operated by Public Safety. These vehicles were driven 24 hours, seven days a week around the RIT campus. In their normal operating mode, these vehicles idled approximately 45% of the time. The third vehicle, RIT 3 was used for trips around the greater Rochester region. For this reason, it was not driven as much as the other two HICE vehicles and spent significantly less time idling as compared with RIT 1 or RIT 2. High idling will cause excessive water vapor in the engine.

All three HICE vehicles ran with standard 5W-30 mineral based motor oil, supplied by Ford until the first oil change. After the first oil change, all three HICE vehicles used a fully synthetic Mobil 1 motor oil.

The oil analysis results are listed in the tables below. The results show the water content, viscosity values and other contaminants in the oil. There was some metal contamination in the early samples which are typical of “break in” oil in the vehicles. The tables contain oil analysis results for RIT 1, RIT 2, RIT 3 and the gasoline powered Ford Escape Hybrid, “RIT 50,” included for comparison.

Both 5W-30 weight mineral and synthetic blend oil specifications state that these oils should have a viscosity between 9-12 centistokes (cSt) when tested a 100°C. The used oil from RIT 1 and RIT 3 after the first oil change had viscosities between 7.5 to 7.5 cSt, when tested at 100°C. These viscosities are below the viscosity range of the 5W-30 weight mineral oil. The oil from RIT 2 after

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the first oil change, on the other hand, was 12.3 cSt, which is slightly above the viscosity range of the 5W-30 weight mineral oil.

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Oil Analysis Report

Oil: Mobile 1 SAE 5W30

0	1	2	3	4
NORMAL		ABNORMAL		CRITICAL

Sample #	Date Sampled	Mileage	Water (KF PPM)	Vis 100C CS	TAN Total Acid	TBN Total Base	I-R OXIDA	I-R NITRA	Contaminant Metals - PPM: Silicon	Sodium	Potassium
RIT 1											
1	03/03/09	2928	-	7.5			15	16	58	9	16
2	05/06/09	5695	3252	8.1	1.79	5.44	8	12	12	307	6
3	07/23/09	8956	1381	9.8	2.58	5.67	12	16	4	19	1
4	09/25/09	12192	1534	8.7	2.8	7.41	7	11	6	11	1
5	12/09/09	16780	1339	8.2	2.23	6	12	20	5	17	1
6	02/01/10	19076	1531	7.9	3.1	6.64	11	19	5	14	0
7	03/26/10	22715	4594	8	3.58	5.85	10	19	4	17	2
8	05/12/10	26654	1184	8.4	2.23	6.21	11	17	5	16	6
RIT 2											
1	03/03/09	2107	-	12.3			9	11	60	7	20
2	05/06/09	5661	704	8.1	3.2	3.65	9	16	15	271	10
3	07/23/09	9517	1868	10	2.88	7.01	12	16	11	18	1
4	09/25/09	12426	1596	8.9	2.08	7.54	7	11	6	8	1
5	12/09/09	15885	1689	8.2	1.88	6.53	11	18	5	17	1
6	02/01/10	19280	10175	8	2.21	6.85	11	17	6	16	1
RIT 3											
1	03/02/09	404	-	7.6			16	19	61	6	22
2	05/05/09	565	13706	8	1.1	9.94	9	17	15	285	15
3	09/28/09	2880	2169	9.7	2.9	8.06	10	16	12	21	3
4	04/20/09	4500	4680	2.6	2.05	8.29	10	18	6	18	5
RIT 50 (Non-Hydrogen)											
1	05/06/09	12686	-	9.0	-	4.07	11	17	13	338	1

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			Wear Metals - PPM									
Sample #	Date Sampled	Mileage	Iron	Chromium	Nickel	Aluminum	Copper	Lead	Tin	Cadmium	Silver	Vanadium
RIT 1												
1	03/03/09	2928	159	4	1	27	23	1	2	1	0	0
2	05/06/09	5695	33	1	0	8	6	0	0	0	0	0
3	07/23/09	8956	13	0	0	3	1	0	0	0	0	0
4	09/25/09	12192	15	0	0	3	1	0	0	0	0	0
5	12/09/09	16780	15	0	0	3	1	0	0	0	0	0
6	02/01/10	19076	15	0	0	1	0	0	0	0	0	0
7	03/26/10	22715	12	0	0	2	0	0	0	0	0	0
8	05/12/10	26654	10	0	0	1	0	0	0	0	0	0
RIT 2												
1	03/03/09	2107	101	4	1	22	21	1	0	1	0	0
2	05/06/09	5661	97	8	0	14	5	0	0	0	0	0
3	07/23/09	9517	36	1	0	3	1	0	0	0	0	0
4	09/25/09	12426	19	0	0	2	0	0	0	0	0	0
5	12/09/09	15885	19	1	0	2	0	0	0	0	0	0
6	02/01/10	19280	15	0	0	1	0	0	0	0	0	0
RIT 3												
1	03/02/09	404	119	3	1	14	19	1	0	0	0	0
2	05/05/09	565	37	1	0	5	5	0	0	0	0	0
3	09/28/09	2880	43	2	0	6	2	0	0	0	0	0
4	04/20/09	4500	13	0	0	2	1	0	0	0	0	0
RIT 50 (Non-Hydrogen)												
1	05/06/09	12686	12	0	0	4	17	0	0	0	0	0

			Multi-Source Metals - PPM						Additive Metals - PPM				
Sample #	Date Sampled	Mileage	Titanium	Molybdenum	Antimony	Manganese	Lithium	Boron	Magnesium	Calcium	Barium	Phosphorous	Zinc
RIT 1													
1	03/03/09	2928	0	38	1	15	1	226	9	1869	0	626	735
2	05/06/09	5695	0	6	0	4	0	29	10	1866	1	755	835
3	07/23/09	8956	0	100	0	0	0	99	13	2538	0	835	919
4	09/25/09	12192	0	111	0	0	0	77	12	2537	0	672	766
5	12/09/09	16780	0	125	0	0	0	69	13	2679	0	731	797
6	02/01/10	19076	0	111	1	0	0	56	13	2333	0	661	722
7	03/26/10	22715	0	123	0	0	0	60	21	2702	0	756	883
8	05/12/10	26654	0	136	0	0	0	67	14	2666	0	845	866
RIT 2													
1	03/03/09	2107	0	38	0	12	1	265	8	1938	0	658	708
2	05/06/09	5661	0	5	0	6	0	16	7	1808	1	760	841
3	07/23/09	9517	0	99	0	0	0	102	13	2527	0	870	948
4	09/25/09	12426	0	109	0	0	0	81	12	2525	0	666	756
5	12/09/09	15885	0	127	0	0	0	81	14	2628	0	721	773
6	02/01/10	19280	0	109	0	0	0	59	24	2275	0	668	734
RIT 3													
1	03/02/09	404	0	36	0	8	0	275	8	1874	0	639	666
2	05/05/09	565	0	7	0	3	0	51	8	1796	1	721	811
3	09/28/09	2880	0	96	0	1	0	107	12	2466	0	794	881
4	04/20/09	4500	0	119	0	0	0	85	12	2589	0	746	661
RIT 50 (Non-Hydrogen)													
1	05/06/09	12686	0	5	1	1	0	9	8	1637	0	669	823

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The oil analyses suggested that the reason for the lower viscosities for the used oil from RIT 1 was there was in fact water in the oil. The used oil taken from RIT 1 contained 0.5% water. While the oil analysis for used oil from RIT 3 did not show a significant amount of water in the oil, a visual inspection of the used oil, Figures 5.1 and 5.2, showed that there was evidence of water in the oil (creamy colored material in sample).

The water content was measured using a Karl Fischer test starting with the second sample from each of the HICE vehicles after the first oil change due to a milky appearance of the oil from RIT 3 during its first oil change.

After reviewing the oil analysis results for the first oil change with Exxon-Mobil representatives, it was decided to switch from a mineral based to fully synthetic blend motor oil (Mobil 1). For this reason, all three HICE vehicles used Mobil 1 for the next 14 months. During these 14 months, oil changes were made on each car after approximately 3,000 miles or after 6 months.

Figure 5-19 Photos of the oil fill cap and fill tube of RIT 3 during its first oil change at 404 miles showing milky deposits symptomatic of water in the oil

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Figure 5-20 Visual comparison of the milky oil from RIT 3 (left) to the oil from RIT 2 (right).

The most probable cause of the milky oil is from the operation of the HICE vehicles for short time intervals. These short intervals do not let the engine heat up enough to evaporate any water that might be in the oil due to any hydrogen blow-by in the cylinders. As seen in the picture above RIT 2's oil does not have any milky appearance as the vehicle was used for longer intervals of time allowing any water formed from hydrogen leakage to evaporate out of the engine oil. This problem did not continue to appear after the initial oil changes for RIT 1 and RIT 3.

Currently there is no system or scale to determine if the water content in the engine oil is high using the Karl Fischer test. The range is in development and will be in place once more data from hydrogen vehicles is collected, according to a representative from the oil analysis lab. Although, through a brief discussion, the representative presented a rough scale for which the water content can be flagged based on what the lab was seeing so far. The scale was presented as any value between 1000 and 1999 ppm would be a level one flag, 2000-2999 ppm level 2 flag, 3000-3999 ppm level 3 flag and anything above 4000 ppm would be a critical level 4 flag.

Using this method the water content of RIT 1 and RIT 2 is flagged at level 1. The viscosity of the oil is one of the biggest concerns when there is any water in the engine oil. Analyzing the viscosity levels for RIT 1, 2 and 3 shows no evidence that the water content is causing any significant effects on the oil. The viscosity data from the milky oil from RIT 1 from its first oil change shows yields a normal value.

The viscosity of the oil for the third sample from RIT 1 and RIT 2 was slightly high. The cause of this could possibly be some residual from the use of a 20w50 oil in each of these vehicles between

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the times when samples 2 and 3 were taken. This oil was tested to see if it was able to absorb and hold higher water content. 5w20 oil was soon replaced in the vehicles, because the 20w50 oil caused the vehicles to have trouble starting. Some 20w50 oil could have caused the oil from sample 3 to have a higher viscosity. This would not have affected the later samples as the oil samples were taken each time the oil was changed. We believe the water that was present in the oil was caused by the vehicle being used for short distances only. The engine never reaches an operating temperature to a point where the water evaporates.

On one occasion the viscosity of the oil was critically low in RIT 3 after its 4500 mile oil change. We suspect this is caused by the effect of not being driven regularly from 9/28/2009 to 4/20/2010. A final area of concern initially with the engine oil was the high amount of some wear metals after the first oil change. These values went down significantly however after the first oil change where one can conclude that the existence of these metals were due to engine break-in.

After this series of oil tests we conclude that there are no significant issues with the engine oil from the HICE vehicles.

Oil Lubricity Testing

In an effort to further analyze the impact of the water contamination on the lubricity properties of the motor oil, CIMS performed an additional, more detailed, lubricity study. The objective of this study was to determine the effect of the water contamination on the lubricating properties of both used mineral-based and fully-synthetic engine oil samples taken over a two-year period from RIT 1, RIT 2 and RIT 3. The lubricating properties of the used engine oil were determined using ASTM D6079 – 04E1, Standard Test Method for Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig (HFRR)[2]. This test measures the lubricity, or ability of a fluid to affect friction, and wear between two surfaces in relative motion under load. The HFRR lubricity tester is an accepted test method for determining the lubricity of diesel fuels. CIMS had constructed the HFRR set up as part of the on-going DOT program.

The HFRR test consists of a ball that is placed on a flat surface. The ball is then rapidly vibrated back and forth using a 1 mm stroke while a 200g mass is applied. After 75 minutes, any flat spot that has been worn on the steel ball is measured with a 100X microscope. The size of the spot is directly associated with the lubrication qualities of the liquid being tested. Results are evaluated against this metric: <u>the smaller the wear spot (scar) the better lubricating properties of the oil.</u>

Figure 5-21 shows both the viscosity and resulting average wear scar length from the HFRR test results for the used mineral from the first oil change for RIT 1, RIT 2 and RIT 3. These test results show that the used mineral oil containing the highest amount of water contamination, RIT 1, produced the largest wear scar after HHFR testing. The used oil from RIT 2, which contained the least amount of water, had the smallest wear scar. RIT 3 which had the intermediate level of water produced a wear scar which was intermediate in length compared to that produced from RIT1 and

[2] Anonymous. 1999b. Standard test method for evaluating lubricity of diesel fuels by the high-frequency reciprocating rig (HFRR). ASTM D 6079. ASTM. West Conshohocken, PA. pp. 1-4.

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RIT 2. This data showed that water contamination in the used mineral oil did reduce the lubricating properties of the mineral oil.

Vehicle	Viscosity[3]	Wear Scar (Microns)
RIT 1	7.5	351
RIT 2	12.3	123
RIT 3	7.6	192

Figure 5-21 Initial Oil Change Test Data (Mineral Oil)

Figure 5-21 also shows that the used mineral oil from RIT 1 contained the highest levels of iron and aluminum, 159 and 22 ppm, while the used mineral oil from RIT 2 contained the lowest levels of iron and aluminum, 101 ppm and 22 ppm. Since both iron and aluminum content in used oil is an indication of engine wear, the increased amount of these particles in the used mineral oil from RIT 1 is an indication that an increased amount of engine wear occurred with this oil. The water contamination in the used mineral oil from RIT 3 also reduced its lubricating properties because this used oil also contained higher levels of iron and aluminum, 119 and 14 ppm respectively, than observed in the used oil from RIT 2. However, the iron and aluminum values for the used mineral oil from RIT 3 might be artificially low because of the very low miles driven between oil changes for RIT 3 compared to RIT 1 and RIT 2. These results show that there was a correlation between the wear scar size after HFRR testing and the amount of engine wear particles in the used oil.

The results of the oil analyses and HFRR test results for the fully synthetic Mobil 1 used oil samples are contained in Figures 5-22, 5-23 and 5-24 and shown in Figures 5-25 and 5-26. (All centipoises measured at 100C.)

Date of Test	Water (ppm)	Viscosity	Wear Scar (Microns)
May 09	3252	8	245
Jul 09	1381	10	211
Sep 09	1534	9	160
Dec 09	1339	8	182
Feb 10	1531	8	143
Apr 10	4594	8	200

Figure 5-22 RIT 1 Synthetic Oil Change Test Data

Date of Test	Water (ppm)	Viscosity	Wear Scar (Microns)
May 09	704	8	214
Jul 09	1864	10	199

[3] Centipoises measured at 100°C

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Sep 09	1596	9	168
Dec 09	1689	8	188
Feb 10	10175	8	202

Figure 5-23 RIT 2 Synthetic Oil Change Test Data

Date of Test	Water (ppm)	Viscosity	Wear Scar (Microns)
May 09	13706	8	170
Sep 09	2169	9.7	200
Apr 10	4680	2.6	164

Figure 5-24 RIT 3 Synthetic Oil Change Test Data

The data in the figures above show for the three vehicles that there was in fact water contamination in the used synthetic oil. The effect of this water dilution on the viscosity of the used synthetic oil from RIT 1 and RIT 2 is shown in Figures 5-25 and 5-26. For comparison, the viscosity range for "as received" 5W-30 synthetic motor oil (red region) is shown in each figure.

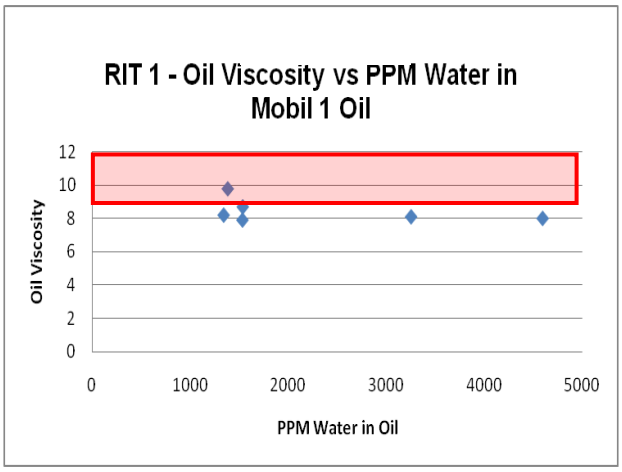

Figure 5-25 RIT 1 Oil Viscosity

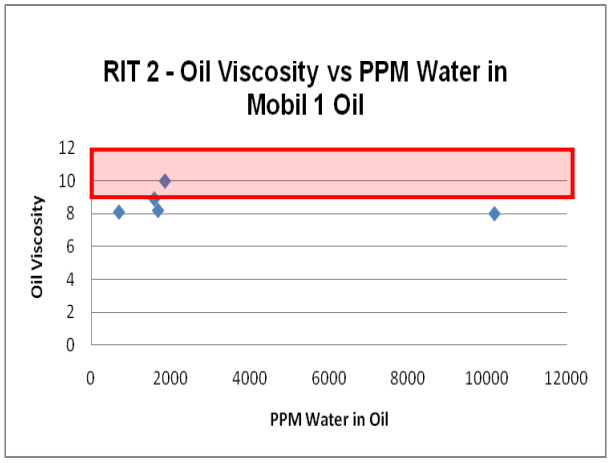

Figure 5-26 RIT 2 Oil Viscosity

Figures 5-25 and 5-26 show that except for one used synthetic oil sample for each HICE vehicle, the effect of the water contamination was to reduce the viscosity of the used synthetic oil samples, measured at 100°C, to a level at or below the minimum viscosity value of the fully synthetic Mobil 1 oil.

Figure 5-27 shows a summary the effect of the water contamination on the size of the wear scar produced during the HHRR test for the Mobil 1 fully synthetic motor oil samples for all three vehicles. For comparison, a HHRR test was run using "as received," uncontaminated 5W-30 Mobil 1 synthetic oil sample. This oil sample produced a 200 micron wear scar and it is shown as the red line in the figure.

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The data shown in Figure 5-27 indicates that the water contamination in the synthetic oil did not affect the size of the wear scar that developed during the HFRR testing. Except for the RIT 1 May 2009, oil sample, all the wear scars produced by the used synthetic oil samples were equal to, or less than the length of the wear scar produced from the "as received" synthetic oil. Since the HFRR wear scars from the used synthetic oil were less than or equal in length than the wear scar from the unused synthetic oil, the HFRR testing showed that the water dilution did not have a significant effect on the lubrication properties of the Mobil 1 synthetic oil. This was also confirmed by the iron and aluminum content of the used fully synthetic oil samples. These values dropped off significantly after the switch to the fully synthetic Mobil 1 oil, and remained at very low levels –13 -19 ppm for iron and 1-3 ppm for the aluminum, for the duration of program.

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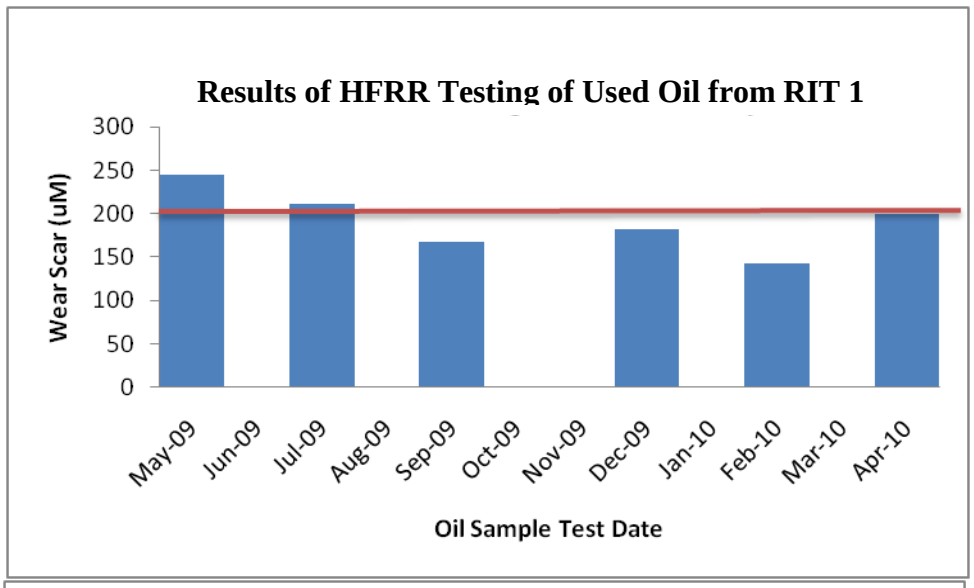

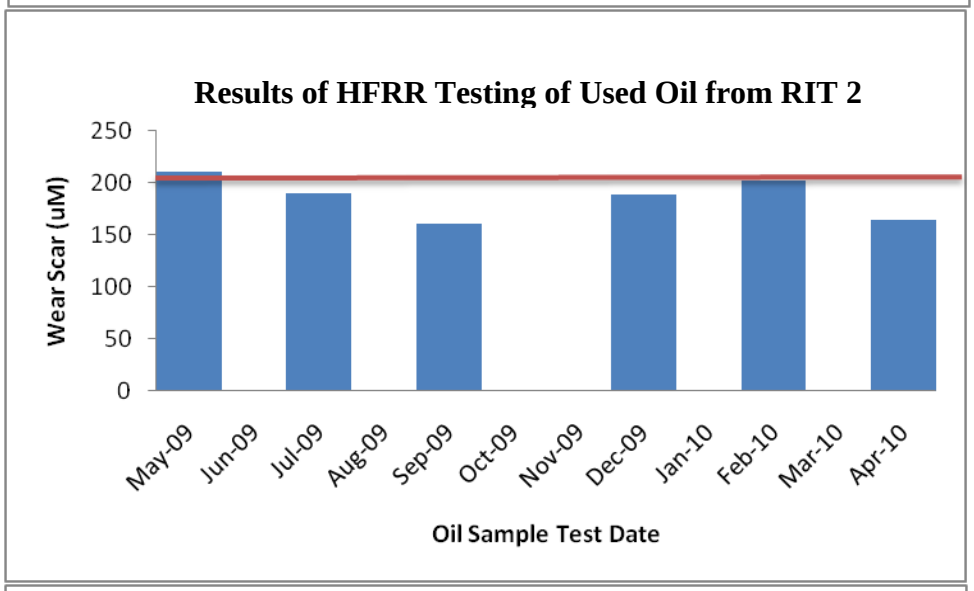

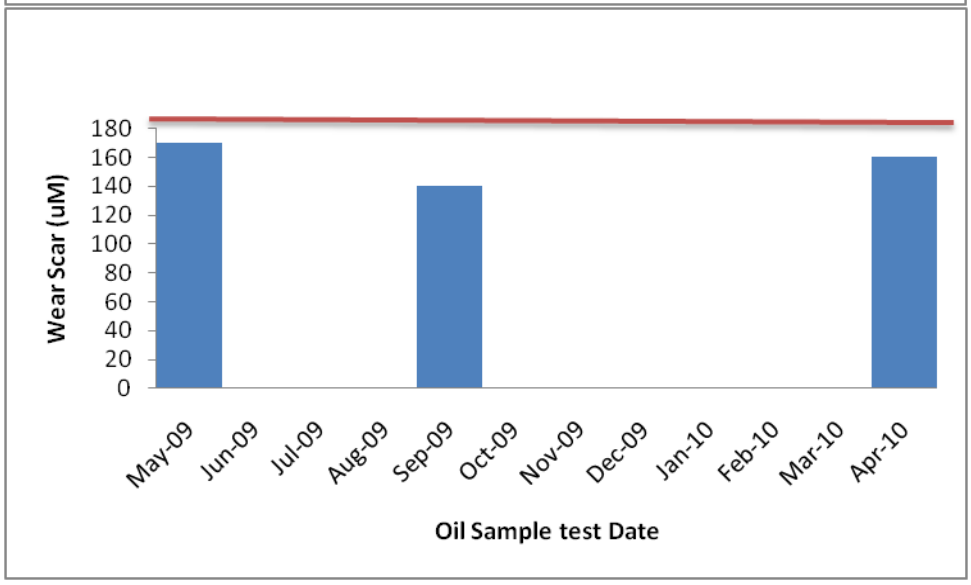

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Figure 5-27 Summary Lubricity Test Results for all three HICE vehicles

The oil analyses from the used oil samples showed that water contamination did occur with all three of RIT's Ford Escape's hydrogen fueled internal combustion engines during this trial. The effect of the water dilution was to reduce the viscosity measured at 100°C for both the mineral based and synthetic motor oils. The wear scars produced from this used mineral oil was almost 1.5 times greater than the wear scars produced from the "as received" mineral oil. In addition, these used oil samples had the highest concentrations of iron and aluminum particles. However, the HFRR testing showed that the used synthetic motor oil samples produced wear scars that were equal or shorter in length than the "as received" Mobil 1 oil sample. Thus, while the water contamination reduced the viscosity of the synthetic Mobil 1 this viscosity decrease had very little effect on the lubricating properties of the used oil. This was also confirmed by the iron and aluminum particle content in the used synthetic oil samples. If the engine oil lubrication properties decreased, there would have been an increase in engine wear increasing the amount iron and aluminum particles in the oil. This did not occur and the iron and aluminum particle content remained at very low levels.

Since water vapor blow-by occurs with hydrogen fueled internal combustion engines and causes water contamination in the engine oil, it is recommended that fully synthetic motor oil, like Mobil 1, be used in these engines because the water contamination does significantly affect its lubrication properties of the fully synthetic motor oil. Water contamination in mineral based oils, on the other hand, does significantly decrease the lubrication properties of this oil.

Vehicle Tailpipe Emissions

Periodically, the HICE vehicles were tested for tailpipe emissions using a Five Gas Analyzer distributed by Snap-On Tools. The vehicles were tested at idle speeds as well as a defined "drive around" loop circling the RIT campus. Emissions results are presented below.

The HICE vehicles were tested for tailpipe emissions once at the beginning of testing in 2008 and once toward the end of testing in July 2010. We wanted to determine if there was any significant degradation over time. The vehicles were tested at idle speeds as well as a "drive around" loop that circled the RIT campus (Figure 5-28.) Emissions results are presented below.

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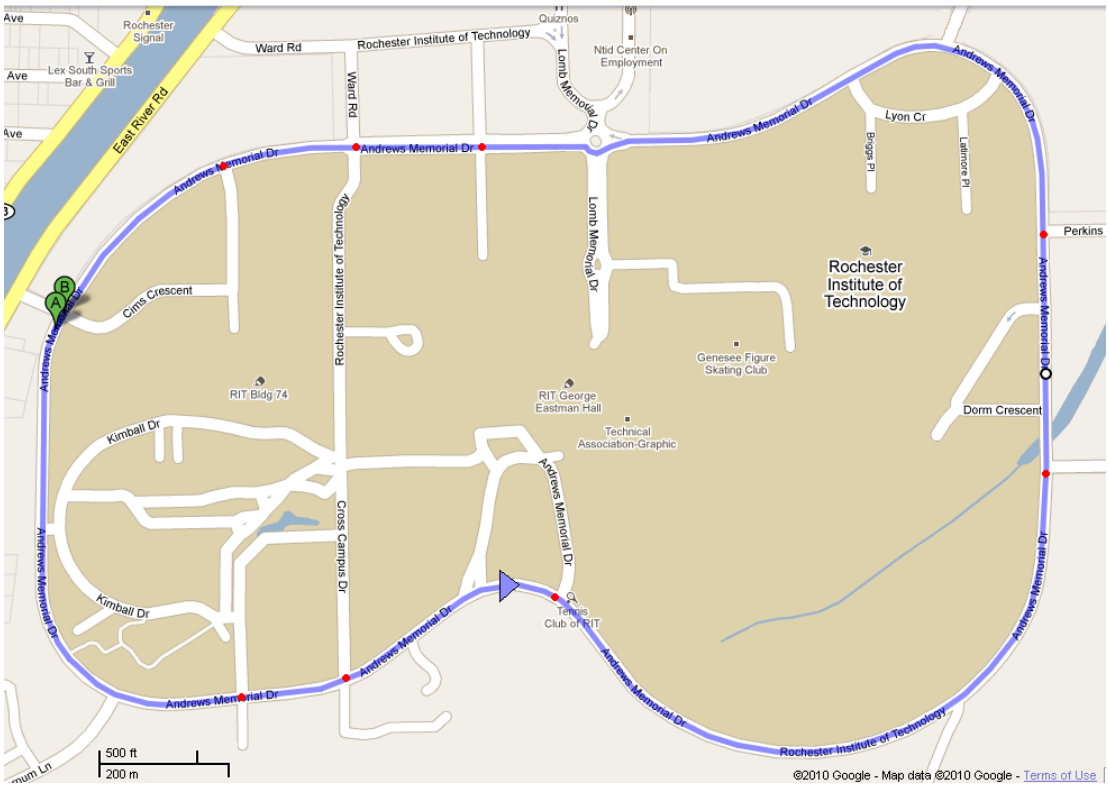

Figure 5-28 Campus loop used for emissions testing (approx 3 mi).

As mentioned above, the equipment used for the testing was a Five-Gas Analyzer sold by Snap On Tools. Although this is a "shop" instrument, it does provide sufficient data and details to determine trends in the emissions. Unfortunately it only gives results expressed in parts per million (PPM)[4] as opposed to grams per mile, which would be more useful for comparison. For that type of data, an expensive chassis dynamometer emissions system is required, and a specialized one that can test hydrogen-fueled vehicles. Such equipment was not available in the upstate NY area.

Emissions testing was not only performed to see what emission the vehicles were emitting but also if there was any change (degradation) in the emissions over time. The Nitrogen Oxide (NOx) emissions for both vehicles for the idle cycle and the drive cycle of emissions testing were considerably low. The highest value was 2.84 ppm for RIT 3 during the drive cycle. The Hydrocarbon (HC) emissions were low at idle, only reaching 1.6 ppm for RIT 3. HC emissions were a bit higher during the drive cycle reaching around 6 ppm to 8 ppm in both vehicles when tested initially in 2008. RIT 2 dropped HC emissions to only .816 ppm in 2010 while RIT 3 maintained HC emissions at around the 6 ppm to 7 ppm value it had in 2008.

The presence of HC emissions is likely due to the fact that the HICE Ford Escape Hybrids do not have a catalytic converter. The catalytic converter works to decrease or remove the HC emissions from a vehicle's exhaust gas. Still the HC values are considerably lower than the maximum 220

[4] To visualize parts per million, one example would be a bin filled with one million marbles, of which only three are blue, thus giving the measurement of 3 ppm.

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ppm standard imposed by the New York State Department of Motor Vehicles for a vehicle at idle made after the year 1981.[5] The Carbon Monoxide (CO) and Carbon Dioxide (CO2) emissions are significantly low, never reaching above .007 percent during any test on both vehicles between 2008 and 2010. The combined CO and CO2 emissions according to the New York State Department of Motor Vehicles cannot exceed 6.0 percent. Emissions results from the HICE vehicles show acceptable values over time.

Hydrogen Emisions Over Time - Idle - RIT 2		
Emission	*2008*	*2010*
Nox (ppm)	0.866	0.316
HC (ppm)	0.016	0.816
CO (%)	0.000	0.000
CO2 (%)	0.000	0.000

Hydrogen Emisions Over Time - Idle - RIT 3		
Emission	*2008*	*2010*
Nox (ppm)	0.000	0.000
HC (ppm)	0.000	1.600
CO (%)	0.000	0.000
CO2 (%)	0.006	0.007

Hydrogen Emisions Over Time - Driving - RIT 2		
Emission	*2008*	*2010*
Nox (ppm)	1.691	0.316
HC (ppm)	7.942	0.816
CO (%)	0.002	0.001
CO2 (%)	0.005	0.006

Hydrogen Emisions Over Time - Driving - RIT 3		
Emission	*2008*	*2010*
Nox (ppm)	2.000	2.840
HC (ppm)	6.476	6.804
CO (%)	0.000	0.000
CO2 (%)	0.001	0.010

The following table reflects the difference between the Hydrogen Hybrid Ford Escape and the Gasoline Hybrid Ford Escape.

Hydrogen vs Gasoline Emisions - Driving Cycle		
Emission	*Hydrogen*	*Gasoline*
Nox (ppm)	2.84	5.00
HC (ppm)	6.80	0.00
CO (%)	0.000062	0.010
CO2 (%)	0.010	11.62

The vehicles were compared using the driving cycle test results. As seen below there is a 2 ppm increase in NOx emissions from the HICE to Gasoline Ford Escape Hybrid, which we can consider to be a low and amount. The difference in Carbon Monoxide (CO) emissions also proved to be insignificant with neither value reaching over .01% of the total exhaust gas. The HC levels in the HICE Ford Escapes were on average 6.80 ppm compared to 0 ppm for the gasoline powered Escape. The values are low and insignificant due to the fact that the HICE vehicle does not have a catalytic converter as explained earlier. The gasoline Escape did contain 11.62 percent Carbon Dioxide (CO2) in its exhaust gas while the HICE vehicle contained only .01 percent. The HICE

[5] New York State DMV Enhanced Emissions Inspection Procedure VS-28, January 2008, and NYS DEC Regulation 217-1.3: Motor Vehicle Exhaust Emission Standards and Inspection Procedures, 30 September 2002.

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vehicle emitted very few harmful emissions proving that they are extremely clean vehicles to drive compared to their gasoline counterparts.

On-Board Vehicle Monitoring System

In order to accurately track and evaluate the performance of the three HICE vehicles, CIMS installed commercial Networkcar vehicle monitoring systems on each vehicle. These were the same units installed on some of the ethanol and biodiesel vehicles used in other parts of the DOT program.

Figure 5-29 Networkcar on-board vehicle monitoring unit and antenna

The Networkcar units connected to the vehicle OBD system and provided GPS tracking, remote diagnostics and vehicle maintenance alerts via a cell phone connection. The Networkfleet web-based service provided summary data on the vehicles such as speed ranges, idle times and overall maintenance alert summaries. Although the system was designed for gasoline vehicles, this information was particularly valuable in detecting potential failures, corrective actions and evaluating performance due to the high idle times of the two Public Safety vehicles. In a number of instances, the timely system alerts allowed us to quickly troubleshoot failures and return the vehicles to operational status.

Sample Networkfleet alerts are shown below in Figures 5-30 and 5-31. A complete listing of all alerts on all three vehicles is provided at Appendix D.

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PROBLEM ALERT NOTIFICATION

Last Update: 08/30/09 07:11 AM Vehicle Mileage: 10209,

Networkfleet has detected a potential problem in your 2008 FORD ESCAPE HYBRID (VIN 1FMCU49H88KD06960, Vehicle Label HYDROGEN 1 - PUBLIC SAFETY). Specifically, the problem is your:

P0193: Fuel Rail Pressure Sensor Circuit High Input

Gasoline delivery system may not be working correctly

Initial Activity: 8/30/09 07:11 AM at 10209 miles

Please contact your preferred vehicle service provider as soon as possible to discuss this problem.

login to networkfleet.

networkfleet.

This e-mail has been generated as part of your Networkfleet service to assist you in the maintenance of your vehicle.

Figure 5-30 Networkcar alert for fuel rail sensor failure

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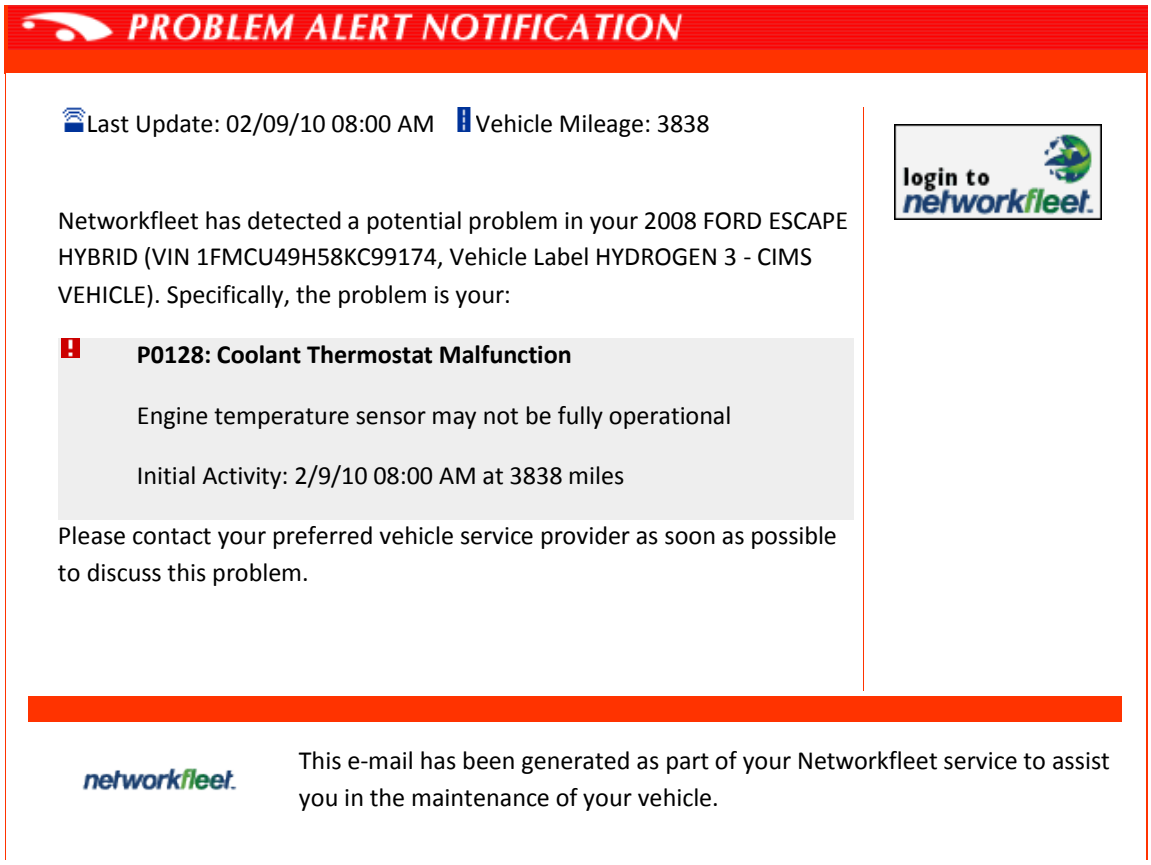

PROBLEM ALERT NOTIFICATION

Last Update: 02/09/10 08:00 AM Vehicle Mileage: 3838

login to networkfleet

Networkfleet has detected a potential problem in your 2008 FORD ESCAPE HYBRID (VIN 1FMCU49H58KC99174, Vehicle Label HYDROGEN 3 - CIMS VEHICLE). Specifically, the problem is your:

P0128: Coolant Thermostat Malfunction

Engine temperature sensor may not be fully operational

Initial Activity: 2/9/10 08:00 AM at 3838 miles

Please contact your preferred vehicle service provider as soon as possible to discuss this problem.

networkfleet

This e-mail has been generated as part of your Networkfleet service to assist you in the maintenance of your vehicle.

Figure 5-31 Networkcar alert for coolant thermostat failure.

HICE Driver Evaluations

A number of individuals had an opportunity to operate the three HICE vehicles over the course of the two-year evaluation. In particular, the Public Safety Department operated them extensively all-day, year-round.

Throughout the operation of the Hydrogen ICE vehicles in RIT's Public Safety fleet, drivers were asked about their opinions and interaction with the HICE vehicles. The drivers were impressed with the state of hydrogen technology, however there were some areas of dissatisfaction with the vehicles. The three major complaints were: the HICE vehicles lacked power compared to the similar non-hydrogen ICE vehicle in their fleet, the CVT transmission created a lot of noise at high RPM's and refueling was slow; all areas which provide a foundation on which to improve. It is important to note that at the same time the Public Safety staff was operating the HICE Ford Escape Hybrids, they were also operating regular gasoline-powered Escape Hybrids. This allowed the drivers to have an immediate comparison between the two vehicle technologies on a daily basis.

In June 2010 drivers from Public Safety who had driven at least one of the Hydrogen ICE vehicles were asked to complete a survey to formally voice their opinions and observations of the vehicles. This allowed the drivers to discuss their reactions to the HICE vehicles. A total of eight surveys

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were completed and collected. The detailed surveys are available at Appendix E. The survey was made up of four sections including; Drivability/Vehicle Performance Issues, User Observations, Vehicle Use and Customer Satisfaction.

The Drivability/Vehicle Performance Issues section provided a list of drivability issues and asked the driver to answer on a predetermined scale how often any problems occurred. They were also asked to state the condition(s) under which they occurred. After CIMS reviewed the survey responses, some of the issues the drivers identified were similar to earlier comments about the HICE vehicles made by other RIT personnel. Four out of eight drivers said that the vehicles lacked power always or most of the time, while another two said that the vehicles sometimes lacked power.

Additionally, most of the drivers said that the vehicles sometimes hesitated or stalled under acceleration if not most of the time. CIMS researchers believe this is probably due to the lack of power the HICE vehicles provided giving the drivers a sense of hesitation during acceleration, particularly when compared to the gasoline powered Escapes. Nearly all the drivers said that the vehicles were excessively noisy, likely due to the CVT transmission. The Hydrogen ICE vehicles operate at higher RPM's at slower speeds than a conventional ICE vehicle. The CVT transmission in turn operates at a higher speed causing the noise of the vehicles to be louder than expected at lower speeds. The drivers also stated that the vehicle sometimes backfired. The drivers experienced no other significant issues with the vehicles other than those summarized above. The full results are summarized below in Fig 5-32.

	Number of Drivers Responded (out of 8)				
Drivability Issues *A-Always; M-Mostly; S-Sometimes R-Rarely; N-Never or Not Apply*	***A***	***M***	***S***	***R***	***N***
Extended Crank Time	1	0	0	1	5
Engine Idles Rough	2	2	2	0	2
Engine Idles Too Fast	3	1	2	0	1
Hesitates or Stalls Under Acceleration	2	1	5	0	0
Misses Under load	0	0	2	1	3
Engine Surges at Constant Speed	0	0	1	2	5
Limited Power	3	1	2	2	0
Pings or Knocks	0	0	3	2	2
Stalls on Deceleration or Stop	0	1	1	2	4
Engine Runs After Key is Turned Off	0	0	1	3	4
Backfires	0	0	6	1	1
Excessive Noise Levels	3	4	0	0	1

Figure 5-32 Drivability Survey Results

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The Vehicle Use section was used to ensure that the HICE vehicles were not treated differently from the Non-HICE vehicles. As expected they operated under the same conditions as the Non-HICE vehicles.

The customer satisfaction section of the survey allowed the driver to provide how content they were while operating these vehicles. These questions concerned how the driver felt about the vehicle during daily use. As we expected, the drivers were very dissatisfied with the ease and time it takes fueling the vehicles. One comment suggested that a vehicle would be out of service for nearly 40 minutes in order to complete the entire refueling process. This deficiency is a function of the refueling infrastructure, not the vehicles. The lack of power the HICE vehicles provided was expressed in this section as well. However, the divers were satisfied with the traction the vehicles provided as well as the ability to run auxiliary electronics required for the Public Safety mission such as radios, computers and emergency lights. The results for each driver's answer is summarized in the table in Figure 5-33 below.

	Number of Drivers Responded (out of 8)				
Customer Satisfaction *1-Very Dissatisfied to 5-Very Satisfied*	***1***	***2***	***3***	***4***	***5***
Ease of Fueling Vehicle	2	3	2	1	0
Time to Fuel Vehicle	4	3	1	0	0
Power & Acceleration	5	3	0	0	0
Power Under Heavy Loads	2	3	2	0	0
Traction	1	1	2	4	0
Ability to Run Aux. Electronic Accessories	0	3	0	3	2

Figure 5-33 Customer satisfaction survey results

Although the drivers voiced a negative opinion of the vehicle's lack of power, noisiness and slowness of refueling; drivers were extremely impressed with and supportive of the hydrogen vehicle program. One driver stated that they understand that Hydrogen ICE vehicles are still a "work in progress" and would stick with it until the vehicle and its processes are perfected. With the views of the drivers who interact with the HICE vehicles daily, it helped us establish which components of Hydrogen technology need to be improved for the future.

Results of the survey and operation of the fleet place this hydrogen ICE technology on a Technology Readiness Level 7 by NASA standards – "system prototype demonstrated in a relevant operational environment." CIMS feels it is not yet ready for full commercial deployment and sales.

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6. Project Information and Results

Education and Outreach

Once our fueling station and vehicle operations were underway, the final task of our program was to develop and present education and outreach events centered around hydrogen vehicle technology. In support of this effort, CIMS presented a wide range of classroom demonstrations, public awareness and technology displays of the hydrogen station and vehicles.

Below are highlights of these education and outreach events.

CIMS Hydrogen Vehicle Outreach & Education Events					
Date	Event	Sponsor	Location	Audience Size	Media Attendance
Jul, Aug-08	Demonstration - Univ. of Rochester	CIMS	Univ. of Rochester; Rochester, NY	10	N
Jul, Aug-08	Demonstration - Genesee Region Clean Communities Coalition	CIMS	CIMS; Rochester, NY	100	N
Jul, Aug-08	Demonstration - Monroe County Fleet Management	CIMS	CIMS; Rochester, NY	7	N
Jul, Aug-08	Demonstration - General Motors Fuel Cell Division	CIMS	CIMS; Rochester, NY	10	N
Jul, Aug-08	Demonstration - RIT Freshman Business Class	CIMS	RIT; Rochester, NY	20	N
Jul-08	"Live in the Lot" at WHAM-13	WHAM 13	WHAM-13 Studio; Rochester, NY	30+ TV	Y
Aug-08	WXXI Radio Interview	WXXI	CIMS; Rochester, NY	N/A	Y
Aug-08	US Dept. of Transportation Visit to CIMS	CIMS	CIMS; Rochester, NY	1	N
Aug-08	"Green Fueling Station" Grand Opening	Monroe County Gov	Monroe County "Green Fueling Station"; Rochester, NY	75	Y
Aug 08	LeRoy, NY Rotary Club Luncheon	LeRoy Rotary Club	LeRoy NY	25	N
Aug-08	GIS meeting to discuss HICE vehicle involvement in coursework	CIMS	RIT; Rochester, NY	N/A	N
Sep-08	CIMS Tour , Including head of Genesee Region Clean Comm	CIMS	CIMS; Rochester, NY	5	N
Sep-08	DOE National Alternative Fuel Vehicle Odyssey Day	GRCC & CIMS	Monroe County "Green Fueling Station"; Rochester, NY	1000+	Y

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Sep-08	M. Haselkorn taught a session of RIT's College of Engineering's Hydrogen Technology class	RIT COE	RIT; Rochester, NY	24	N
Jan-09	Hydrogen Works (HyWo) team visit to CIMS	CIMS	CIMS; Rochester, NY	3	N
Jan-09	US Rep. Eric Massa visit to CIMS	CIMS	CIMS; Rochester, NY	3	N
Feb-09	TV Demonstration of Hydrogen Program	WROC Channel 8	CIMS; Rochester, NY	N/A	Y
Feb-09	M. Haselkorn taught RIT College of Science Hydrogen course	CIMS	RIT; Rochester, NY	20	N
Feb-09	6 training sessions on operation of vehicle and refueling system	CIMS	CIMS; Rochester, NY	30	N
Mar 09	BOCES Student Tour of CIMS	CIMS	CIMS; Rochester, NY	40	N
Mar-09	Presentation - The Rochester Chapter of the American Society of Mechanical Engineers	CIMS	CIMS; Rochester, NY	25	N
Apr 09	Workforce Innovation Student Orientation	RIT	CIMS; Rochester, NY	30	Y
Apr-09	Perry, NY Rotary Club Luncheon	Perry Rotary Club	Perry, NY	45	Y
May 09	Imagine RIT Wow Center	RIT	RIT; Rochester, NY	8000	Y
May-09	Presentation - RIT Mechanical Engineering Technology students on the HICE Ford Escape	CIMS	RIT; Rochester, NY	29	N
May-09	RIT Administrative Personnel Begin to Drive RIT 3	CIMS	RIT; Rochester, NY	N/A	N
Jun 09	Presentation on Hydrogen Vehicles to Edison Tech	Edison Tech	Edison Technical HS, Rochester	25	N
Jul-09	Wegmans Public Demonstration	Wegmans	Monroe Ave Wegmans; Rochester, NY	500+	N
Jul 09	NREL and Oak Ridge National Labs Visit	CIMS	CIMS; Rochester, NY	2	N
Jul-09	RIT 3 Participates in Walworth, NY Going Green Parade	Town of Walworth, NY	Walworth, NY	2000+	Y
Aug-09	Wegmans Thursday Night "Drive In"	Wegmans	Wegmans; Canandaigua, NY	300	N
Aug 09	Interview with Rochester *City Newspaper*	CIMS	CIMS; Rochester, NY	N/A	y
Aug 09	RIT Freshman Orientation	CIMS	CIMS; Rochester, NY	200+	N
Aug-09	Wegmans Public Demonstration; 2 Radio	Wegmans	Monroe Ave Wegmans; Rochester, NY	500+	Y

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	Interviews				
Sep-09	Demonstration - Home schooled students	CIMS	CIMS; Rochester, NY	25	N
Feb 2010	Albion, NY Rotary Club Luncheon	Albion Rotary Club	Albion NY	20	N
April 2010	Workforce Innovation Student Orientation	RIT	CIMS; Rochester, NY	30	Y
May 2010	Imagine RIT Wow Center Green Vehicle Display	RIT	RIT; Rochester, NY	10,000 est.	Y
May 2010	Alternative Vehicle/Clean Commute Display	RIT	RIT; Rochester, NY	50	Y
June 2010	GRCC Alternative Vehicle Symposium	GRCC	RIT Inn and Conference Center	250	N

In addition to these dedicated events, dozens of other visitors to CIMS had a chance to view the vehicles and hydrogen station during tours of Building 78. CIMS considers our outreach events to be very successful, and has raised awareness across Western NY of the potential for hydrogen-powered transportation.

Performance Comparison of Hydrogen Powered Vehicles

An additional NYSERDA program objective was for CIMS to support the NYS Hydrogen Transportation Development Program by aggregating and analyzing vehicle and site level project data and information from all of NYSERDA's demonstration projects funded under PON 1082. At the start of the CIMS contract, this was projected to be four of five other sites and up to 20 HICE vehicles. However, as the NYSERDA program developed, eventually only two sites other than CIMS became operational. The Albany Airport hydrogen site services four vehicles (two converted Toyota Prius HICE and two converted Chevy Silverado HICE). The Hempstead, L.I. site was not operational until late 2009 and is servicing a single HICE shuttle bus for the town of Hempstead.

Initially, CIMS was to collect vehicle and fueling performance data from all three sites and report this to NYSERDA on a monthly basis. As the NYSERDA program did not fully develop as intended NYSERDA revised this data collection task to an evaluation of the differences in performance between HICE and fuel cell vehicles.

CIMS accomplished this task in two phases: a detailed miles-per-kilogram evaluation of the HICE Escapes (and comparison with gasoline Escapes) and a comparison of the HICE data with results from a Department of Energy fuel cell vehicle program.

This inquiry was conducted between November 2009 and February 2010 and was designed to analyze the fuel economy of three Ford Escape vehicles. Collecting data on these vehicles and maintaining these vehicles has been the responsibility of the Center of Integrated Manufacturing Studies which is located on the Institute's campus. Using data recorded at the hydrogen filling station as well as data recorded by Network Fleet's Fleet Management system installed in each of the vehicles, the fuel economy of each vehicle was monitored for thirteen months (February 2009 to

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February 2010). This data was then taken and compared to data provided by the National Renewable Energy Laboratory on their fleet of hydrogen fuel cell vehicles and the estimated fuel economy of Ford Escape gasoline hybrid vehicles at are currently on the road today.

At the conclusion of this comprehensive look into the fuel economy of the different types of vehicles it was demonstrated that the hydrogen fuel cell vehicles and the hydrogen internal combustions engine vehicles have a comparable fuel economy which is greater than that of the gasoline hybrid. They hydrogen vehicles had a combined fuel economy of approximately 40 miles per kilogram of hydrogen compared to the EPA estimated combined fuel mileage of 32 miles per gallon of gasoline for the gasoline Escape (Figure 6-1). However, the cost of both fuels are difficult to evaluate directly since hydrogen is only available in a few limited locations and is not a true "road fuel." It was calculated that at present, the cost of one kilogram of hydrogen would be equivalent to the cost of 1.2 times the cost of a gallon of gasoline. This provided an economic model for the cost comparison of hydrogen and gasoline.

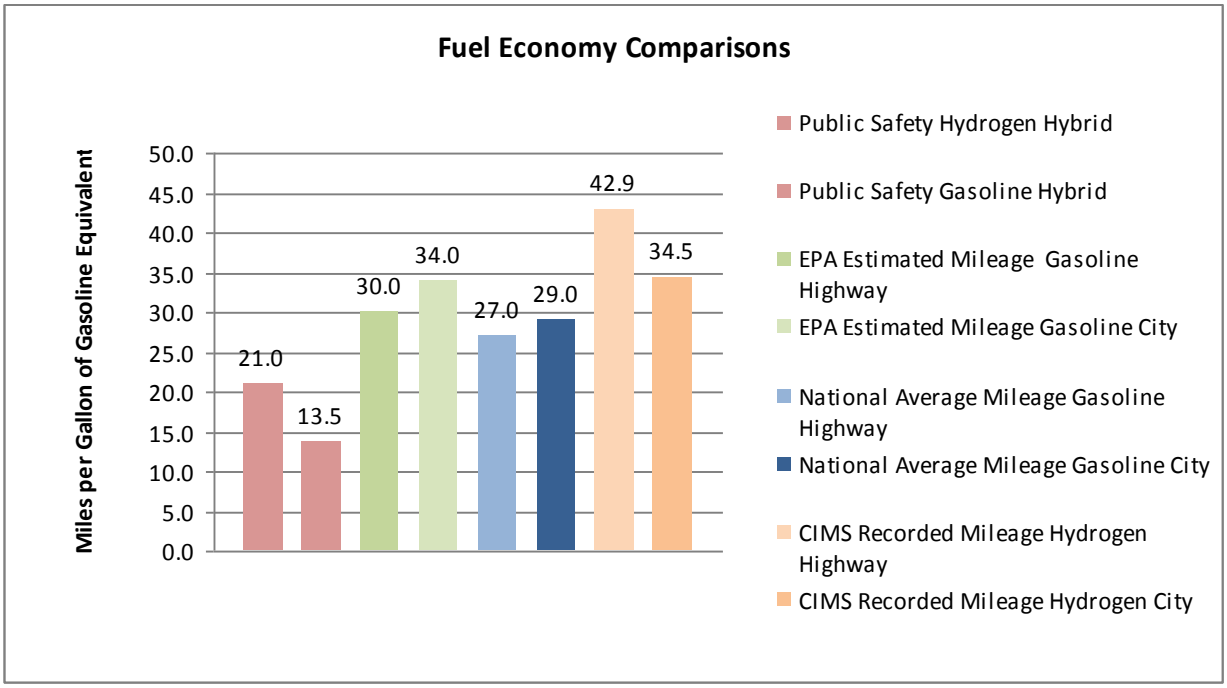

Figure 6-1 Fuel Economy Comparisons of gasoline and hydrogen Escapes.

The complete results of that analysis are presented in Appendix C.

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Project Cost Summary

NYSERDA Program Expenditures as of 11 September 2010:

Fueling Station Construction	$543,657
(3) HICE vehicles, conversion, warranty and shipping	$362,107
CIMS Labor (NYSDERA contract)	$83,500
Travel	$1,200
Tools, equipment	$9,500
NYSERDA Program Total	**$999,964**

The remaining funding for the program came from the U.S. DOT Alternative Fuels grant funds. This was used for hydrogen fuel and storage equipment lease, data collection, vehicle and station maintenance, project management and reporting, and education and outreach event support.

Remaining program costs (all from DOT funding):

Fuel storage (24 months)	$26,400 (entire program)
Hydrogen Fuel Usage ($3.65/100 cu ft)	$45,000 (entire program)
Networkcar units and service	$7030
CIMS labor, driver time, software, repair parts, inspections, publications, education and outreach materials	$426,000
DOT Total cost share	**$504,438**

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7. Lessons Learned and Recommendations

A number of lessons came out of our experiences with hydrogen infrastructure and vehicles. Probably the primary lesson was that the public perceives hydrogen as an dangerous fuel and the urban legend of the "Hindenburg syndrome" continues to pervade the public consciousness. This is in contrast to the perception that gasoline is a "safe" fuel, in spite of the number of gasoline-related mishaps each year. Further education is still necessary for the safety comparisons of both fuels and the advantages of hydrogen to be appreciated by the consumer.

Hydrogen Dispensing Infrastructure

On the infrastructure side, our project to construct a permanent hydrogen station was the first of its kind in the Rochester area. Although Monroe County installed a similar facility, since it was on county airport property and away from buildings, the construction was much easier. The myriad of regulation compliance and permits required added significant time to the construction of the station. Overlapping federal and local jurisdictions made the effort even more complex. The installation of the refueler at RIT took longer than anticipated because the local safety officials, code inspectors, and the contractor selected by RIT had very little experience with hydrogen equipment. For example, even though hydrogen was stored as a gas, RIT was required to place gravel around the refueler in case of a hydrogen leak. The infrastructure development process would have been quicker and less confusing if there were codes strictly for hydrogen usage and dispensing and the regulatory process did not have to fall back on existing gasoline dispensing codes.

Once the station was completed, it soon became obvious that the Quantum fueler we had purchased was not adequately designed for cold-weather environments. When delivered to CIMS, the refueler was not able to operate at temperatures below 32°F. As a result, we had to manually heat the air compressor every day in order to get the refueler to operate. In addition, improved weather stripping had to be applied to prevent snow from entering the refueler components. Once these modifications were made the reliability of the refueler in the cold weather was improved. However, this led to the conclusion that hydrogen infrastructure equipment should be more robust and able to handle more severe environmental extremes. This situation was compounded by the regulations that we interpreted as preventing us from putting a cover over the station to prevent water intrusion and ice build-up.

Software problems also arose in the refueler. Several times, electrical contacts were "jumped" to overcome software problems and open a valve. In addition, corrosion problems were also encountered with the electrical connections on the communication cables that attach to the vehicle during refueling requiring Quantum to supply a new cable after approximately one year of operation. Finally, there were multiple other problems with the refueler during the first year of operation such as thermocouple control and valve operating problems and a first head leak on the compressor which prevented the refueler from operating during the first year of this program. Quantum supplied fixes for these problems and for this reason, the station operated without problems during the second year of this program until a touch screen failure was encountered.

In addition to the reliability problems with the fueler, the other significant drawback to the system was the time required to refuel the vehicle. When the storage tanks were nearly empty, it took at

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least 25 minutes to fuel the vehicle once the fuel transfer operation had started. Even topping off the tanks took a minimum of 15 minutes. These refuel times are perceived by many operators to be too long for the average consumer, particularly when the station cannot be covered and the driver must be exposed to the elements. So-called "fast fill" systems have been developed, but they were outside the budget for this program.

HICE Vehicle Operation

On the vehicle side, the key constraint to successful vehicle operation was the performance of the fuel injectors with the gaseous hydrogen fuel. The on-board vehicle monitoring system mentioned previously (Networkcar) was very valuable in tracking vehicle performance and component failures. It is recommended that it be used (or a similar system) for other prototype vehicle evaluations.

While this program was successful in demonstrating the viability of HICE vehicles and raised the public awareness of the potential for hydrogen to be a safe viable fuel that could potentially displace petroleum based fuels, it also demonstrated that the durability of the Ford Escape hybrid-electric vehicles with hydrogen internal combustion engines was poor. One reason for the poor durability of the vehicles was corrosion of the electrical connections for the hydrogen flow values in the fuel tanks and under the hood. However, these problems can be easily corrected by improving the sealing around the electrical connectors.

The major durability issue was with the fuel injectors. We experienced continuing failures and replacements of the fuel injectors throughout the program. At first, the injectors lasted between 3000 to 4000 miles between changes. This was increased to approximately 8,000 miles by several changes made by Quantum. With gasoline fueled internal combustion engines, the fuel injectors usually last the entire lifetime of an engine (as much as 150,000 miles). The durability of the fuel injectors for the HICE engine needs to be improved significantly to make this technology viable.

Due to the numerous problems we encountered and the significant down time of the vehicles (as well as the station) it would have been sensible to pre-position some Quantum technical support in the local area for service, parts and repairs. CIMS was fortunate in that we have an experienced cadre of electrical and mechanical technicians who could troubleshoot and solve most minor vehicle problems. They were also able to install new Quantum components when necessary without any significant instruction. Other users or regular consumers would not have access to this robust maintenance support for a new vehicle.

As far as driving and operation, when they were operational, the Escapes drove essentially like a normal small SUV. Most of the negative driver impressions of the hydrogen ICE vehicles centered around the excessive noise from the Continuously Variable Transmission (CVT). This soured a number of operators on the technology, but was not in fact a shortfall of the hydrogen capability. Perhaps a different vehicle (sedan or pickup) with a different transmission would have achieved more favorable results. The other complicating factor was that the Escapes retained their hybrid drive system. This was also the first experience for many of the operators with a hybrid vehicle. That served to distract some users from the features hydrogen ICE operation. A conventional ICE vehicle platform might have been more appropriate for demonstrating the hydrogen technology.

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On a related issue, at the same time RIT was deploying the three HICE vehicles on campus, General Motors was engaged in deploying Chevy Equinox fuel cell vehicles in the Rochester area under their "Project Driveway." As a result several program participants had a chance to drive and evaluate both the Escape HICE vehicles and the Equinox. The fuel cell vehicles were quieter and had significantly more power and acceleration. Unfortunately, as this report was in preparation, a mishap occurred at the county fueling station when a portion of a hydrogen tanker truck ruptured and exploded. There was only one injury, but the county station operations were suspended indefinitely pending the results of an investigation.

Recommendations

CIMS provides the following recommendations for future hydrogen or alternative fuel vehicle programs:

1. Selection of the vehicle platform must be compatible with the alternative fuel technology. Ideally the vehicle platform should be sized to provide the energy storage capacity for 300 miles of normal driving before the vehicles are deployed to regular users. So-called "range anxiety" is a key characteristic of alternative fuel vehicles.

2. Testing both a developmental fueling infrastructure and a developmental vehicle will lead to unintended consequences and render study of each system more difficult. We recommend test and evaluation of only one system at a time, or allowing the fueling infrastructure to mature ahead of the vehicle.

3. A vehicle test program is just that. Program personnel should be educated in the objectives of the program as well as the constraints. A certain amount of expectation management is required with new technology. Sufficient resources should be available to handle failures, repairs and modifications as well as track deficiencies and corrective actions.

4. Public awareness and education are critical to consumer adoption of new technologies. A sustained public diplomacy effort should be tightly linked with the technology development and implementation. In conjunction with discussing the safety of the new technology, it should be contrasted to the safety levels of the technology it is intended to replace.

5. Safety and construction codes for hydrogen infrastructure must receive more attention and standardization nationwide.

Acknowledgements

The CIMS staff would like to recognize the contributions of our outstanding group of RIT co-op students who supported this project from 2008 to 2010. They are: Patrick Villaume, Matthew Tranter, Ryan Enyeart, Dan Beardslee, Kelsey McConnaghy, Brittany Borella, Christina Smith and Jonathan Seaman.

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Appendices separately submitted as PDF files

A. Hydrogen Vehicle Driver Comment Card
B. Refueling Protocols
C. Fuel Mileage Comparisons
D. Networkcar Alert Summary
E. Driver Survey Results

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[i] "Edmunds.com Forecasts 2010 Automotive Trends" News release dated December 9, 2009, from www.edmunds.com.

[ii] White House Press Release, May 19, 2009, "**President Obama Announces National Fuel Efficiency Policy."** **Available at** www.whitehouse.gov**.**

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Vehicle Drivability Issue Report

NYSERDA, DOT & ROCHESTER INSTITUTE OF TECHNOLOGY
A Partnership for our Community's Future

DEPLOYING GREEN VEHICLE TECHNOLOGIES

Operator Name: _____

Vehicle ID number		Date	
Vehicle odometer		Time	

Hydrogen Start (Kg's): _____ Hydrogen Finish (Kg's): _____

(From Refueler Screen)

Refueling Time: Start Time: _____
End Time: _____

This vehicle is a part of the NYSERDA, DOT, & RIT study on alternative fuels. Please fill out the information below:

Outside temperature _____ Weather conditions (raining, snow, etc) _____

Please check issue:

- ☐ Difficult to start engine
- ☐ Backfiring
- ☐ Stall after start
- ☐ Stall in traffic
- ☐ Hesitation at acceleration
- ☐ Lack of power
- ☐ Engine running rough
- ☐ Poor idling
- ☐ Check engine light
- ☐ Strange odor
- ☐ Unknown noise
- ☐ Engine surging
- ☐ Other_____

☐ Error codes from refueler _____
_____
_____
_____

Return it to:

RIT VEHICLES
Rochester Institute of Technology
133 Lomb Memorial Dr, Building 78, Rm 1430
Rochester, NY 14623

Appendix A. Driver Comment Card

Center for Integrated Manufacturing Studies

CIMS at R·I·T

increasing the competitiveness of manufacturers through applied technology and training

Hydrogen Vehicle Refueling Protocols

July 13, 2009

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Properties of Hydrogen

- **What Is Hydrogen?**
  - Hydrogen is a colorless, odorless, tasteless, flammable nontoxic gas. It is the lightest of all gases, with a specific gravity of 0.0695.
  - The hydrogen content of atmospheric air at sea level is 0.5 ppm.

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Hydrogen Safety

- As the lightest and smallest element in the universe, confining hydrogen is very difficult.
- Hydrogen is much lighter than air and rises at a speed of almost 20 meters per second — two times faster than helium and six times faster than natural gas — which means that when released, it rises and disperses quickly
- Combustion cannot occur in a tank or any contained location that contains only hydrogen. An oxidizer, such as oxygen, must be present

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Hydrogen Safety

- Hydrogen burns very quickly.
  - Under optimal combustion conditions, the energy required to initiate hydrogen combustion is significantly lower than that required for other common fuels, such as natural gas or gasoline.
  - At low concentrations of hydrogen fuel in air, the energy required to initiate combustion is similar to that of other fuels.
- Hydrogen flames have low radiant heat.
  - A hydrogen fire has significantly less radiant heat when compared to a hydrocarbon fire.
  - Since low levels of heat are emitted near a hydrogen flame (the flame itself is just as hot), the risk of secondary fires is lower.

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Hydrogen Safety

- With the exception of oxygen, any gas can cause asphyxiation in high enough concentrations.
  - In most scenarios, however, because hydrogen rises and disperses so rapidly, it is unlikely to be confined where asphyxiation might otherwise occur.
- Hydrogen is non-toxic and non-poisonous. It will not contaminate groundwater (it's a gas under normal atmospheric conditions), and a release of hydrogen is not known to contribute to atmospheric pollution or water pollution.

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Flammability and Explosivity Are Primary Hazards

- The primary physical hazards associated with hydrogen gas are its flammability and explosivity.
  - This is because hydrogen can form a flammable mixture with air over a wide range of concentrations (4%-75%), and very low energy is needed to ignite hydrogen-air mixtures.
  - Once hydrogen is ignited, the reaction can proceed either by deflagration (subsonic propagation) or detonation (supersonic propagation).
  - Deflagration in a closed volume can cause a pressure increase of almost eight times the initial pressure.
- Hydrogen detonations, although rare, are characterized by pressure increases so rapid that pressure-relief devices are usually ineffective.

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Fuel Properties

Property	Hydrogen	CNG	Gasoline
Density (kg/m3)	0.0824	0.73	730
Flammability Limits (Volume percent in air)	0.1-7.1	0.4-1.6	1.4-7.6
Autoignition temp in air (K)	858	723	550
Minimum Ignition energy (mj)	0.02	0.28	0.24
Flame Velocity (m/s)	1.85	0.38	.037-0.43
Adiabatic Flame Temperature (K)	2480	2214	2580
Heat of Combustion MJ/kg_{air}	3.37	2.9	2.83
Stoichiometric Fuel/Air Ratio	0.029	0.069	0.068

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Vehicle Specifications

- Current horsepower: 100
- 4.0 kg of compressed H2 stored on board
- Vehicle achieves 29 miles/kg
- Total range: 116 miles
- Tank Working Pressure: 5,000 psi (350 bar)
- Pressure reduced twice going to engine 5000 psi to 220 psi to 50 psi
- 50 psi hydrogen inside the fuel rail

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Hydrogen Vehicle Refueling Procedure

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Safety and Caution

- Do not fill the fuel storage tank with hydrogen if the display screen indicates tank pressure is less than 363 psi (2.5 MPa) **AND** the tank temperature is less than -31° F (-35° C).
- Only trained and qualified personnel must operate the hydrogen refueling system. The system is not for use by the general public.
- Hydrogen is extremely flammable. Ignited it could cause severe burns.
    - Keep sparks, flames and ignition sources a minimum of 5 meters (16 feet) from hydrogen.
    - Do not smoke near hydrogen or while refueling or defueling a vehicle.
    - Turn the vehicle's electrical system OFF while refueling or defueling.
- Use the proper grounding procedures to prevent static electricity build-up during refueling or defueling.

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Refueling

- Turn the ignition key to the **OFF** position
- Open the *refueling system* panel doors

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Safety Strategy –Materials and Equipment Used

- 4 x Burst required on all materials
- Hydrogen compatible materials used throughout the process plumbing
- All 316 stainless steel materials for tubing, fittings and valves
- ASME/CE Certifications on all components
- Diaphragm compressor section
- TUV testing on gas equipment and electrical equipment
- North American and European certification for EMI/EMC
- All service documentation and training developed

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Safety Strategy-Primary (Start-up sequence)

- Multiple safety layers implemented
- Purging & Process strategy
- Cabinet Ventilation
- Verification of ventilation
- Redundant H2 concentration monitoring
- Start-up interlock circuitry located in explosion-proof enclosure

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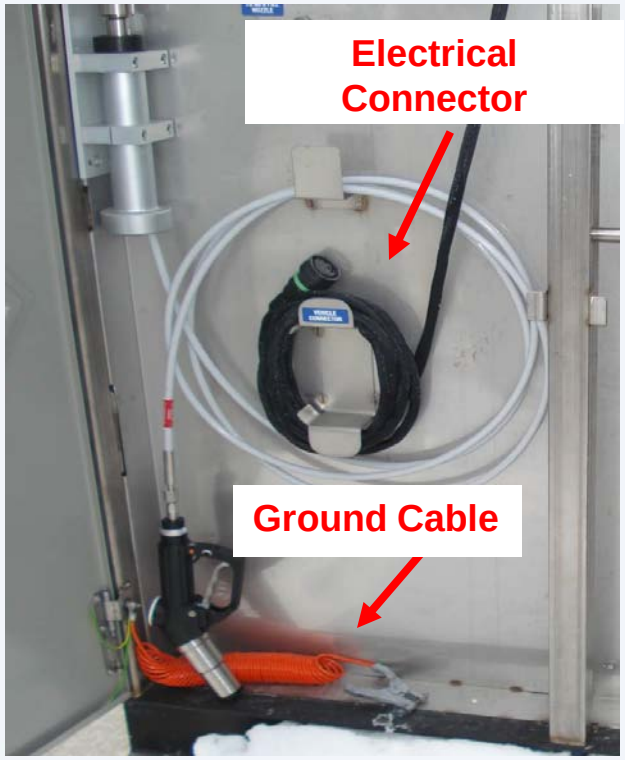
Refueling

- **Connect the Electrical Connector to the Electrical Receiver on the rear of the vehicle. If vehicle has no Electrical connector connect ground cable to vehicle.**



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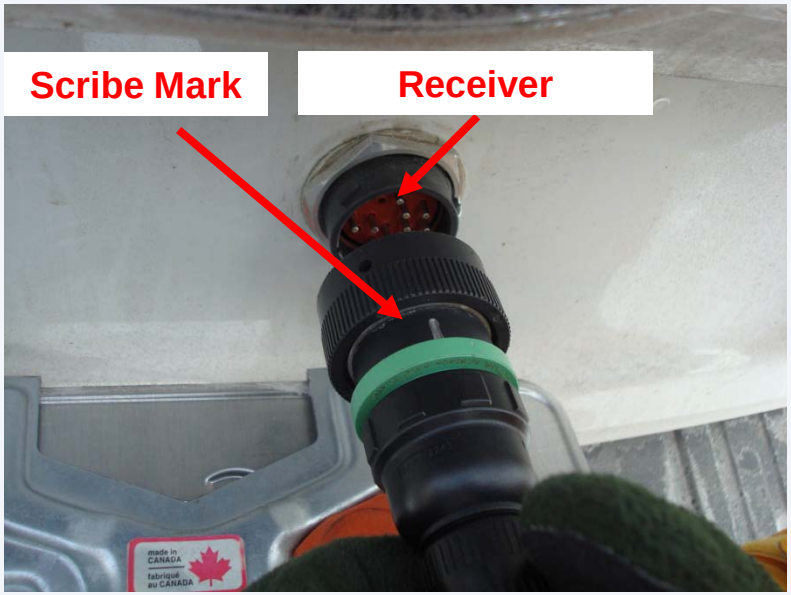
Connecting the Electrical Connector

- **Flip down the rear license plate. With the *wide notch* and *scribe mark* face up, place the *fueling station electrical connector* on the *vehicles electrical receiver.***
- **Next turn the outer collar clockwise until it stops**



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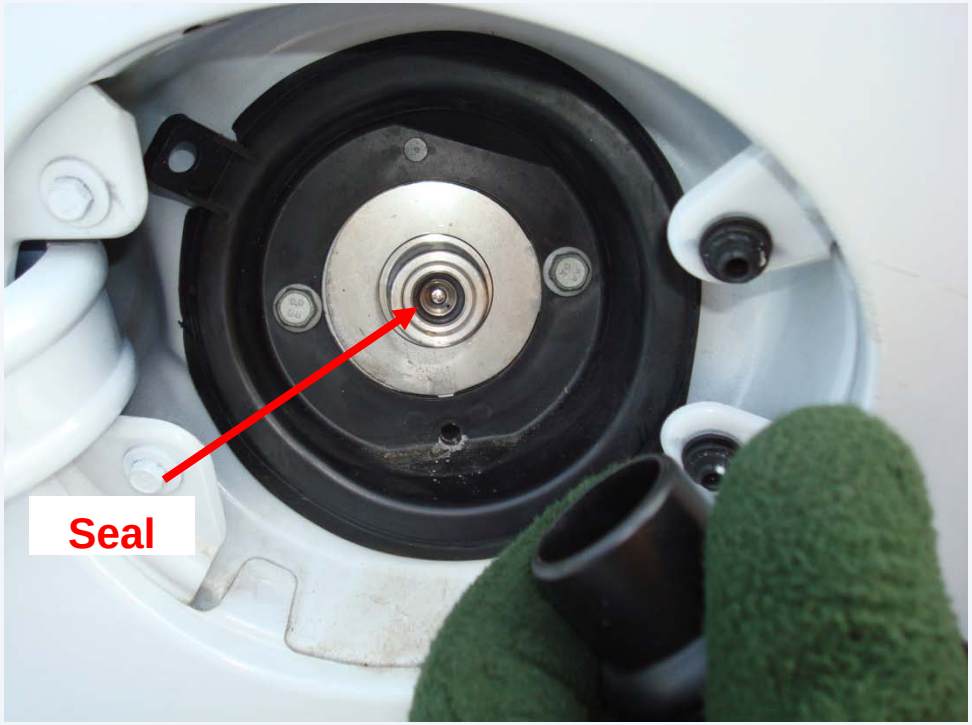
Refueling

- Open the *fuel fill door* and remove the *fill receptacle cap.*
- Inspect the *full fill nozzle* and *vehicle receptacle* for debris and verify the seal is in place.
- If debris is found or seal is cracked or missing DO NOT proceed until this is corrected. **If you notice damage or debris in the receptacle, contact Michael Haselkorn at (585) 475-5408.**



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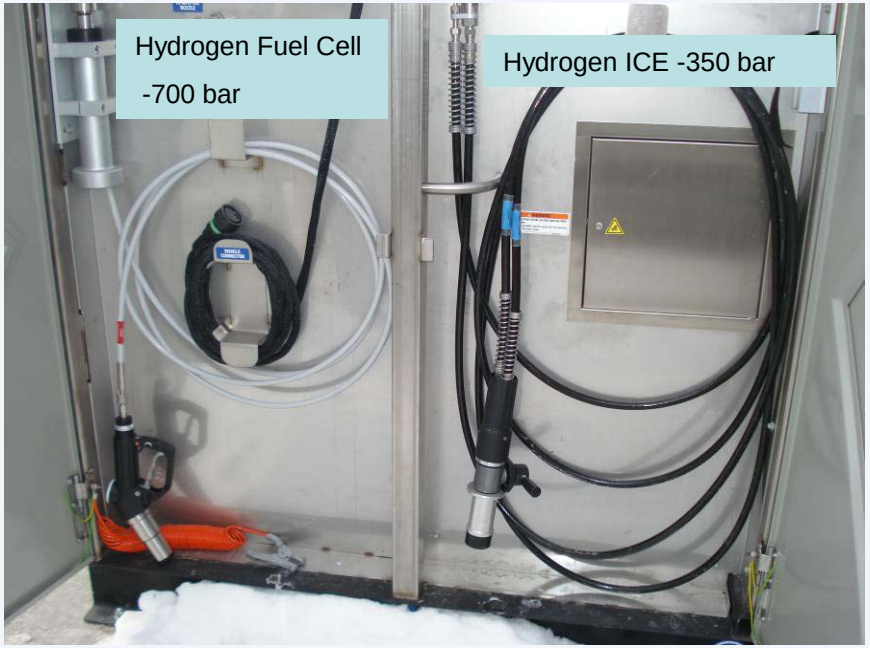
Refueling

- Select correct fueling nozzle –
  - Hydrogen ICEs – 350 Bar
  - Hydrogen Fuel Cell Vehicles -700 or 350 bar
  - 700 bar nozzle will not fit on 350 bar fill vehicles
  - 350 bar nozzle will fit on all vehicles



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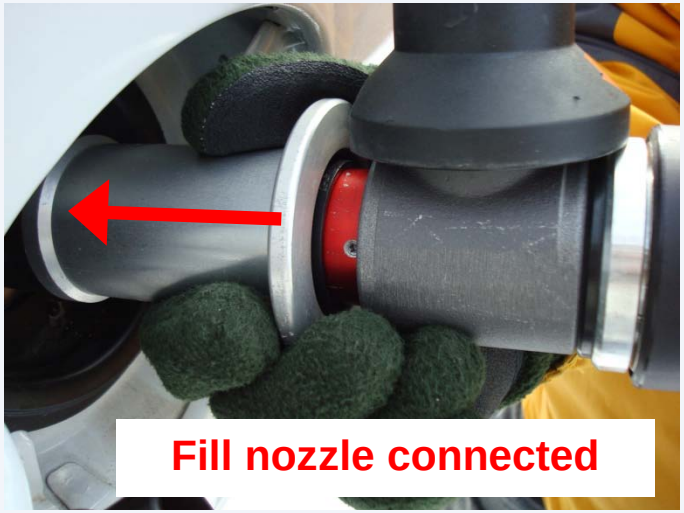
Refueling

Place nozzle in off position
Lock: Fully retract the *fuel fill nozzle's collar* to secure connection.
Place the *fuel fill nozzle* over the *fill receptacle.*



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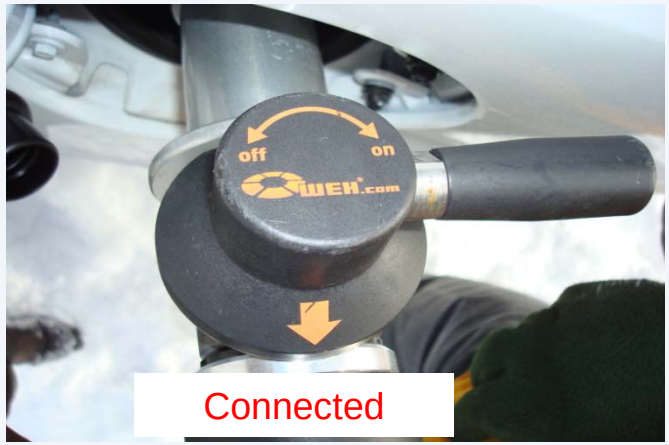
Refueling

Turn the *fuel fill nozzle handle* 180° clockwise locking the nozzle into the *fill receptacle and handle* to allow fuel to flow through the nozzle into the vehicle.

System will not fill if not connected.



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Refueling

Press the START button on the refueling system's *control panel*.

The system will stop when the vehicle is full or when the STOP button is pressed.

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Refueling

After Pressing Start Button the **Show Keypad Icon** will appear on the screen

Press **Show Keypad Icon** and the keypad will appear

Enter Vehicle Number and Press Enter

Fuel Filling will start automatically

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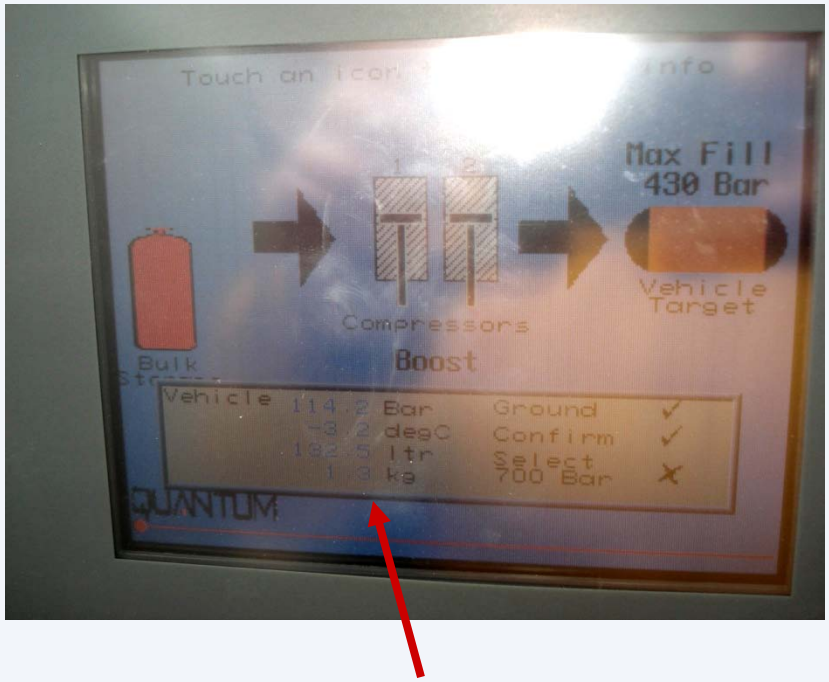
Refueling

To determine how much hydrogen is dispensed Touch the Quantum logo in the lower left corner of the touch screen on the refueling system.



Shows amount of Hydrogen dispensed

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Refueling

When Hydrogen Fill is completed you will hear the refueler venting and this screen will appear telling you to remove nozzle and electrical connection from vehicle

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Removing the Nozzle

First rotate the *fuel fill nozzle handle* 90 degrees counter clockwise to vent the pressure

Then turn the *fuel fill nozzle handle* an additional 90 degree counter clockwise to the off position to unlock the *fuel fill nozzle* from the *fill receptacle.*

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Refueling

When fueling complete return nozzle to unit Ensure that nozzle is facing toward the ground- this prevent water buildup in the nozzle

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Refueling

Remove electrical connection from vehicle and replace in refueler

Return the license plate to the original position.

Insure cap is placed back on fuel tank and lit is closed

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Comparison of Hydrogen Internal Combustion Engine Vehicles

With Hydrogen Fuel Cell Vehicles and Gasoline Hybrid Vehicles

Prepared By:
Brittany Borella and Kelsey McConnaghy

Abstract

This inquiry was conducted between November 2009 and February 2010 and was designed to analyze the fuel economy of three Ford Escape hydrogen internal combustion engine vehicles that have been operating at the Rochester Institute of Technology in Rochester, NY since July 2008. Collecting data on these vehicles and maintaining these vehicles has been the responsibility of the Center of Integrated Manufacturing Studies which is located on the Institute's campus. The Rochester Institute of Technology also implemented a semi permanent filling station to support these vehicles over there lifespan. Using data recorded at the hydrogen filling station as well as data recorded by Network Fleet's Fleet Management system installed in each of the vehicles, the fuel economy of each vehicle was monitored for thirteen months (February 2009 to February 2010). This data was then taken and compared to data provided by the National Renewable Energy Laboratory on their fleet of hydrogen fuel cell vehicles and the estimated fuel economy of Ford Escape gasoline hybrid vehicles at are currently on the road today.

At the conclusion of this comprehensive look into the fuel economy of the different types of vehicles it was demonstrated that the hydrogen fuel cell vehicles and the hydrogen internal combustions engine vehicles have a comparable fuel economy which is greater than that of the gasoline hybrid. They hydrogen vehicles had a combined fuel economy of approximately 40 miles per kilogram of hydrogen compared to the EPA estimated combined fuel mileage of 32 miles per gallon of gasoline. However, after a cost comparison of the fuel economy it was determined that gasoline is still much more economical than hydrogen because of the lack of availability of hydrogen fuel. It was determined that the cost of one kilogram of hydrogen would be equivalent to the cost of 1.2 times the cost of a gallon of gasoline. This provided an economic model for the cost comparison of hydrogen and gasoline. The improvements that are necessary to allow hydrogen to be competitive in the fuel market are improvements in the vehicle and fueling stations technology and a considerable amount of infrastructure. These topics are covered in an in depth discussion following the conclusion of the investigation.

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5.4Conclusion

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10. Appendix……*page 18*

1. Introduction:

The spike in fuel costs over the past few years has produced an increased interest in alternative fuel vehicles and their availability to the public. Many companies have developed electric hybrids or "flex-fuel" vehicles in order to market to customer needs in the current economy. The industry has also been developing hydrogen powered vehicles as an alternative fuel; however, there are concerns about using it as an automotive fuel. It is explosive and since it is a gas fuel verses a liquid fuel it makes it more difficult to transport and store. There also is a lack in infrastructure, proving difficult to implement hydrogen vehicles like fuel cells.

Most of the focus on hydrogen has been on fuel cell vehicles. Fuel cells are still in the early development stages in the automobile industry it makes it difficult to use this technology to solve the escalating fuel crisis right now. Another option to use hydrogen in vehicles is using a conversion package that converts an internal combustion engine to run on hydrogen. These vehicles are called HICEV (Hydrogen Internal Combustion Engine Vehicles). This conversion can be used in a gasoline power vehicle and allows it to run on hydrogen with only a few other modifications.

An important benefit of hydrogen is its impact on emissions. The combustion of hydrogen with oxygen produces only water ($2H_2 + O_2 = 2H_2O$). However, real world combustion with air also creates Nitrous Oxides ($H_2 + O_2 + N_2 = H_2O + N_2 + NO_x$). Nevertheless, by adjusting the fuel to air ratio, compression ratio, and ignition timing, as well as ensuring that the engine is not burning oil can reduce the harmful emissions to almost zero (just a few ppm).

2. Background:

In 2009 the Center for Integrated Manufacturing Studies (CIMS) at the Rochester Institute of Technology (RIT) purchased three hydrogen powered Ford Escape Hybrid ICE vehicles and installed a semi-permanent hydrogen fueling station under the NYSERDA contract #10150. Two vehicles are currently being used by RIT Public Safety for everyday patrols while the third is being used by CIMS for research and public outreach. Data collected is used to research the readiness of the technology on the vehicles and their practicality in the real world. The station also requires frequent deliveries of 99.999% pure hydrogen fuel to keep our vehicles as well as local fuel cell vehicles operating.

Figure 1: Hydrogen Storage Tanks (left) and Re-Fueler (right)

Figure 2: Hydrogen ICE Vehicle

Figure 3: Hydrogen Fuel Cell Vehicle

3. Objective:

Over the past thirteen months the Hydrogen program at CIMS has been collecting and analyzing data on the overall performance of all three hydrogen vehicles. Since the program only had a two year duration a closer look at the vehicles performance was taken to evaluate the true capabilities of the Ford Escape Hybrid ICE vehicles. The objective of this project is to obtain an understanding of the fuel economy of the hydrogen powered Ford Escape Hybrid ICE and a cost correlation between hydrogen hybrid vehicles, gasoline hybrid vehicles, and fuel cell vehicles.

4. Investigation 1:

4.1 Objective:

The first investigation into RIT's Hybrid ICE fuel economy was to determine the average fuel usage, mileage and operation conditions for RIT's three vehicles between February 2009 and February 2010. This information was calculated using the monthly averages that are collected from the hydrogen fueling station located on campus and the Network Fleet Data Acquisition System that tracks all three vehicles. This data was then compared to data provided by the National Renewable Energy Laboratory on Hydrogen Fuel Cell vehicles. After processing the data provided on their web page, it was concluded that they tested 140 fuel cell vehicles over a period of 4.25 years. The total operating time exceeded 100,000 hours and the vehicles traveled a total of 2.3 million miles. (Hydrogen and Fuel Cells Research Composite Data Products by Topic).

4.2 Analysis:

After analyzing the data collected at RIT, CIMS determined that the three hydrogen vehicles traveled roughly 36,000 miles. RIT 1 and RIT 2 traveled almost 17,000 miles a piece and RIT 3 traveled about 3,500 miles. The average fuel economy for all uses (city and highway driving) and all three vehicles was calculated to be 21.7 miles per kilogram and is shown in Figure 4. The data provided on NREL's website for the average fuel economy of their vehicles is also shown in Figure 5.

Figure 4: Rochester Institute of Technology; Average Fuel Economy

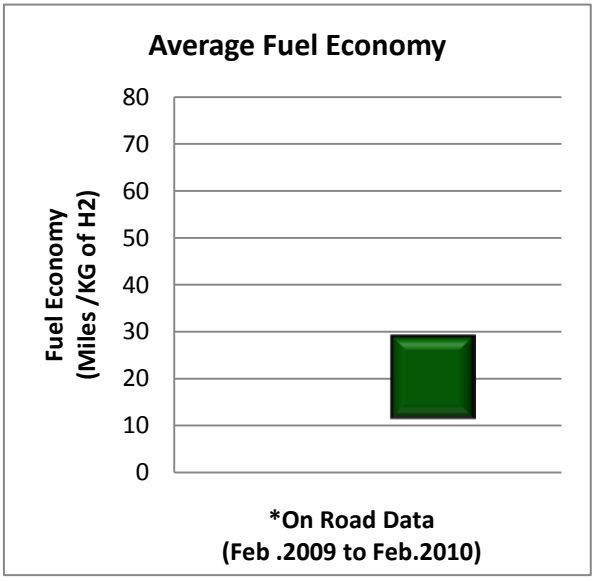
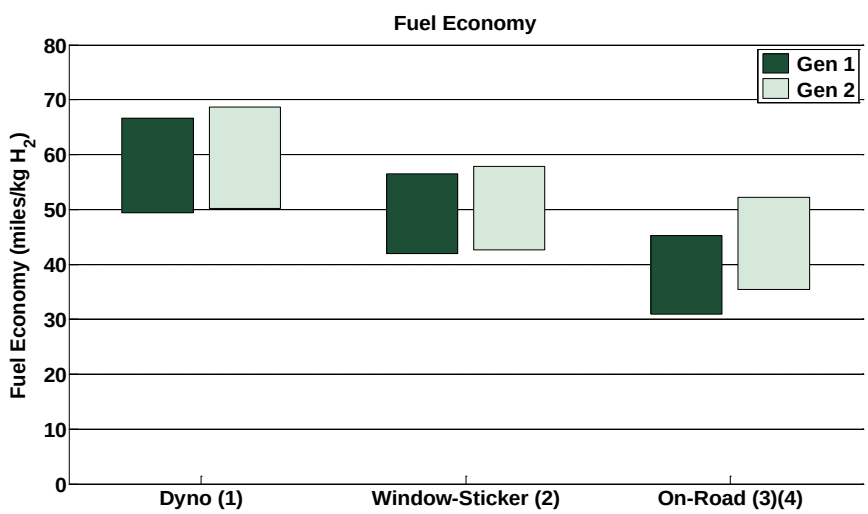


Figure 5: National Renewable Energy Laboratory; Average Fuel Economy



(1) One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAE J2572.
(2) Adjusted combined City/Hwy fuel economy (0.78 x Hwy, 0.9 x City).
(3) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(4) Calculated from on-road fuel cell stack current or mass flow readings.

Since the average fuel economy is substantially lower than the "On-Road" data provided by NREL, a closer look at the data was necessary. After evaluating all recorded information for RIT's vehicles over the nine month period a correlation for the percentage of time the vehicle spends idling and the average fuel economy was seen.

Figure 6: Percentage of Idle Time for HICEV's RIT1, RIT2, and RIT3

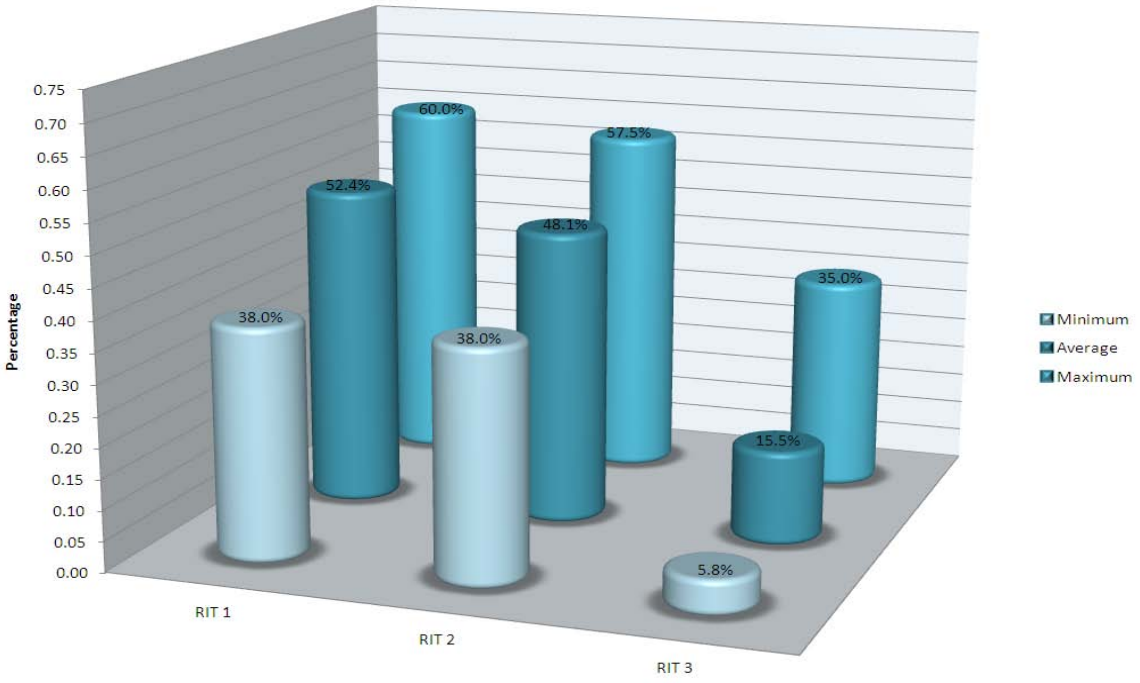
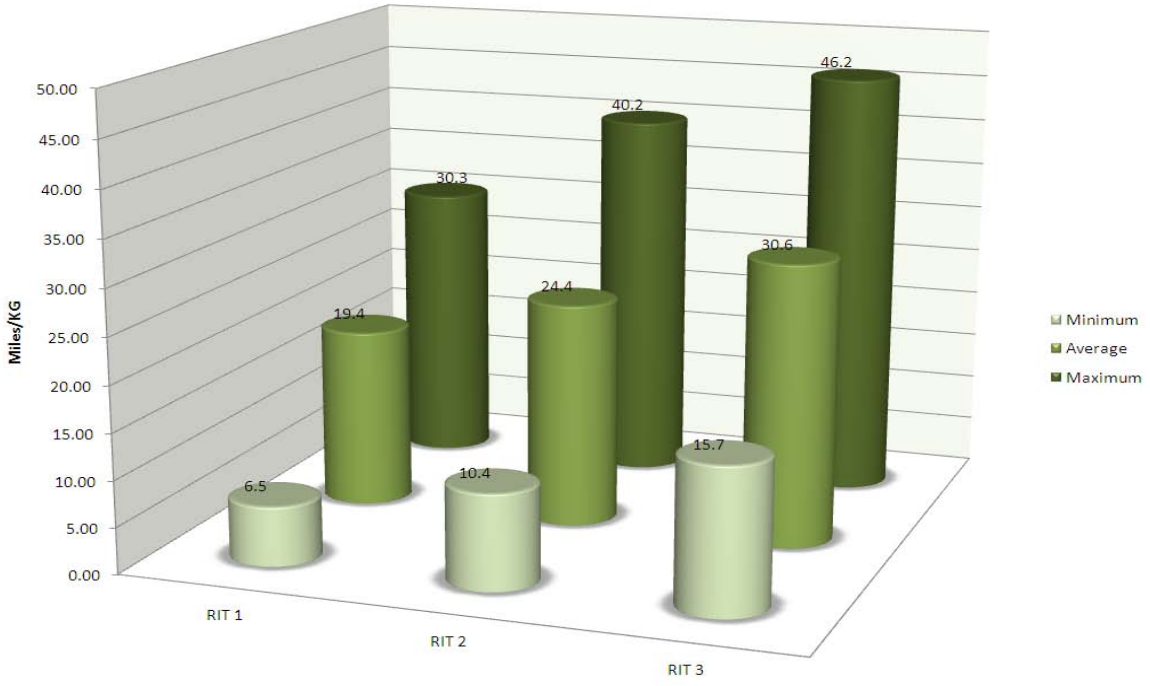


Figure 7: Miles per Kilogram of Hydrogen for HICEV's RIT1, RIT2, and RIT3



4.3 Conclusion:

After evaluating the data shown above it was determined that the data for the fuel economy shown by the National Renewable Energy Laboratory was calculated excluding any trips with a distance less than a mile long. Since the RIT Campus is only a three mile loop the majority of trips made by Public Safety vehicles are less or approximately one mile in length. It was also noted that RIT's Hybrid ICEs, which are used for Public Safety Patrol vehicles (RIT1 and RIT2) have a much lower fuel economy than the CIMS RIT Hybrid ICE. This is shown to be an effect of the amount of time the vehicle spends idling. Shown above, RIT1 spent the greatest percentage of its time idling and has the lowest fuel economy.

For another comparison, Public Safety was asked to log the vehicle mileage for their gasoline hybrid vehicle on campus for one week. The fuel economy for that vehicle was 13.6 mpg, which is 42% less than its 32.2 mpg EPA sticker rating. This proves that the driving habits of Public Safety causes the fuel economy calculated in this investigation for both the hydrogen and gasoline hybrids to be much lower than their actual fuel economies.

Since the data was determined to not correlate with the data provided by the National Renewable Energy Laboratory, a second investigation was designed to test the overall fuel economy of the H ICEVs. In order to form a better evaluation of their performance, additional data must be collected for longer trips at higher speeds. This information will be very useful when evaluating the feasibility of the hydrogen powered Ford Escape Hybrids at the end of this project.

5. Investigation 2:

5.1 Objective:

For the second investigation a high-mileage fuel consumption test was developed. This test was designed to calculate the average highway and city mileage for the Hydrogen ICE vehicles. Using the "real-world" mileage would allow for a better comparison to the National Renewable Energy Laboratory's data as well as the current mileage of Ford Escapes which are gasoline hybrid models.

5.2 Analysis:

The two tests that were conducted were a Highway "High Mileage" test and a "City Mileage" test. Three speeds were chosen to be used in the Highway Test to calculate the mileage, 55mph, 60mph and 65 mph. Each test was run twice. The City Test was based on the posted speed limit and 2 routes were driven. The first route consisted of 12 possible traffic lights to best represent constant accelerating and decelerating of city driving. The second route included 8 traffic lights and multiple hills.

The Network Fleet Data Acquisition System 3500 was used to map and document the routes taken. It has capabilities to monitor and remotely provide engine diagnostics from the engines computer and from additional sensors programmed to detect certain " voltage events". It also records the vehicles speed and position every two minutes while the vehicle

is operating using GPS. Figures 8 through 10 are examples of this data recording system and show the complete routes for all tests.

Figure 8: Highway Test, 54 miles round-trip

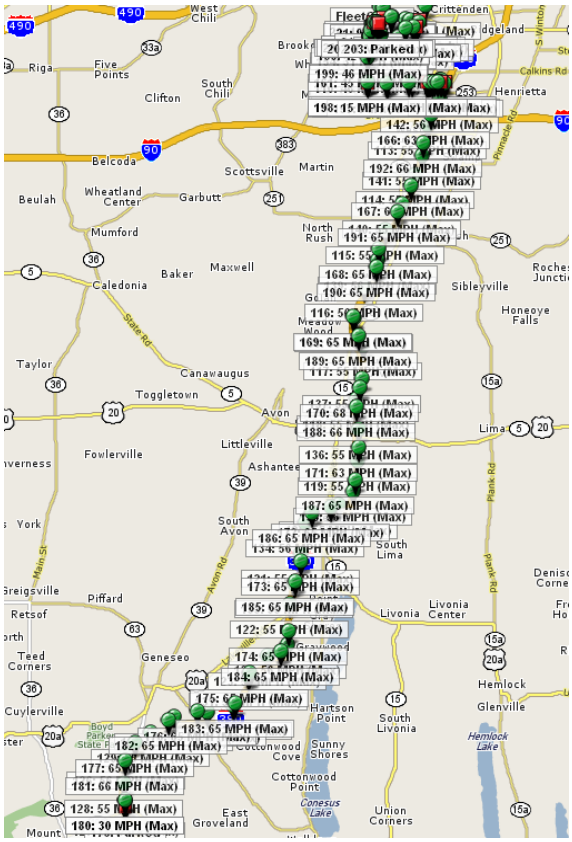
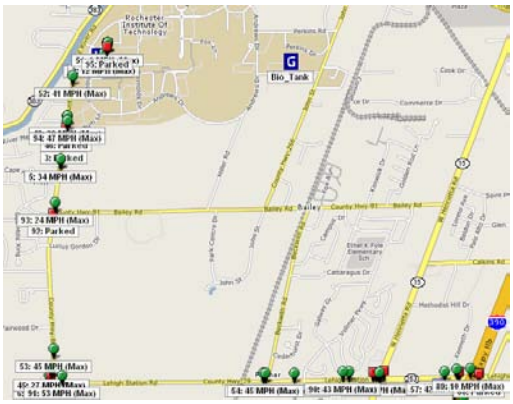


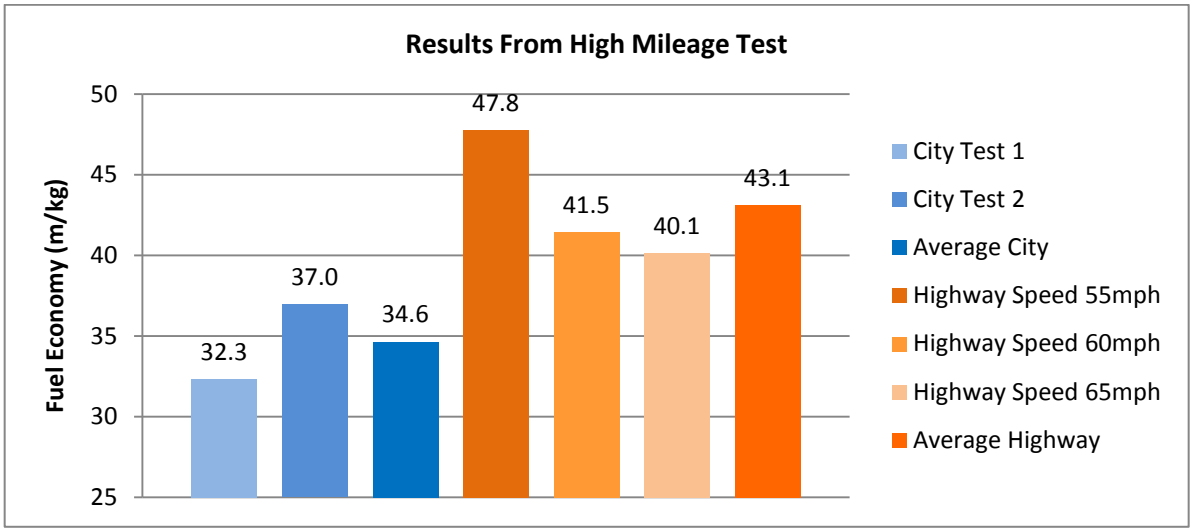
Figure 9: City Test 1, 7.5 miles round-trip

Figure 10: City Test 2, 8.6 miles round-trip



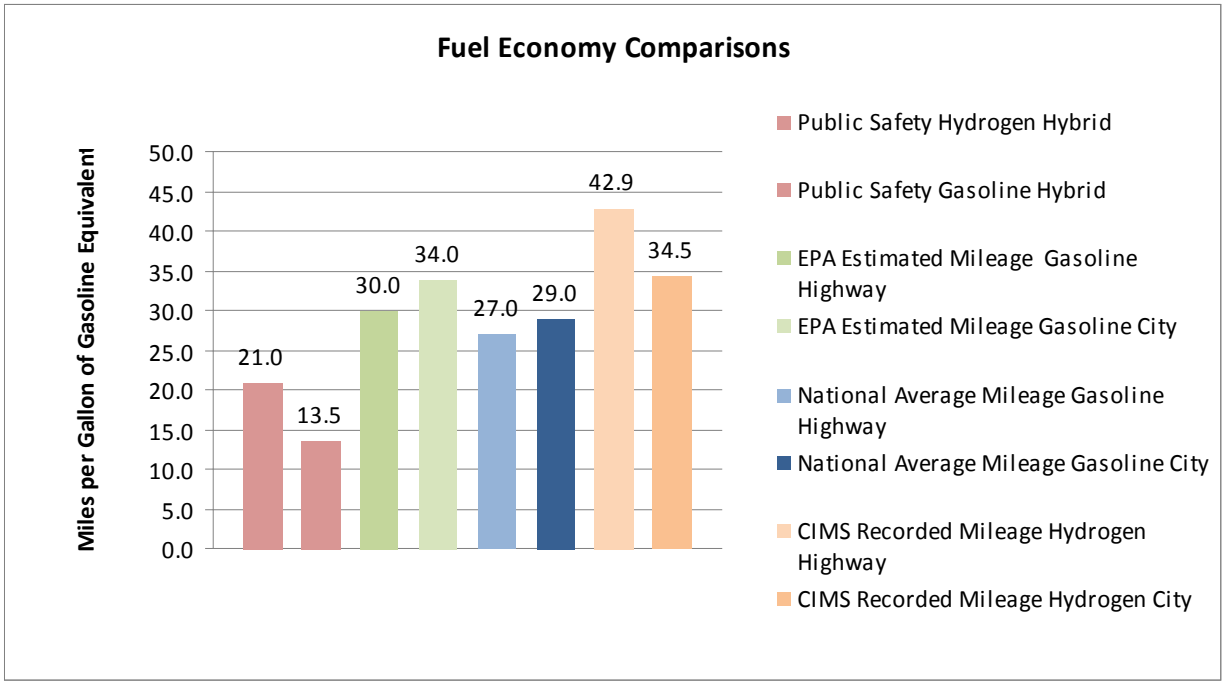
For the three different speeds, and two different city routes, the averages of these tests were used to calculate the average city and highway mileage. The results are shown in Figure 11.

Figure 11: City and Highway Mileage Results



The average city and highway mileages were then compared to the fuel economy that Public Safety was seeing on patrols as well as data given by the EPA and national averages found on Edmunds and Kelly Blue Book websites for Gasoline Hydrid Ford Escapes. This Data is shown in Figure 12. (www.fueleconomy.gov), (www.edmunds.com) and (www.kbb.com).

Figure 12: Comparison of Gasoline Hybrids and HICE Hybrids



Both the City and Highway fuel economies for the Hydrogen Ford Escape Hybrid were better than any fuel economy given for the Gasoline Ford Escape Hybrid. The combined city-highway mileage was calculated then compared again to NREL's data for hydrogen "On-Road" tests. The data collected is shown on Figure 13 to be almost equivalent to the 1st generation of fuel cell vehicles used.

Figure 13: Rochester Institute of Technology; Average Fuel Economy

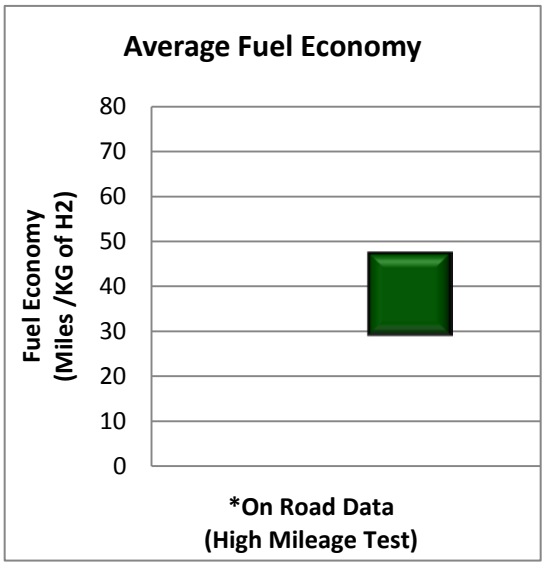
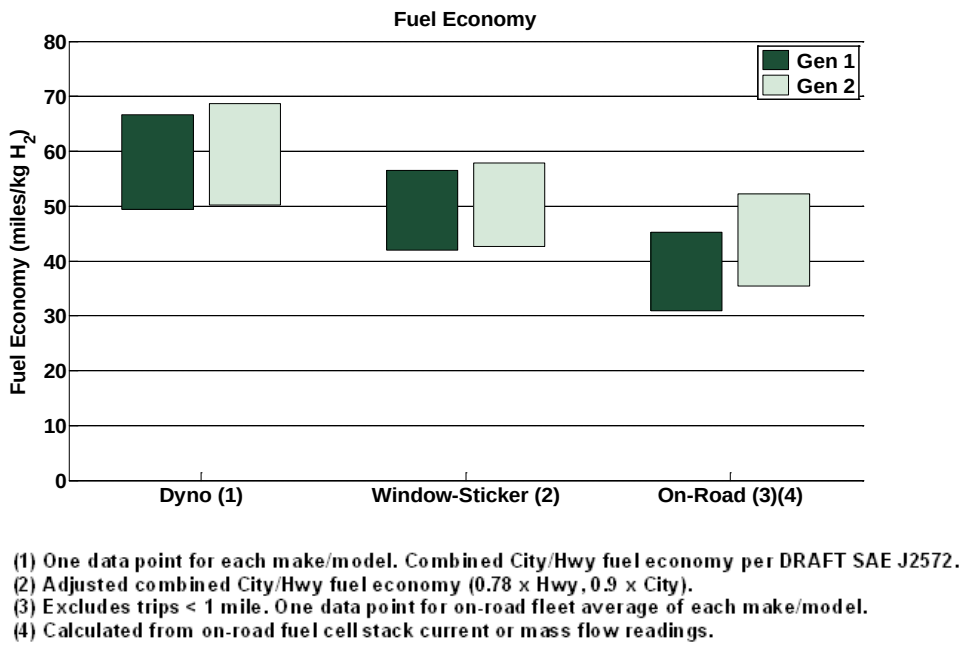


Figure 14: National Renewable Energy Laboratory; Average Fuel Economy



5.3 Calculations:

The next step in the analysis was to try to identify a cost comparison between hydrogen fuel and gasoline. Below are the equations and computations used to obtain the data:

Cost of Hydrogen per Kilogram (Values provided by AirGas)

$$\left(\frac{423.2\ ft^3}{1\ kg}\right)\left(\frac{\$3.65}{100 ft^3}\right) = \frac{\$15.45}{1\ kg}$$

A **Cost Per Mile Equation** was developed to compare how much it costs to drive a gasoline hybrid Escape in Rochester with today's gas prices of $2.85, with a Hydrogen hybrid Escape using RIT's price per kilogram of $15.45.

$$\frac{\left(\frac{Cost}{Qty}\right)\left(\frac{Qty}{gge}\right)}{\left(\frac{Miles}{Qty}\right)\left(\frac{Qty}{gge}\right)} = \left(\frac{Cost}{Mile}\right)$$

(Equation 1)

EPA Gasoline Hybrid Fuel Economy:	$\frac{\left(\frac{\$2.85}{Gallon}\right)\left(\frac{Gallon}{1\ gge}\right)}{\left(\frac{32.2\ Miles}{Gallon}\right)\left(\frac{Gallon}{1\ gge}\right)} = \left(\frac{\$0.09}{Mile}\right)$
CIMS Hydrogen Hybrid Fuel Economy:	$\frac{\left(\frac{\$15.45}{kg}\right)\left(\frac{1.004kg}{1\ gge}\right)}{\left(\frac{38.4\ Miles}{kg}\right)\left(\frac{1.004kg}{1\ gge}\right)} = \left(\frac{\$0.40}{Mile}\right)$

5.4 Conclusion:

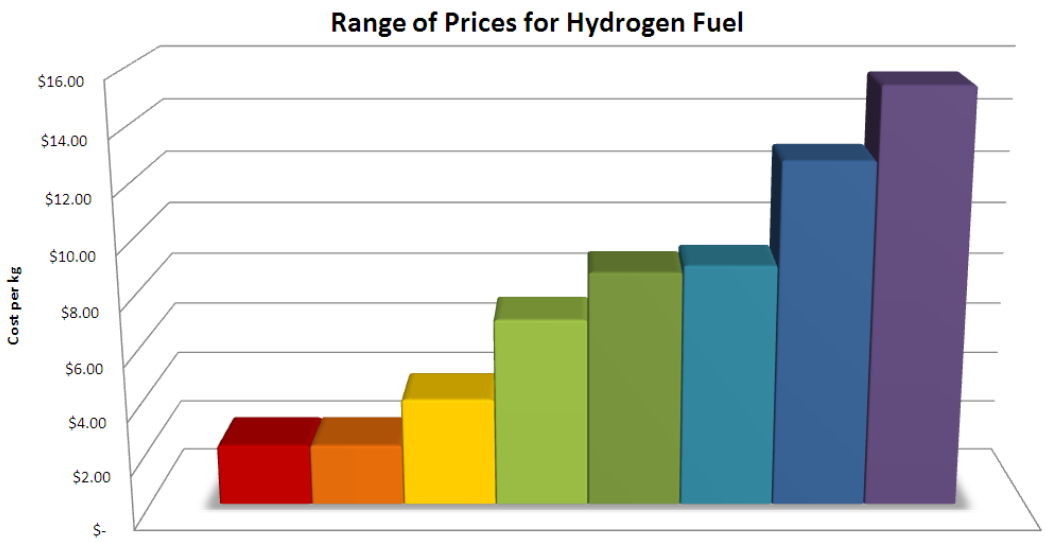
The high-mileage test demonstrates that the hydrogen-electric hybrid has an equal if not better fuel economy than the gasoline-electric hybrid and hydrogen fuel cell vehicles. Since the fuel cell vehicles from NREL had a similar fuel economy to our Hydrogen ICE vehicles, their cost per mile would be similar. Therefore, the cost of operating *any* hydrogen powered vehicle today would be the same however, this cost compared to the cost of gasoline power vehicles is still extremely high. Comparing a cost per mile between the Ford Escape HICE and the Ford Escape Gasoline Hybrid Vehicle the cost per mile is 345% more. This means a consumers fuel cost would increase almost 350% based on the price of fuel above if they were using a HICEV.

Having a zero emission vehicle like the HICEV's is still a significant technical accomplishment, however when the cost to operate the vehicle causes a consumer to spend three and a half times the amount they would spend on a reduced emission vehicle for fuel, it becomes extremely difficult to sell. The vehicles themselves also cost much more because of the conversion kits required to run the engine on hydrogen. Therefore, even thought the vehicles provide an excellent alternative and do have excellent gas mileage, they are extremely hard to convince consumers to spend the extra money to own and operate.

6. Hydrogen Fuel Today:

Figure 15 displays the available costs of hydrogen across the country. The average cost is $7.69 per kilogram. However, this spread of cost reflects the way in which the hydrogen is processed before being used as a fuel. At the Army base in Michigan, and at RIT CIMS, the hydrogen is delivered from a supplier by truck. Therefore, the cost per kilogram from the supplier is high because of the cost to transport the fuel using their vehicle. At the Army base in Hawaii and in Long Island, NY the hydrogen is produced on site using electrolysis. This method of producing the hydrogen on site greatly reduces the cost of hydrogen, which in turn makes the cost per mile decrease as well. If you take the $4.00 per kilogram cost from the Army base in Hawaii and apply it to the **Cost per Mile Equation,** the cost to drive a mile using hydrogen fuel is only 11¢ compared to the cost of 9¢ when using gasoline. This is only a 22% increase in fuel cost, which would be much more reasonable for a consumer to consider. (These costs do not include capital equipment costs).

Figure 15: Cost for Hydrogen Fuel



	Cost per Kilogram
Thousand Palms, CA	$2.25
Phoenix, AZ	$2.25
Hawaii Army	$4.00
Long Island, NY	$7.00
Diamond Bar, CA	$8.75
Riverside, CA	$9.00
Michigan Army	$12.79
Henrietta, NY RIT CIMS	$15.45

The values for Thousand Palms, CA and Phoenix, AZ were taken from the National Hydrogen Associations website and they did not include any additional information, so accuracy of these values is unknown. Other values were provided by contacts in the industry that operate/oversee the stations. These contacts are referenced in the Works Cited section located after the Appendix.

7. Economic Model of Hydrogen Fuel

A **Cost Correlation Equation** was developed in order to compare the price of gasoline with a price of hydrogen that would make it a competitive fuel in the market. It was then used to create a graph depicting today's current prices of hydrogen compared to gasoline and when they will be low enough to make hydrogen an economically viable fuel source.

$$\frac{Price_{Gasoline}}{Fuel\ Economy_{Gasoline}} = \frac{Price_{Hydrogen}}{Fuel\ Economy_{Hydrogen}}$$

$$\frac{Fuel\ Economy_{Hydrogen}}{Fuel\ Economy_{Gasoline}}(Price_{Gasoline}) = Price_{Hydrogen}$$

$$\frac{\left(38.4\frac{miles}{kg}\right)\left(\frac{1.004kg}{1\ gge}\right)}{\left(32.2\frac{miles}{gallon}\right)}(Price_{Gasoline}) = Price_{Hydrogen}$$

$$\left(1.198\frac{gallon}{gge}\right)(Price_{Gasoline}) = Price_{Hydrogen} \qquad \textit{(Equation 2)}$$

Figure 16: Economic Feasibility of Hydrogen

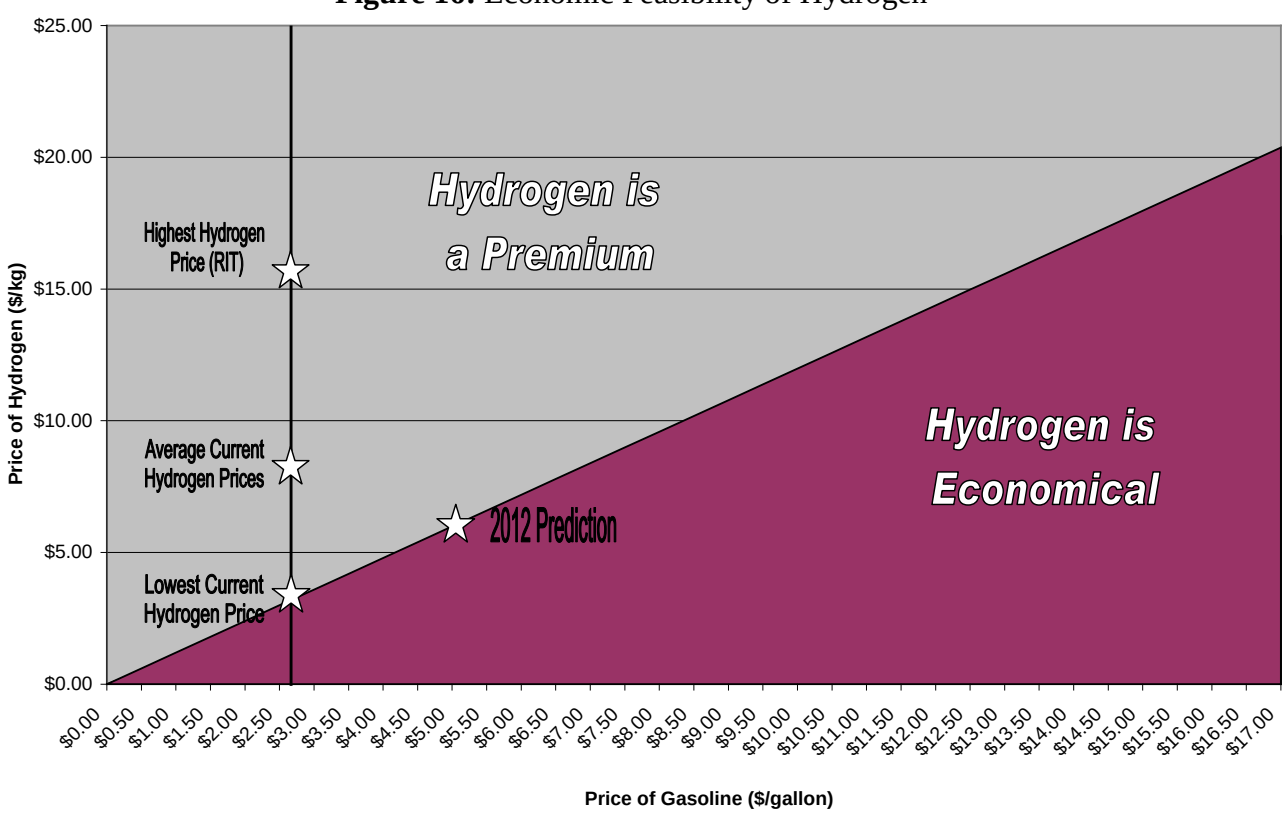


Figure 16 illustrates the national average price of gasoline (approximately $2.60, represented by the black line) and at what price hydrogen would become economically feasible (represented by the

purple shaded region). The stars on the graph represent current prices of hydrogen from Figure 15. Predictions show that in 2012 a gallon of gasoline will cost approximately $5.00, and therefore hydrogen would need to cost $5.99 per kilogram in order to be competitive with gasoline. The current average cost of hydrogen, shown on the graph, is $7.69, which means the cost per kilogram would need to be reduced by $1.70 by 2012. With today's technologies, this could be possible; however, many adjustments need to be made with the infrastructure for hydrogen in a very short amount of time.

8. Conclusion:

Overall, this project provided excellent data to correlate hydrogen hybrid vehicles to gasoline hybrid vehicles and adequate data to compare to the hydrogen fuel cell vehicles. The goal of this experiment was to provide concrete numbers to compare a HICEV with a hydrogen fuel cell vehicle, as well as gasoline hybrid. Because the gasoline hybrids have been in the market since 2008 there was plenty of data on the fuel economy and driving capabilities of these vehicles however, because so much of the data related to fuel cells is proprietary, the data related to the fuel cell vehicles was more limited.

The first investigation determined that the HICE vehicles that were being used by RIT Public Safety were getting only 50% of the On-Road mileage provided by NREL. However, the Public Safety vehicles were spending 45% of the time idling which directly correlated with the fuel mileage. The second investigation provided data that was more comparable with the NREL data. After running the Highway and City tests in the second investigation, the average fuel economy was shown to be approximately the same as the NREL's 1st Generation On-Road fuel economy. Unfortunately, NREL was not able to provide us with any additional information regarding the types of vehicles used or the exact fuel economy for the graphs shown in this paper so no statistics can be produced to compare exact data.

The second investigation also provided an excellent comparison of the *Ford Escape Hybrid ICE* and the *Ford Escape Gas-Electric Hybrid.* Using the fuel cost per mile for the two different Escapes, a cost correlation for the two different fuels was drawn. This relationship was then used to find the economic value of hydrogen compared to gasoline. After analyzing this graph it is reasonable to believe that hydrogen could become a feasible fuel for the next generation of automobiles. If the cost of gasoline increases to $5.00 a gallon then the cost of hydrogen would have to be $6.00 per kilogram to have the same cost per mile. With some additional improvement of infrastructure and production, $6.00 per kilogram is an achievable target. Specific improvements to infrastructure and production as well as the vehicles themselves are detailed below.

9. Necessary Improvements:

9.1 Vehicle Technology:

Hydrogen Internal Combustion Engines are an excellent way to start the hydrogen revolution. They run, drive, and sound similar to convention gasoline engines of today and therefore could be implemented in everyday vehicles without noticeable change for consumers in the way in which they drive, fuel and act. They would provide an excellent transition into fuel cell vehicles, which would also require a hydrogen infrastructure, and will probably be the alternative technology of choice in the long run. However, hydrogen ICE vehicle technology would need to improve drastically, not only to provide reliable transportation, but also to create vehicles in a price range affordable to the average customer. It does not matter how much hydrogen costs or the fact that it is available nationwide if the cost of a hydrogen ICE vehicle is closer to $100,000 rather than $30,000.

Several issues that also have risen from the use of the vehicles at RIT as well as a Fleet run at an army base in Michigan include a high level of water in the oil, the 12 volt battery has trouble keeping a charge, and the fuel injectors have needed to be replaced on several occasions. The combustion of hydrogen produces water as exhaust, and this water can dilute the lubricating oil of the engine. The failure of the fuel injectors results from the reduced lubrication of a gaseous fuel versus a liquid fuel. Gasoline provides lubrication for the moving parts inside of the injectors, but with a hydrogen gas, there is little lubrication and therefore increased wear.

Additionally, since the fuel is stored onboard the vehicle as a gas instead of a liquid, it takes up significantly more room and reduces the amount that can be stored. The vehicles at RIT CIMs can only travel 100-120 miles per full tank of hydrogen. This is less than 1/3 of the distance most gasoline vehicles can travel per fueling. For any type of normal use, the distance traveled on one tank of hydrogen needs to be drastically increased.

9.2 Fuel Technology:

The current trend of hydrogen fuel prices indicates that it is more economical to produce hydrogen on-site via electrolysis than to have it delivered from an outside source. Stations that produce their own hydrogen have a higher start up cost for the electrolysis machine and compressor, and have to pay for the electricity, but the cost of their hydrogen is between ⅓ and ¼ of the price of hydrogen purchased from industrial gas companies, such as Airgas. The price of electricity can also be offset by the installation of solar panels, wind turbines, or other alternative energy sources.

Hydrogen trucked in not only costs more, but utilizes diesel trucks as transportation, which ultimately defeats the purpose of hydrogen in general, because it reduces the positive environmental impact it creates. Additionally, if producing the electricity used to make hydrogen generates a larger carbon footprint than using the hydrogen offsets, it doesn’t make sense to switch to hydrogen. Therefore, electrolysis on site using alternative energy as the source of electricity seems like the most beneficial direction to move towards.

A study should also be done on the quality of Hydrogen necessary to run hydrogen internal combustion engines. The station located on the RIT campus utilizes five 9's pure hydrogen (99.999% pure) because both hydrogen ICEs and hydrogen fuel cell cars fuel up at the station and fuel cell cars need five 9's pure. However, that high of quality may not be necessary for hydrogen ICEs. By using less pure hydrogen, it could reduce its cost.

Hydrogen is also commonly mixed with compressed natural gas and run in internal combustion engines. While this does not provide the emissions benefits that running pure hydrogen does, it is a good intermediate step while building a hydrogen infrastructure, because a compressed natural gas infrastructure is already partially in place.

9.3 Infrastructure:

Currently the infrastructure for hydrogen distribution is not in place. There needs to be a large installation of hydrogen filling stations to be able to support vehicles across the country. In the paper titled "*Analysis of the Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen-Fueled Vehicles" (Conference Paper* NREL/CP-540-37903) from the National Renewable Energy Laboratory a prediction was made in 2005 for the cost to create enough stations across the country to supply the nation. In section 5.2 it states; "the overall infrastructure cost is approximately $837 million, based on 2020 demand for hydrogen." This means that in the next ten years the United States would have to spend $837 million to implement enough hydrogen filling stations to support hydrogen vehicles. It may seem like a lot however, in 2008 the United States consumed 7.14 billion barrels of oil ("U.S. Energy Information Administration; Independent Statics and Analysis") at an average cost of approximately $91.40 a barrel ("InfaltionData.com"). This means in 2008 the United States spent approximately $652.6 billion dollars on oil alone. If the U.S. reduced their dependence on oil and therefore saved money on the reduction of use, the $837 million to create hydrogen infrastructure could easily be obtained from this savings.

Mechanics of the fueling stations would also need to be improved. For example, it currently takes the fueling station at RIT CIMS approximately 30-45 minutes to fill the car from empty to full. The average user would get very impatient at this wait time. By installing compressor in the filling stations they hydrogen can be compressed to the correct pressure for the vehicle from the fuel tanks before being fueled into the vehicle. This cuts the wait time down from 30 minutes to about 3minutes, which is typical of today's gasoline pumps. This compressor makes the customer wait less but also increase the cost of the facility. Included below is a calculation of the cost per station based on the production method of hydrogen. Electrolysis on site, or hydrogen transported via pipeline is the most economical at this point.

Figure 17: Standard Station Configurations and their Construction Costs

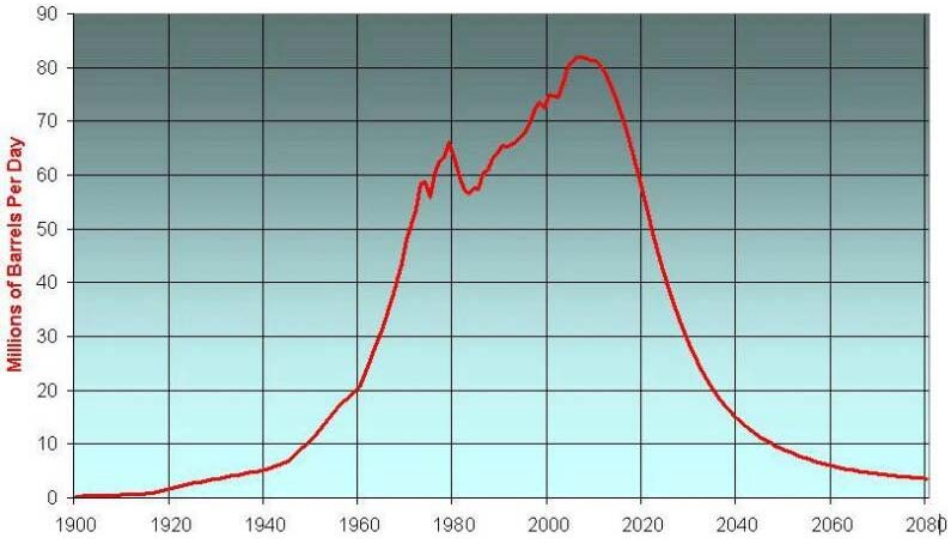
Station Type	Cost per Station	Abbreviation
Steam Methane Reformer, 100 kg/day	$1,052,921	SMR100
Steam Methane Reformer, 1,000 kg/day	$5,078,145	SMR1000
Electrolyzer, grid, 30 kg/day	$555,863	EL30G
Electrolyzer, grid, 100 kg/day	$945,703	EL100G
Electrolyzer, renewable, 30 kg/day	$667,402	ER30R
Mobile Refueler, 10 kg/day	$248,897	MR10
Delivered Liquid Hydrogen, 1,000 kg/day	$2,617,395	DLH21000
Pipeline Station, 100 kg/day	$578,678	PIPE

(Melendez and Milbrandt 12)

9.4 Predictions for Gasoline:

Many of the economists currently investigating the cost of oil predict that it is only a matter of time until its cost is unaffordable. Some say that $5.00 a gallon will be likely in 2015 and some say as early as 2012, with prices increasing steadily from there. Figure 18 is a graphical representation that shows the total world production of oil from the past 110 years and the predicted production of oil for the next 70 years. This curve shows that within the next 10 years the production of oil world-wide will be at least 20 million of barrels per day less than it is now. This will cause a massive increase in the cost of oil around the world and will greatly affect the United States because of the decency on oil.

Figure 18: World Oil Production



The author, Matt Savinar, also states that; “worldwide oil production in the year 2030 will be the same as it was in 1980. However, the world’s population in 2030 will be both much larger (approximately twice) and much more industrialized (oil-dependent) than it was in

1980. Consequently, worldwide demand for oil will outpace worldwide production of oil by a significant margin. As a result, the price will skyrocket…" (Savinar).

The predictions show that even if we do not "run out" of oil, eventually it will no longer be economically feasible to use it as our main source of fuel. Don Huberts of Shell Hydrogen states "The Stone Age did not end because we ran out of stones, and the Oil Age will not end because we run out of oil." Advancements in "green-vehicle" technology, including the field of hydrogen, natural gas, or electric powered vehicles, will soon cause gasoline to be an outdated technology, with more practical sources of fuel, such as hydrogen, to be the norm.

10. Appendix

Table 1: HICE Vehicle Uptime

Month	RIT 1 Uptime	RIT 2 Uptime	RIT 3 Uptime
Feb-09	100%	27%	100%
Mar-09	100%	66%	100%
Apr-09	43%	100%	100%
May-09	36%	81%	100%
Jun-09	100%	100%	100%
Jul-09	100%	100%	100%
Aug-09	85%	100%	100%
Sep-09	100%	90%	100%
Oct-09	100%	100%	100%
Nov-09	100%	40%	100%
Dec-09	100%	100%	100%
Jan-10	94%	98%	100%
Feb-10	89%	54%	100%

*Collision damage, not mechanical problems

*Taken from Hydrogen Driving Data, NOT Monthly Report	*Data concluded to be erroneous, not included in calculations

Table 2: Hydrogen Data for Each Vehicle

Month	Vehicle	Number of Fills	Total Amount of H2 Filled (KG)	Average Amount of Hydrogen per Fill (KG)	Average Fill Time (Min)	Miles per KG of Hydrogen	Miles Per Month	Idle Time	Miles per Month
February-09	RIT 1	26	55.1	2.10	22.8	18.7	1030	60.0%	1111
March-09	RIT 1	55	96.1	1.74	25.0	21	1818	57.0%	1852
April-09	RIT 1	16	27.1	1.70	23.0	20.7	504	49.0%	604
May-09	RIT 1	15	27	1.80	20.0	8.9	215	55.0%	506
June-09	RIT 1	40	67.3	1.68	21.7	18.9	1273	48.0%	1466
July-09	RIT 1	40	121.3	3.03	16.0	11.5	575	53.0%	1277
August-09	RIT 1	4	6.3	1.60	24.0	NA	1167	32.0%	1210
September-09	RIT 1	42	70.6	1.70	18.6	29.9	2212	38.0%	1819
October-09	RIT 1	42	57.7	1.20	18.3	30.3	1750	48.0%	1771
November-09	RIT 1	49	74.6	1.52	25.1	16.5	1438	49.0%	1581
December-09	RIT 1	64	105.2	1.60	20.9	17.7	1866	56.0%	2047
January-10	RIT 1	61	126.4	2.10	14.0	6.3	800	57.3%	817
February-10	RIT 1	76	85.3	1.10	9.3	19.1	1245	57.9%	1431
February-09	RIT 2	5	8.4	1.70	22.2	23.7	199	48.0%	160
March-09	RIT 2	25	44.6	1.78	25.0	22.9	1573	46.0%	920
April-09	RIT 2	51	84.4	1.70	21.5	26	2014	43.0%	2148
May-09	RIT 2	33	56	1.70	20.0	23	1293	46.0%	1388
June-09	RIT 2	45	76.7	1.71	22.5	28.8	2212	54.0%	1565
July-09	RIT 2	36	111.8	3.11	14.0	10.6	1235	45.0%	1264
August-09	RIT 2	6	12	2.00	19.0	NA	1263	37.0%	1310
September-09	RIT 2	39	59.9	1.50	19.3	30	1792	38.0%	1587
October-09	RIT 2	31	34.1	1.10	16.9	40.2	1372	44.0%	1439
November-09	RIT 2	15	23.8	1.58	23.8	19.2	459	49.0%	1581
December-09	RIT 2	50	82.6	1.70	22.0	22.3	1839	55.0%	857
January-10	RIT 2	71	136.6	1.90	17.5	14.6	1997	51.5%	1938
February-10	RIT2	32	60.1	1.90	13.8	20.7	708	57.5%	660
February-09	RIT 3	1	2.1		37.0	35.7	70	20.0%	33
March-09	RIT 3	3	4.1	1.37	15.0	36.8	87	16.0%	100
April-09	RIT 3	3	4.1	1.37	15.0	36.8	154	13.0%	155
May-09	RIT 3	8	13	1.57	17.0	32	417	19.0%	430
June-09	RIT 3	9	14.7	1.64	21.0	12.9	190	7.0%	488
July-09	RIT 3	12	14.2	1.20	9.0	30	442	35.0%	464
August-09	RIT 3	3	3.6	1.20	19.0	NA	412	9.0%	472
September-09	RIT 3	8	8.6	1.10	25.3	46.2	398	11.2%	404
October-09	RIT 3	1	1.2	0.50	8.0	NA	46	15.0%	68
November-09	RIT 3	3	7.6	1.51	16.6	19.3	156	19.0%	167
December-09	RIT 3	1	0.9	0.90	15.0	NA	48	19.0%	77
January-10	RIT 3	18	16.6	0.90	10.0	29.8	496	5.8%	559
February-10	RIT3	4	7	1.75	17.0	17.7	123	8.9%	186

Table 3: Calculated verse Recorded Miles per KG

Month	Vehicle	Miles per KG of Hydrogen	Miles per KG of Hydrogen Calculated		
February-09	RIT 1	18.7	20.16		
March-09	RIT 1	21	19.27		
April-09	RIT 1	20.7	22.29		
May-09	RIT 1	8.9	18.74		
June-09	RIT 1	18.9	21.78		
July-09	RIT 1	11.5	10.53		
August-09	RIT 1	NA	192.06		
September-09	RIT 1	29.9	25.76		
October-09	RIT 1	30.3	30.69		
November-09	RIT 1	16.5	21.19		
December-09	RIT 1	17.7	19.46	Average of Provide MpKG	Average of Calculated
January-10	RIT 1	6.3	6.46		
February-10	RIT 1	19.1	16.78	18.29	19.43
February-09	RIT 2	23.7	19.05		
March-09	RIT 2	22.9	20.63		
April-09	RIT 2	26	25.45		
May-09	RIT 2	23	24.79		
June-09	RIT 2	28.8	20.40		
July-09	RIT 2	10.6	11.31		
August-09	RIT 2	NA	109.17		
September-09	RIT 2	30	26.49		
October-09	RIT 2	40.2	42.20		
November-09	RIT 2	19.2	66.43		
December-09	RIT 2	22.3	10.38	Average of Provide MpKG	Average of Calculated
January-10	RIT 2	14.6	14.19		
February-10	RIT 2	20.7	10.98	23.50	24.36
February-09	RIT 3	35.7	15.71		
March-09	RIT 3	36.8	24.39		
April-09	RIT 3	36.8	37.80		
May-09	RIT 3	32	33.08		
June-09	RIT 3	12.9	33.20		
July-09	RIT 3	30	32.68		
August-09	RIT 3	NA	131.11		
September-09	RIT 3	46.2	46.98		
October-09	RIT 3	NA	56.67		
November-09	RIT 3	19.3	21.97		
December-09	RIT 3	NA	85.56	Average of Provide MpKG	Average of Calculated
January-10	RIT 3	29.8	33.67		
February-10	RIT 3	17.7	26.57	29.72	30.61

Table 4: Standard Deviation for all Values shown in Table 1 and Table 2

Standard Deviation	Vehicle	Number of Fills	Total Amount of H2 Filled (KG)	Average Amount of Hydrogen per Fill (KG)	Average Fill Time (Min)	Miles per KG of Hydrogen	Miles Per Month	Idle Time	Miles per Month	Miles per KG of Hydrogen Calculated
	RIT 1	18.70	32.48	0.49	4.68	7.23	620.95	6%	506.61	6.32
	RIT 2	17.34	36.36	0.47	3.66	7.56	647.68	6%	558.83	15.95
	RIT 3	5.22	5.11	0.27	8.09	10.27	164.59	9%	188.57	8.80

Table 5: Average for all Values shown in Table 1 and Table 2

Average	Vehicle	Number of Fills	Total Amount of H2 Filled (KG)	Average Amount of Hydrogen per Fill (KG)	Average Fill Time (Min)	Miles per KG of Hydrogen	Miles Per Month	Idle Time	Miles per Month	Miles per KG of Hydrogen Calculated
	RIT 1	43.83	76.14	1.77	19.56	18.29	1227.17	52%	1356.83	19.43
	RIT 2	36.08	64.92	1.78	19.88	23.50	1391.08	48%	1292.25	24.36
	RIT 3	6.90	9.20	1.38	18.29	29.72	253.30	15%	298.60	30.61

Table 6: Maximum for all Values shown in Table 1 and Table 2

Maximum	Vehicle	Number of Fills	Total Amount of H2 Filled (KG)	Average Amount of Hydrogen per Fill (KG)	Average Fill Time (Min)	Miles per KG of Hydrogen	Miles Per Month	Idle Time	Miles per Month	Miles per KG of Hydrogen Calculated
	RIT 1	76.00	126.40	3.03	25.10	30.30	2212.00	60%	2047.00	30.69
	RIT 2	71.00	136.60	3.11	25.00	40.20	2212.00	58%	2148.00	42.20
	RIT 3	18.00	16.60	1.75	37.00	46.20	496.00	35%	559.00	46.98

Table 7: Minimum for all Values shown in Table 1 and Table 2

Minimum	Vehicle	Number of Fills	Total Amount of H2 Filled (KG)	Average Amount of Hydrogen per Fill (KG)	Average Fill Time (Min)	Miles per KG of Hydrogen	Miles Per Month	Idle Time	Miles per Month	Miles per KG of Hydrogen Calculated
	RIT 1	15.00	27.00	1.10	9.30	6.30	215.00	38%	506.00	6.46
	RIT 2	5.00	8.40	1.10	13.80	10.60	199.00	38%	160.00	10.38
	RIT 3	1.00	2.10	0.90	9.00	12.90	70.00	6%	33.00	15.71

Table 8: Sum of Selected Values shown in Table 1 and Table 2

SUM	Vehicle	Number of Fills	Total Amount of H2 Filled (KG)				Total Miles		Total Miles	Miles per KG of Hydrogen Calculated
	RIT 1	526.00	913.70				14726.00		16282.0	
	RIT 2	433.00	779.00				16693.00		15507.0	
	RIT 3	69.00	92.00				2533.00		2986.0	

Table 9: Calculations for All Vehicles

Month	Total Amount of H2 Filled (HG)	Miles per Month	Miles per Month	Average Mileage for ALL Vehicles (mile/Hg)	Average Mileage for ALL Vehicles (mile/Hg)	Cumulative Miles for ALL Vehicles	Cumulative Miles for ALL Vehicles
February-09	65.6	1304	1299	19.88	19.80	1304	1299
March-09	144.8	2872	3478	19.83	24.02	4176	4777
April-09	115.6	2907	2672	25.15	23.11	7083	7449
May-09	96	2324	1925	24.21	20.05	9407	9374
June-09	158.7	3519	3675	22.17	23.16	12926	13049
July-09	247.3	3005	2252	12.15	9.11	15931	15301
August-09							
September-09	139.1	3810	4402	27.39	31.65	19741	19703
October-09	93	3278	3168	35.25	34.06	23019	22871
November-09	106	3329	2053	31.41	19.37	26348	24924
December-09	188.7	2981	3753	15.80	19.89	29329	28677
January-10	279.6	3314	3293	11.85	11.78	32643	31970
February-10	152.4	2277	2076	14.94	13.62	34920	34046
Average of All Months	148.90	2910.00	2837.17	21.67	20.80		

Calculation 1: Cost per Mile of Hydrogen

Cost:	**$15.45**	**Hg**
Using Average Mileage shown:	**$0.743**	**$0.713**

$$\left(\frac{\$3.650}{100\,ft^3}\right)\left(\frac{11.986\,m^3}{1\,kg}\right)\left(\frac{35.315\,ft^3}{1\,m^3}\right) = \frac{\$15.45}{1\,kg}$$

Calulation 2: Cost per Mile of Gasoline

Gas Hybrid:	**36**	**mpg**	**Highway**
	31	**mpg**	**City**
	33.25	**mpg**	**Calculated Average**
Cost:	**$2.75**	**gallon**	**Average Regular Gasoline 2009**
Using Average Mileage shown:	**$0.083**		

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Networkcar Vehicle Monitoring System Alert History
RIT 1 – Public Safety Vehicle

Alert	Initial Read, Odometer	Last Active Read, Odometer
27000 MILE SERVICE Scheduled Maintenance Please schedule your 27,000 mile service appointment	5/12/10 02:03 PM, 26662	5/28/10 08:37 AM, 27495
24000 MILE SERVICE Scheduled Maintenance Please schedule your 24,000 mile service appointment	4/7/10 02:22 PM, 23861	4/15/10 09:50 AM, 24488
21000 MILE SERVICE Scheduled Maintenance Please schedule your 21,000 mile service appointment	2/27/10 10:10 AM, 20500	3/9/10 11:14 AM, 20999
18000 MILE SERVICE Scheduled Maintenance Please schedule your 18,000 mile service appointment	12/20/09 09:13 PM, 17504	12/29/09 07:51 PM, 18152
15000 MILE SERVICE Scheduled Maintenance Please schedule your 15,000 mile service appointment	11/9/09 07:45 PM, 14502	11/25/09 04:16 AM, 15496
12000 MILE SERVICE Scheduled Maintenance Please schedule your 12,000 mile service appointment	9/16/09 04:24 AM, 11517	9/30/09 04:13 AM, 12499
P0193(Pending) Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	8/29/09 11:04 AM, 10149	9/3/09 09:15 AM, 10590
P0193 Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	8/30/09 07:11 AM, 10209	9/3/09 09:15 AM, 10590
9000 MILE SERVICE Scheduled Maintenance Please schedule your 9,000 mile service appointment	7/21/09 04:28 PM, 8844	8/10/09 06:55 PM, 9495
6000 MILE SERVICE Scheduled Maintenance Please schedule your 6,000 mile service appointment	5/14/09 02:09 AM, 5505	6/10/09 08:01 PM, 6489
P0351(Pending) Ignition Coil A Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly	5/20/09 01:42 PM, 5538	5/20/09 01:42 PM, 5538
P0352(Pending) Ignition Coil B Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly	5/20/09 01:42 PM, 5538	5/20/09 01:42 PM, 5538
P0353(Pending) Ignition Coil C Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly	5/20/09 01:42 PM, 5538	5/20/09 01:42 PM, 5538
P0354(Pending) Ignition Coil D Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly	5/20/09 01:42 PM, 5538	5/20/09 01:42 PM, 5538
P0193(Pending) Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	4/8/09 01:19 PM, 5177	4/13/09 04:44 AM, 5346
P0193 Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	4/8/09 03:24 PM, 5178	4/13/09 04:44 AM, 5346
P0461 Fuel Level Sensor Circuit Range/Performance Fuel gauge may not be working properly	1/6/10 04:57 PM, 3655	1/8/10 07:18 AM, 3747
P0461(Pending) Fuel Level Sensor Circuit Range/Performance Fuel gauge may not be working properly	1/6/10 03:28 PM, 3646	1/7/10 12:12 PM, 3715
3000 MILE SERVICE Scheduled Maintenance Please schedule your 3,000 mile service appointment	2/20/09 11:50 PM, 2501	2/26/09 10:00 AM, 2713

RIT 2 – Public Safety Vehicle

Alert		Initial Read, Odometer	Last Active Read, Odometer
?	21000 MILE SERVICE Scheduled Maintenance Please schedule your 21,000 mile service appointment	3/30/10 04:54 AM, 20505	4/7/10 09:50 AM, 20701
!	P0128 Coolant Thermostat Malfunction Engine temperature sensor may not be fully operational	3/30/10 05:04 AM, 20505	3/31/10 11:41 AM, 20548
!	P0128(Pending) Coolant Thermostat Malfunction Engine temperature sensor may not be fully operational	3/27/10 02:20 AM, 20316	3/31/10 11:41 AM, 20548
!	P0128(Pending) Coolant Thermostat Malfunction Engine temperature sensor may not be fully operational	2/7/10 10:09 AM, 19570	2/22/10 08:57 AM, 19918
!	P0128(Pending) Coolant Thermostat Malfunction Engine temperature sensor may not be fully operational	1/14/10 04:43 AM, 17791	1/22/10 08:24 AM, 18488
?	18000 MILE SERVICE Scheduled Maintenance Please schedule your 18,000 mile service appointment	1/10/10 02:14 AM, 17504	1/19/10 01:22 PM, 18292
!	P0068 Throttle Body Airflow Performance (PCM) / MAP / MAF - Throttle Position Correlation Vehicle is reporting a potential powertrain sensor malfunction	3/24/10 04:42 AM, 15115	3/24/10 04:42 AM, 15115
!	P0068(Pending) Throttle Body Airflow Performance (PCM) / MAP / MAF - Throttle Position Correlation Vehicle is reporting a potential powertrain sensor malfunction	3/24/10 04:42 AM, 15115	3/24/10 04:42 AM, 15115
!	P0068(Pending) Throttle Body Airflow Performance (PCM) / MAP / MAF - Throttle Position Correlation Vehicle is reporting a potential powertrain sensor malfunction	3/18/10 11:06 AM, 14999	3/18/10 11:06 AM, 14999
?	15000 MILE SERVICE Scheduled Maintenance Please schedule your 15,000 mile service appointment	11/10/09 03:57 PM, 14500	11/16/09 10:15 AM, 14666
?	12000 MILE SERVICE Scheduled Maintenance Please schedule your 12,000 mile service appointment	9/7/09 10:32 PM, 11505	9/27/09 01:35 AM, 12494
?	9000 MILE SERVICE Scheduled Maintenance Please schedule your 9,000 mile service appointment	7/6/09 06:44 AM, 8504	7/10/09 12:22 PM, 8705
?	6000 MILE SERVICE Scheduled Maintenance Please schedule your 6,000 mile service appointment	5/4/09 10:21 AM, 5567	5/28/09 06:32 PM, 6496
!	P0193(Pending) Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	5/8/09 07:11 PM, 5831	5/20/09 02:10 PM, 6192
!	P0193 Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	5/8/09 07:33 PM, 5833	5/20/09 02:10 PM, 6192
!	P0193 Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	4/16/09 11:41 AM, 4067	4/21/09 01:58 PM, 4454
!	P0193(Pending) Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly	4/16/09 06:57 AM, 4057	4/21/09 01:58 PM, 4454
?	3000 MILE SERVICE Scheduled Maintenance Please schedule your 3,000 mile service appointment	3/20/09 11:17 PM, 2513	4/8/09 12:27 AM, 3494
!	P0606(Pending) PCM Processor Fault Vehicle's computer may not be working properly	10/7/09 06:16 PM, 2555	10/8/09 05:32 AM, 2556
!	P0068 Throttle Body Airflow Performance (PCM) / MAP / MAF - Throttle Position Correlation Vehicle is reporting a potential powertrain sensor malfunction	3/18/09 09:38 AM, 2299	3/18/09 09:38 AM, 2299
!	P0351	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299

	Ignition Coil A Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0352	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil B Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0353	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil C Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0354	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil D Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0068(Pending)	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Throttle Body Airflow Performance (PCM) / MAP / MAF - Throttle Position Correlation Vehicle is reporting a potential powertrain sensor malfunction		
!	P0351(Pending)	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil A Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0352(Pending)	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil B Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0353(Pending)	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil C Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	P0354(Pending)	3/18/09 08:46 AM, 2299	3/18/09 09:38 AM, 2299
	Ignition Coil D Primary/Secondary Circuit Malfunction Engine's electrical system may not be working properly		
!	B1300 FORD(Pending)	3/6/09 02:46 PM, 2188	3/6/09 02:46 PM, 2188
	Engine Coolant Temp. for Hydraulic Cooling Fan Circuit Malfunction Engines cooling system may not be working efficiently		
!	P0193	3/6/09 01:11 PM, 2184	3/6/09 01:11 PM, 2184
	Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly		
!	P0193(Pending)	3/6/09 12:42 PM, 2181	3/6/09 01:11 PM, 2184
	Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly		
!	P0606(Pending)	3/4/09 01:52 PM, 2113	3/5/09 03:59 AM, 2135
	PCM Processor Fault Vehicle's computer may not be working properly		
!	P0193	2/23/09 07:50 AM, 383	3/2/09 01:22 PM, 487
	Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly		
!	P0193(Pending)	2/23/09 06:27 AM, 381	3/2/09 01:22 PM, 487
	Fuel Rail Pressure Sensor Circuit High Input Gasoline delivery system may not be working correctly		
!	P0122	2/10/09 01:18 PM, 329	2/10/09 01:18 PM, 329
	Throttle/Petal Position Sensor/Switch A Circuit Low Input Gasoline delivery system may not be working correctly		
!	P0223	2/10/09 01:18 PM, 329	2/10/09 01:18 PM, 329
	Throttle/Petal Position Sensor/Switch B Circuit High Input Gasoline delivery system may not be working correctly		
!	P2110	2/10/09 01:18 PM, 329	2/10/09 01:18 PM, 329
	Unknown DTC Vehicle is reporting a potential sensor malfunction		
!	P0122(Pending)	2/10/09 01:18 PM, 329	2/10/09 01:18 PM, 329
	Throttle/Petal Position Sensor/Switch A Circuit Low Input Gasoline delivery system may not be working correctly		
!	P0223(Pending)	2/10/09 01:18 PM, 329	2/10/09 01:18 PM, 329
	Throttle/Petal Position Sensor/Switch B Circuit High Input Gasoline delivery system may not be working correctly		
!	P2110(Pending)	2/10/09 01:18 PM, 329	2/10/09 01:18 PM, 329
	Unknown DTC Vehicle is reporting a potential sensor malfunction		

RIT 3 – CIMS Vehicle

Alert		Initial Read, Odometer	Last Active Read, Odometer
	P0128(Pending) Coolant Thermostat Malfunction Engine temperature sensor may not be fully operational	2/8/10 08:36 PM, 3827	2/9/10 10:27 AM, 3847
	P0128 Coolant Thermostat Malfunction Engine temperature sensor may not be fully operational	2/9/10 08:00 AM, 3838	2/9/10 10:27 AM, 3847
	3000 MILE SERVICE Scheduled Maintenance Please schedule your 3,000 mile service appointment	9/1/09 07:20 AM, 2518	9/1/09 07:31 AM, 2524

Center for Integrated Manufacturing Studies
ROCHESTER INSTITUTE OF TECHNOLOGY

(1)

Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6-7-10

Driver name: Margaret Goodwin

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☑	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	☐	☐	☐	☐	☐	?
Engine idles rough	☐	☐	☐	☐	☑	G, H, J, K
Engine idles too fast	☐	☐	☐	☐	☐	
Hesitates or stalls under acceleration	☐	☐	☑	☐	☐	B, F, G, J
Misses under load	☐	☐	☐	☐	☐	?
Engine surges at constant speed	☐	☑	☐	☐	☐	
Limited power	☐	☑	☐	☐	☐	
Pings or knocks	☐	☐	☑	☐	☐	M
Stalls on deceleration or stop	☐	☑	☐	☐	☐	
Engine runs after key is turned off	☑	☐	☑	☐	☐	M
Backfires	☐	☐	☑	☐	☐	
Excessive Noise Levels	☑	☐	☐	☐	☐	A, B

Other (describe) _____

①

Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☐	☑

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☑	☐
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☑	☐
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☐	☑

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐	☐	☑
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☑	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☑	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☐	☐	☑	☐	☐
Time to fuel Hydrogen vehicle. *Comments:* Vehicle would require being out of service for almost 40 minutes	☑	☐	☐	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:* Vehicle had very limited Acceleration	☑	☐	☐	☐	☐
Power under heavy load. *Comments:*	☐	☑	☐	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☑	☐	☐	☐	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☑	☐	☐	☐

(i)

Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☑
Overall, I have had a good experience using Hydrogen.	☐	☑
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☐	☑

Comments: My personal opinion is that the hydrogen vehicles are not good public safety vehicles. The lack of acceleration, length of time it takes to fill them and how quickly they need to be refueled is making them difficult to use. While they are good cars and environmentally better, they should not be used in the public safety department.

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(2)

Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6-5-10

Driver name: _____

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☒	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

when Eng. lights, Eng. Response, Vehicle Shut down.

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID ?
Extended crank time	☒	☐	☐	☐	☐	
Engine idles rough	☒	☐	☐	☐	☐	
Engine idles too fast	☐	☐	☐	☐	☒	
Hesitates or stalls under acceleration	☐	☐	☒	☐	☐	
Misses under load	☐	☐	☒	☐	☐	
Engine surges at constant speed	☒	☐	☐	☐	☐	
Limited power	☐	☐	☐	☐	☒	
Pings or knocks	☐	☐	☒	☐	☐	
Stalls on deceleration or stop	☒	☐	☐	☐	☐	
Engine runs after key is turned off	☒	☐	☐	☐	☐	
Backfires	☐	☐	☒	☐	☐	
Excessive Noise Levels	☐	☐	☐	☒	☐	

Other (describe) _____

②

Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☐	☐

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☐	☒
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☒	☐
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☐	☒

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐	☐	☒
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☒	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☒	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☐
Time to fuel Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐
Power under heavy load. *Comments:*	☐	☒	☐	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☐	☐	☒	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☒	☐	☒	☐

②

Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☒
Overall, I have had a good experience using Hydrogen.	☐	☒
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☒	☐

Comments:

- Too loud
- Too high RPM's (noisy)
- Too long to fuel up at pump.
- Too much of a hassel to connect hoses to fuel up.

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Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6/5/10

Driver name: Ryan Hicks

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☒	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	☐	☒	☐	☐	☐	H
Engine idles rough	☐	☐	☐	☒	☐	
Engine idles too fast	☒	☐	☐	☐	☐	
Hesitates or stalls under acceleration	☐	☐	☐	☒	☐	B
Misses under load	☒	☐	☐	☐	☐	
Engine surges at constant speed	☒	☐	☐	☐	☐	
Limited power	☐	☐	☒	☐	☐	
Pings or knocks	☐	☐	☐	☐	☐	
Stalls on deceleration or stop	☐	☒	☐	☐	☐	
Engine runs after key is turned off	☐	☒	☐	☐	☐	
Backfires	☐	☐	☒	☐	☐	
Excessive Noise Levels	☐	☐	☐	☐	☒	

Other (describe) _____

3

Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☐	☒

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☒	☐
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☐	☒
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☐	☒

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐	☒	☐
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☒	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☒	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☐	☐	☒	☐	☐
Time to fuel Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☐
Power under heavy load. *Comments:*	☒	☐	☐	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☐	☒	☐	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☐	☐	☒	☐

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Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☒
Overall, I have had a good experience using Hydrogen.	☐	☒
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☐	☒

Comments:

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(4)

Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 06-04-10

Driver name: Kenneth J. Pettis

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☒	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	☒	☐	☒	☐	☐	☒
Engine idles rough	☐	☐	☒	☐	☐	
Engine idles too fast	☐	☐	☒	☐	☐	B
Hesitates or stalls under acceleration	☐	☐	☒	☐	☐	A
Misses under load	☐	☒	☐	☐	☐	
Engine surges at constant speed	☐	☐	☒	☐	☐	A
Limited power	☐	☐	☐	☒	☐	B
Pings or knocks	☐	☒	☐	☐	☐	M
Stalls on deceleration or stop	☐	☐	☒	☐	☐	A
Engine runs after key is turned off	☐	☒	☐	☐	☐	
Backfires	☒	☐	☐	☐	☐	
Excessive Noise Levels	☐	☐	☐	☒	☐	B
Other (describe)						

(4)

Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☐	☒

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☐	☒
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☐	☒
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☐	☒

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐	☐	☒
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☒	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☒	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☒
Time to fuel Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☒

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☐
Power under heavy load. *Comments:*	☐	☐	☒	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☐	☐	☒	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☐	☐	☐	☒

(4)

Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☒
Overall, I have had a good experience using Hydrogen.	☐	☒
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☒	☐

Comments:

The acceleration with the Hydrogen Vehicle is not very good. When you do accelerate the RPM goes up to 5 or 6. The noise when accelerating is extremely loud and has scared pedestrians as their walking. It also takes to long to fill the vehicle and the fuel station seems to break down in cold weather. I know that this is a relatively new way to run vehicles and it is a work in progress. I think that it is amazing that engineers have been able to accomplish what this technology represents. If it's going to help the planet, I'll put up with the inconvenience (inconvenience) until it's perfected.

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Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6-5-2010

Driver name: Dale LAZAR

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	■	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	■	☐	☐	☐	☐	
Engine idles rough	■	☐	☐	☐	■	
Engine idles too fast	☐	☐	■	☐	☐	
Hesitates or stalls under acceleration	■	☐	☐	☐	■	
Misses under load	■	☐	☐	☐	■	
Engine surges at constant speed	■	☐	☐	☐	☐	
Limited power	☐	■	☐	☐	☐	
Pings or knocks	■	☐	☐	☐	■	
Stalls on deceleration or stop	■	☐	☐	☐	■	
Engine runs after key is turned off	■	☐	☐	☐	☐	
Backfires	☐	■	☐	☐	☐	on start up
Excessive Noise Levels	☐	☐	☐	■	☐	

Other (describe) _____

8

Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☒	☐

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☒	☐
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☒	☐
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☐	☒

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐	☐	☒
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☒	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☒	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐
Time to fuel Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐
Power under heavy load. *Comments:*	☐	☐	☒	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☐	☐	☒	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☐	☐	☐	☒

(8)

Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☒
Overall, I have had a good experience using Hydrogen.	☒	☐
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☒	☐

Comments:

(5)

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Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6-5-10

Driver name: Entwistle, Jim

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☒	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	☒	☐	☐	☐	☐	–
Engine idles rough	☒	☐	☐	☐	☐	–
Engine idles too fast	☐	☐	☐	☒	☐	–
Hesitates or stalls under acceleration	☐	☐	☒	☐	☐	ABC
Misses under load – I DO NOT UNDERSTAND?	☐	☐	☐	☐	☐	–
Engine surges at constant speed	☒	☐	☐	☐	☐	–
Limited power	☐	☐	☒	☐	☐	HK
Pings or knocks	☐	☐	☒	☐	☐	L
Stalls on deceleration or stop	☒	☐	☐	☐	☐	–
Engine runs after key is turned off	☐	☒	☐	☐	☐	L
Backfires	☐	☐	☒	☐	☐	ABL
Excessive Noise Levels	☐	☐	☐	☒	☐	ABL

Other (describe) _____

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Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☒	☐

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☒	☐
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☒	☐
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☒	☐

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐	☐	☒
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☒	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☒	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐
Time to fuel Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐
Power under heavy load. ? *Comments:*	☐	☐	☐	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☐	☒	☐	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☒	☐	☐	☐

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5

Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☒
Overall, I have had a good experience using Hydrogen.	☐	☒
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☐	☒

Comments:

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(6)

Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6/4/10

Driver name: Mark Koehler

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☑	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	☐	☐	☐	☐	☑	B
Engine idles rough	☐	☐	☑	☐	☐	M
Engine idles too fast	☐	☐	☐	☐	☑	M
Hesitates or stalls under acceleration	☐	☐	☐	☐	☑	B
Misses under load	☑	☐	☐	☐	☐	M
Engine surges at constant speed	☑	☐	☐	☐	☐	M
Limited power	☐	☐	☐	☐	☑	L
Pings or knocks	☑	☐	☐	☐	☐	M
Stalls on deceleration or stop	☑	☐	☐	☐	☐	M
Engine runs after key is turned off	☑	☐	☐	☐	☐	M
Backfires	☐	☐	☑	☐	☐	L
Excessive Noise Levels	☐	☐	☐	☐	☑	L

Other (describe) _____

6

Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☐	☒

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☐	☒
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☒	☐
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☒	☐

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☒	☐	☐
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☒	☐	☐	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☒	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☐	☒	☐	☐	☐
Time to fuel Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☒	☐	☐	☐	☐
Power under heavy load. *Comments:*	☐	☒	☐	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☐	☐	☒	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☐	☐	☒	☐

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Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☒
Overall, I have had a good experience using Hydrogen.	☐	☒
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☐	☒

Comments:

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Hydrogen Drivability Survey

Vehicle: 2008 Ford Escape Hybrid Date: 6-5-10

Driver name: Brad Leeson

Typical Vehicle use: RIT Public Safety

	Yes	No
I have driven both a Hydrogen powered and a Non-Hydrogen powered RIT Public Safety Ford Escape Hybrid. (If *Yes*, please continue.)	☑	☐

Please rate your vehicle's performance issues. If an issue has occurred, please note a condition when the issue occurred. Use the condition key to the right if possible. You can note more than one condition if applicable.

Please fill out all three (3) pages of the survey.

ID	Condition when failure occurs
A	constant steady speed
B	acceleration
C	deceleration (foot off accelerator)
D	braking
E	turning
F	high electric load (e.g. Air conditioner)
G	hot day
H	cold day
I	humid / rainy day
J	hot engine
K	cold engine
L	other
M	unknown

A-Always; M-Mostly; S-Sometime; R-Rarely; N-Never or Not Apply

Drivability / Vehicle Performance Issues	N	R	S	M	A	Condition ID
Extended crank time	☑	☐	☐	☐	☑	
Engine idles rough	☐	☐	☐	☑	☐	
Engine idles too fast	☐	☐	☐	☐	☑	C
Hesitates or stalls under acceleration	☐	☐	☑	☐	☐	
Misses under load	☐	☐	☑	☐	☐	
Engine surges at constant speed	☐	☑	☐	☐	☐	
Limited power	☐	☐	☐	☐	☑	
Pings or knocks	☐	☑	☐	☐	☐	
Stalls on deceleration or stop	☐	☐	☐	☑	☐	
Engine runs after key is turned off	☑	☐	☐	☐	☐	
Backfires	☐	☐	☑	☐	☐	K
Excessive Noise Levels	☐	☐	☐	☐	☑	A

Other (describe) _____

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Hydrogen Drivability Survey

	Better		Equal		Worse
Rate the Hydrogen Ford Escape's performance relative to the Non-Hydrogen Ford Escape's performance.	☐	☐	☐	☐	☑

User Observations

	Yes	No
Have you seen your Check Engine light on while driving your vehicle on Hydrogen?	☑	☐
Have you noticed any abnormal smells coming from the vehicle's engine or exhaust?	☑	☐
Have you seen any smoke or other emissions coming from the engine or tailpipe?	☐	☑

Vehicle Use

	A	M	S	R	N
This vehicle was not required to perform any atypical activities relative to the other Public Safety Ford Escapes	☐	☐	☐ ?	☐	☑
The daily vehicle usage (routes, tasks) is basically the same as the Non- Hydrogen Public Safety Ford Escapes	☑	☐	☑	☐	☐
This vehicle was used to run auxiliary electronic accessories such as laptop computers, lights and radios when in use.	☑	☐	☐	☐	☐

Customer Satisfaction

*Please rate the following on a scale of **1** to **5**; **5** being **very satisfied**, and **1** being **very dissatisfied***

	1	2	3	4	5
Ease of fueling Hydrogen vehicle. *Comments:*	☐	☐	☐	☑	☐
Time to fuel Hydrogen vehicle. *Comments:*	☐	☐	☑	☐	☐

The following are in comparison to the Non-Hydrogen powered Public Safety Ford Escapes

Power and Acceleration of Hydrogen vehicle. *Comments:*	☑	☐	☐	☐	☐
Power under heavy load. *Comments:*	☑	☐	☐	☐	☐
Traction (Snow, Ice, Off-road) *Comments:*	☐	☑	☐	☐	☐
Ability to run auxiliary electronic accessories. (Laptop computers, lights, radios, ect.) *Comments:*	☐	☐	☐	☑	☐

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Hydrogen Drivability Survey

	Yes	No
I would drive a Hydrogen powered vehicle as my personal vehicle.	☐	☑
Overall, I have had a good experience using Hydrogen.	☐	☑
I am comfortable using Hydrogen fuel in my Public Safety vehicle.	☑	☐

Comments: