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Hydrogen Storage Needs for Early Motive Fuel Cell Markets

J. Kurtz, C. Ainscough, L. Simpson,
and M. Caton

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November 2012

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Acronyms and Abbreviations

AV	autonomous vehicles & unmanned vehicles
ARRA	American Recovery and Reinvestment Act
DLA	Defense Logistics Agency
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
SV	specialty vehicles
MHE	material handling equipment
GSE	ground support equipment
MTTR	mean time to repair
NREL	National Renewable Energy Laboratory
R&D	research and development

Executive Summary

Objective

The National Renewable Energy Laboratory's (NREL) objective for this project is to identify performance needs for onboard energy storage of early motive fuel cell markets by working with end users, manufacturers, and experts. The performance needs analysis is combined with a hydrogen storage technology gap analysis to provide the U.S. Department of Energy (DOE) Fuel Cell Technologies Program with information about the needs and gaps that can be used to focus research and development activities that are capable of supporting market growth.

Method

NREL selected the early motive fuel cell markets studied based on the DOE Fuel Cell Technologies Program's market transformation activity focus on specialty vehicles, which includes material handling equipment, ground support equipment, public transit, and autonomous vehicles. NREL collected information about the performance needs in these markets during workshops and with electronic questionnaires. The performance needs were identified without selecting a particular storage technology to facilitate a clear understanding of the end user's performance expectations without a technology bias.

Results

NREL completed the analyses per a specific application, but a few themes were common across applications. A common focus was the performance of incumbent technologies that are well established, familiar, and generally simple. A hydrogen storage technology needs to be simple, flexible, safe, low cost (capital and operation), and robust to compete with the incumbent technologies.

These markets tend to be risk averse and demand systems with high technology readiness levels and manufacturing readiness levels. Hydrogen storage technologies that have near-term potential to be readily available, reliable, and capable of satisfying the demanding operation environment are a must for market acceptance. This is obvious from the number of discussions and responses focusing on reliability, maintenance costs, operating conditions (e.g., temperature as well as shock and vibration) and mean time to repair. The top five "must-have" attributes (along with a few important "linear" attributes) by application are listed in Table ES-1.

Table ES-1. "Must-Have" Attributes of Hydrogen Storage Technologies

Material Handling Equipment	Public Transit	Autonomous Vehicles
Shock and vibration	Environment	Storage capacity
Mean time to repair	Storage capacity	End-of-life costs
Reliability/availability	Fill rate	Reliability/availability
Greenhouse gas emissions	Shock and vibration	Shock and vibration
Operation temperature	Operation lifetime	Mean time to repair
Fill rate, maintenance costs, and storage capacity	Maintenance costs, reliability/ availability, preventative maintenance frequency, and mean time to repair	Fill rate, operation temperature, maintenance cost, preventative maintenance frequency, and warranty

Hydrogen storage technologies capable of accelerating market acceptance should:

- Be capable of satisfying all of the “must-have” performance needs
- Be simple, easy to use, safe, and effective (particularly from the operator’s perspective)
- Integrate with the fuel cell systems and hydrogen infrastructure in a way to decrease infrastructure complexity and cost
- Have near-term potential as a readily available technology.

Recommendations

Compressed hydrogen tanks are the most common hydrogen storage technology implemented and capable of satisfying many of the performance needs for these markets. However, there is potential for performance gains by developing alternative hydrogen storage technologies to:

- Lower onboard storage system costs
- Lower infrastructure costs resulting in expanding the potential market beyond high count fleet sites
- Simplify infrastructure without the need for compression and high pressure hardware
- Increase scalability to be capable of multiple, sequential fills without a decrease in fill amount or time
- Improve volumetric capacity and weight.

A summary of the performance needs for the specialty vehicle market that combines data from workshop, questionnaire, and active deployments appears in Table ES-2.

Table ES-2. Summary of Specialty Vehicle Performance Needs

Need	Value	Comments
Volume	<120 liters	0.5–2 kg current onboard capacity for fuel cell material handling equipment units (Class I, II, and III) ~ 1,200 Wh/L
Cycles (operation life)	5,000 – 10,000 fills	~10 years
Fill rate	<0.7 kg/min	3 min fills
Shock and vibration	3–15 g	
Ambient temperature	-40°C to 60°C	
Operation temperature		Safe for close proximity to operators

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1 Background and Introduction

1.1 Objective

The National Renewable Energy Laboratory's (NREL) objective for this project is to identify performance needs for onboard energy storage of early motive fuel cell markets by working with end users, manufacturers, and experts. The performance needs analysis is combined with a hydrogen storage technology gap analysis to provide the U.S. Department of Energy (DOE) Fuel Cell Technologies Program with information about the needs and gaps that can be used to focus research and development (R&D) activities capable of supporting market growth.

1.2 Scope

The DOE Fuel Cell Technologies Program focuses on the R&D of materials and approaches that will enable widespread commercialization of fuel cell systems for diverse applications across stationary, portable, industrial, and transportation sectors. The market adoption of motive fuel cell systems can be accelerated by improving storage system technologies. Effective improvements in hydrogen storage systems could result in extended product run times, increased productivity, decreased capital and operating costs, improved integration between the equipment and facility, and facilitation of siting and permitting processes. These improvements can be achieved through focused R&D efforts based on an in-depth understanding of storage requirements in key early markets.

1.2.1 Motive Market Selection

NREL selected the early motive markets based on the DOE Fuel Cell Technologies Program's focus of its market transformation activity on specialty vehicles (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy 2010). For the purpose of this report, the markets are categorized as the following:

- **Specialty vehicles.** This market includes material handling equipment (MHE) such as traditional forklifts and pallet jacks for used in warehouses and manufacturing facilities, as well as other ground support equipment (GSE) used in airports, mining operations, and grounds keeping and maintenance operations.
- **Public transit.** This market includes transit services (urban routes, commuter, and paratransit) and shuttle services (airport, campus, and large events).
- **Autonomous vehicles and other niche applications.** These markets include applications for autonomous vehicles, and other military autonomous motive applications.

To gather supporting data for the analysis and identification of motive market-specific performance needs and current hydrogen storage technology gaps, NREL identified target audiences and contacted them for participation through market-specific workshops and questionnaires. The target audience where end users, fuel cell manufacturers, and hydrogen storage experts in the motive markets selected.

1.2.2 Hydrogen Storage Technologies

The DOE Fuel Cell Technologies Program focuses on R&D of several technologies to provide hydrogen storage, including metal hydrides, chemical hydrides, sorbents, compressed tanks, liquid hydrogen, and cryo-compressed tanks. Lower pressure, materials-based technologies include chemical hydrides, metal hydrides, and sorbents. Figure 1 compares 2011 projections of hydrogen storage system gravimetric and volumetric capacities for light duty vehicles, including compressed hydrogen; cryo-compressed hydrogen; liquid hydrogen; and lower-pressure, materials-based technologies.

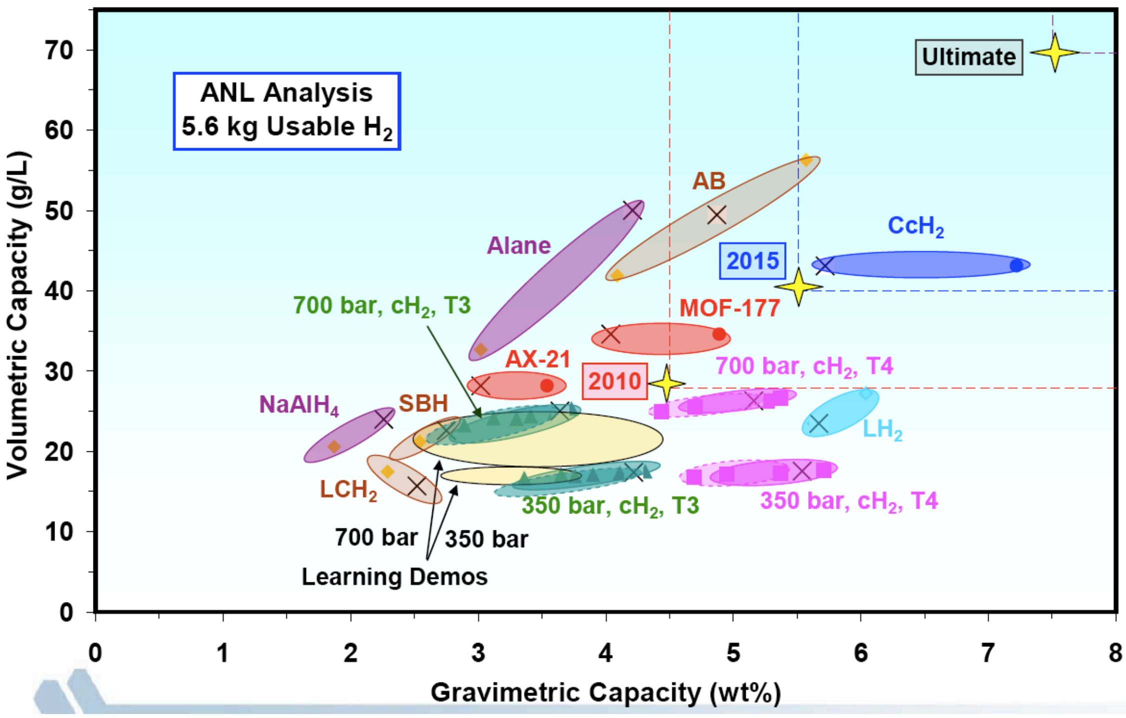
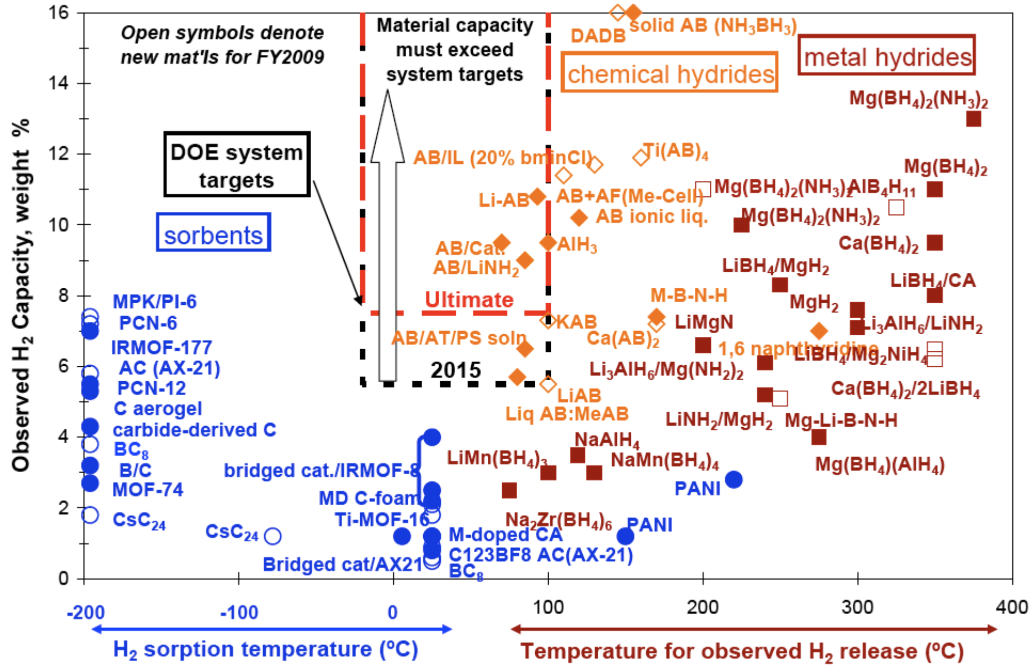


Figure 1. Plot of projected volumetric and gravimetric capacities for different hydrogen storage system technologies as applied to light duty vehicles

The plot includes representative system technologies involving compressed hydrogen (cH_2, at ambient temperature), cryo-compressed hydrogen (CcH_2, at ~35 K), liquid hydrogen (LH_2, at ~20 K), sorbents (AX-21 and MOF-177 at ~100 K), metal hydrides (alane, $NaAlH_4$), and chemical hydrides (liquid carrier [LCH_2], sodium borohydride [SBH], ammonia borane [AB]). (Ahluwalia 2011)



DOE: G. Thomas (2007), G. Sandrock (2008), B. Bowman (2009-10)

Figure 2. Different hydrogen storage material capacities—developed by DOE projects (Stetson 2011)

Key factors for hydrogen storage system performance are capacities (Figure 2), retention of hydrogen, low system cost (Figure 3), high-purity hydrogen with good well-to-drive system energy efficiency, low associated emissions such as carbon dioxide, and little impact on the overall hydrogen fuel costs.

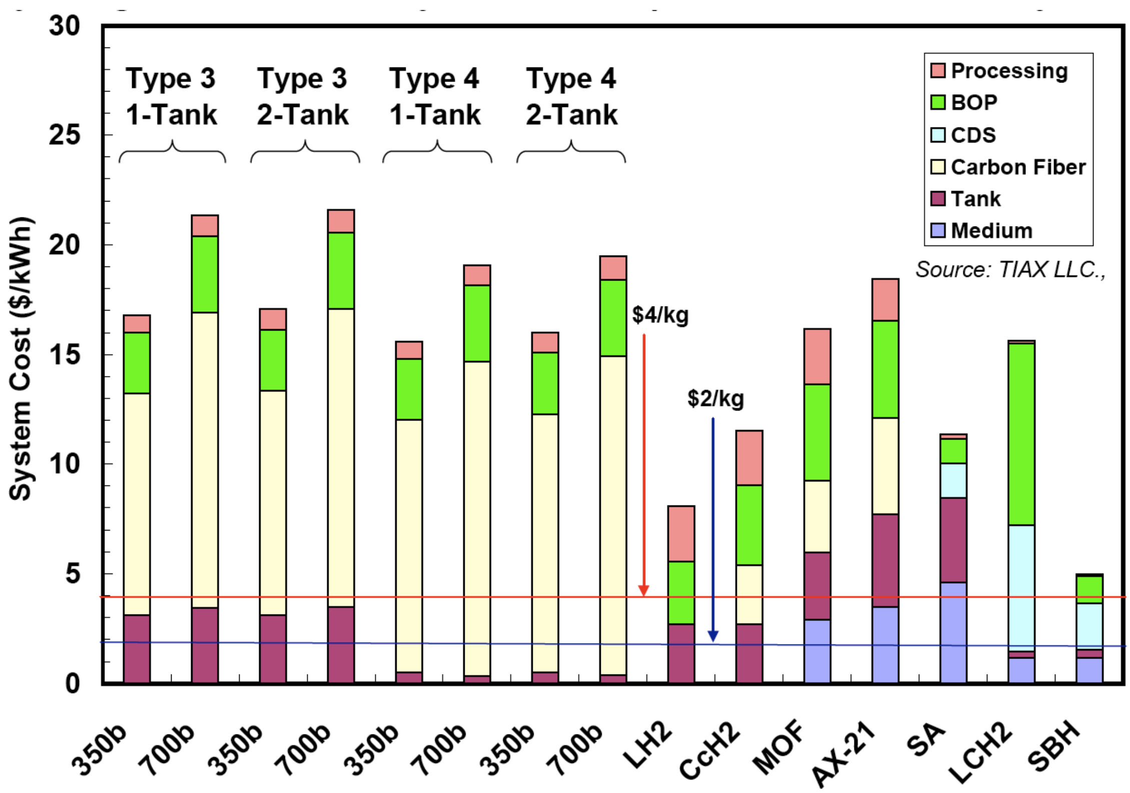


Figure 3. Projected hydrogen storage system costs for different technologies
(Ahluwalia 2011)

2 Method

The performance needs for onboard energy storage are technology agnostic to facilitate a clear understanding of the end user's performance expectations without a technology bias.

NREL developed a questionnaire using the Kano Analysis Method and distributed it to stakeholders both electronically and during interactive workshops to gather supporting information and provide a better understanding of the industries identified for motive fuel cell applications. The results were used for analysis and assessment.

NREL then assessed the current hydrogen storage technologies and compared them to the needs and expectations that were identified by the target audiences. This method enabled us to identify gaps in hydrogen storage R&D activities.

2.1 Information Gathering – Workshops

NREL conducted three workshops to gather input from equipment developers, manufacturers, end users, and expert stakeholders on the important performance requirements of motive power applications and onboard energy systems in near-term markets for hydrogen-fueled motive power applications. The workshops were held in conjunction with conferences already being attended by the targeted stakeholder groups. The first workshop was held February 16, 2011, in conjunction with the Fuel Cell and Hydrogen Energy Association annual conference in National Harbor, Maryland. The second two workshops were held March 21, 2011, in Chicago, Illinois, in conjunction with ProMat 2011, an annual conference and trade show for the material handling and logistics industry. Participants' experience with fuels cells, hydrogen, or other onboard energy storage technologies ranged from expert to layperson. Information on the autonomous vehicle category was gathered via email and phone contact as well as at the workshop held in February.

Each workshop featured small group discussion sessions led by professional facilitators from Energetics Incorporated. The February 16 workshop included two breakout groups: one focused on onboard energy storage needs for transit buses, and one focused on MHE and GSE. The two half-day workshops held on March 21 were targeted toward the MHE industry. As shown in the agendas included in Appendix A, the workshop facilitators structured the discussion sessions around two focus questions used to initiate conversation in particular topic areas. The facilitators prompted participants to share information and experiences with motive power applications general performance requirements, and, more specifically, the requirements for the onboard energy storage system. Participants were asked to share strengths and weaknesses of current onboard energy storage technologies for meeting performance needs, and to identify opportunities for improvement. The facilitators documented results of the session, which are summarized in Section 2.2.

2.2 Information Gathering – Questionnaires

Japanese Professor Noriaki Kano developed the Kano Analysis Method to determine customer wants and needs. The method is widely applied in industry as a tool for market research to drive customer satisfaction. It is a key tool in the six-sigma quality movement. The method breaks customer desires into the following five categories:

- **Must-have -** These are attributes that a product needs if it is to be adopted (e.g., a system in an autonomous vehicle that requires an in-place operator).
- **Linear** - These attributes are of the "more is better" type (e.g., an increased operation temperature range for MHE power packs is not required by most fleet managers, but it could improve overall operation capability).
- **Exciters** - These are unexpected attributes that the customer can live without, but they really add a new level of convenience that the customer did not know was possible (e.g., a simple maintenance training program for public transit buses that decreases training requirements). Exciter attributes tend to become must-haves over time as they become more common.
- **Reverse** - These are attributes that make a product less desirable (e.g., a storage capacity that would require more than one fill per shift or mission).

- **Indifferent** - These are attributes that the customer does not care about (e.g., the color of the storage system).

To determine which category a particular attribute falls into, potential customers are asked the following questions:

- A positive question (e.g., How would you feel if you could operate many shifts in a row without needing to replenish your energy storage system?).
- A negative question (e.g., How would you feel if you had to replenish your energy storage system many times in a shift?).

Answers to the questions are limited to mutually exclusive multiple choice options such as: "like it," "expect it," "do not care," "live with it," and "dislike it." These responses correspond to numerical ratings of 1 to 5.

The answers to each question are plotted on a positive versus negative Cartesian plane (see Table 1). Depending on where most responses lie, one can determine which Kano category applies to that attribute.

Table 1. Kano Attributes Space

<table>
<tr><td></td><td></td><td colspan="5">Negative Question</td></tr>
<tr><td></td><td></td><td>Dislike It</td><td>Live With It</td><td>Neutral</td><td>Expect It</td><td>Like It</td></tr>
<tr><td rowspan="5">Positive Question</td><td>Like It</td><td>Linear</td><td colspan="3">Exciter</td><td>Inconsistent</td></tr>
<tr><td>Expect It</td><td rowspan="3">Must-Have</td><td colspan="3" rowspan="3">Indifferent</td><td rowspan="4">Reverse</td></tr>
<tr><td>Neutral</td></tr>
<tr><td>Live With It</td></tr>
<tr><td>Dislike It</td><td>Inconsistent</td><td colspan="3">Reverse (having this attribute is bad)</td></tr>
</table>

NREL made an extension to the model for the purposes of this project. In addition to the standard Kano method, NREL added a third question to each question topic to determine quantitative values for the customer's specific needs. For instance, on the hydrogen storage topic of hydrogen fill rate, the following questions were asked:

- Positive: How would you feel if your vehicle could be fueled quickly?
- Negative: How would you feel if your vehicle took a long time to fill?
- Follow-up: What would you consider to be quick (in minutes)?

NREL included the topics in Table 2 in the questionnaire in cooperation with Sandia National Laboratories. Each topic included a question triplet (positive, negative, and follow-up). The order of the questions was randomized to avoid grouping the triplets together. This approach forced the users to address each question with fresh minds, and therefore produced more genuine responses. Grouping the triplets together could cause respondents to provide answers they think the questioners are seeking, rather than legitimate responses. The questionnaire can be viewed in Appendix B.

Table 2. Questionnaire Topics

End-of-Life Costs	Operator Training	Weight	Maintenance Costs
Environment	Preventative maintenance frequency	Site air quality	Operation temperature
Fill rate	Maintenance training	Warranty	Reliability/availability
Fuel cost	Storage capacity	Operation lifetime	Robustness
Safety	Mean time to repair (MTTR)	Volume	Shock and vibration

3 Results

NREL separated the results from the workshops and questionnaires by application in the following subsections. For each application, NREL identified attributes that are important to the end user through discussions and the Kano results for "Must-Have," "Linear," and "Exciter" categories. Detailed figures for each Kano topic are grouped and plotted as in Figure 4. Refer to Appendix C for detailed results by application and questionnaire topic.

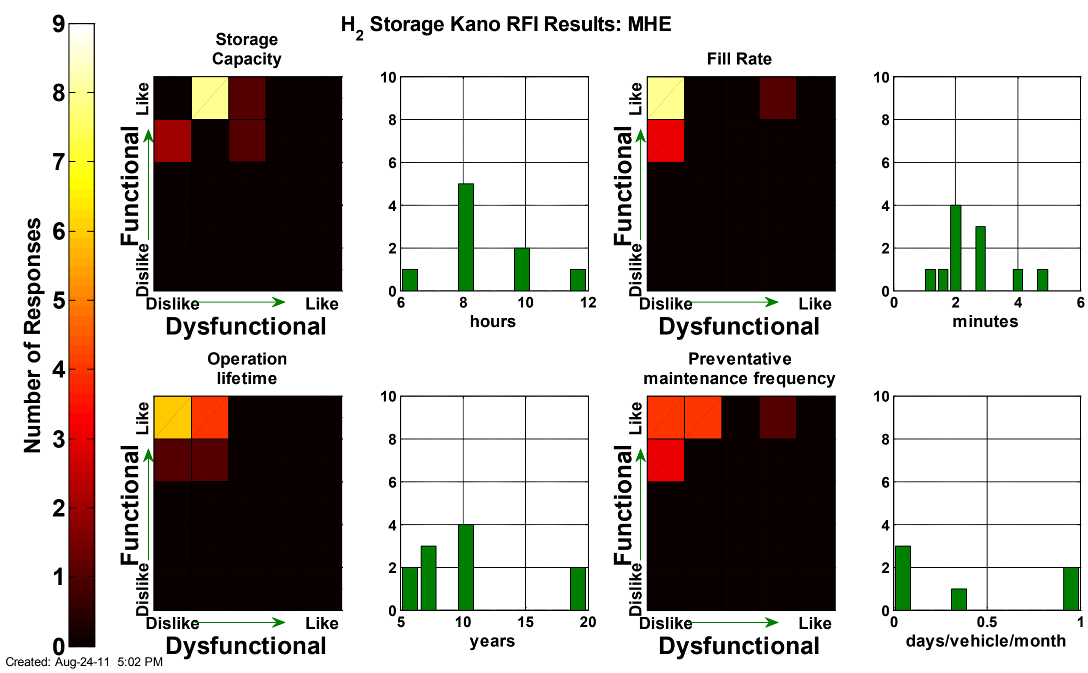


Figure 4. Example of MHE Kano results for topics relating to operation

The analysis includes 33 responses, most of which are from the MHE application group (see Figure 5). This is reflective of industry projects, market size, and available contacts for the applications. Each Kano question set has two graphs, one for identifying whether the attribute is important to the responder, and one for the expected performance. The detailed results include each response value, and the summary information contains statistical values such as the mean and one standard deviation of the quantitative performance attributes. Respondents in the other category did not specify an application or represented multiple applications.

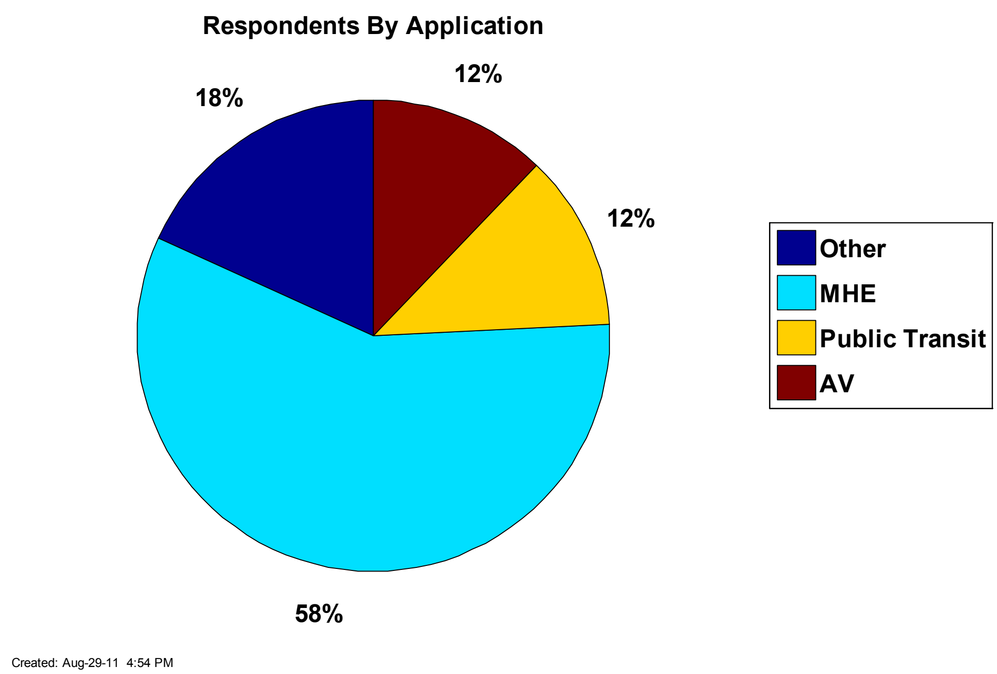


Figure 5. Questionnaire respondents by application

3.1 Specialty Vehicles (SV)

3.1.1 Overview

Specialty vehicles includes MHE and GSE applications. MHE includes a variety of powered industrial trucks used in material receiving, storage, loading, packing, and shipping operations. Common types of MHE include forklifts, tugs, stock pickers, pallet trucks, and hand trucks. There are seven major classes (Class I–VII) of lift trucks, each designed for a specific type of application, demand (e.g., power and speed), and locale. Classes I–III are typically used in warehouse-type settings, such as distribution centers or shipping and receiving, as well as grocery stores. Classes IV–VII are typically used outdoors (though Class IV trucks are sometimes operated indoors) in applications such as construction, agriculture, manufacturing, trucking, paper industries, recycling, and shipping.

Table 3. Lift Truck Power Sources and Operating Characteristics

Power Source	Fuel	Characteristics
Internal combustion engine	Gasoline, diesel, liquefied petroleum gas, or compressed natural gas	Can handle heavy loads over a full shift Quick refueling via liquid or gas fuel dispenser Noisy operations Potentially harmful exhaust emissions in indoor environments
Battery-driven electric motor	Stored electricity, typically in lead-acid batteries	Battery drained faster with heavy loads Quiet, emissions-free operation
Fuel-cell-driven electric motor	Hydrogen or methanol	Performs as well as, or better than, battery systems with no power drop during operation Quick refueling via hydrogen or methanol dispenser Quiet, emissions-free operation

The lift truck industry is a multibillion dollar, global industry. The top 15 lift truck manufacturers in 2009 had annual revenues of $19.6 billion (Rogers 2010), and included companies in Asia, Europe, and the United States. About 900 companies (Mahadevan et al. 2007) utilize MHEs and companies such as FedEx, Coca-Cola, Walmart, BMW, and Sysco Foods have experience with fuel cell MHEs.

User requirements for MHE will vary, depending on the application. Decision factors important to MHE end users include reliability, ease of use, lifetime, fuel availability, and costs (operation and capital) (Mahadevan et al. 2007). Other considerations include constant power; peak power loads; lift capacity; stability; and ambient operating conditions such as temperature, humidity, and space.

GSE is used to service aircraft between flights. GSE comprises a diverse array of specialty vehicles and equipment designed to perform a variety of functions, including starting, fueling, and maintaining aircraft; towing aircraft; providing ground-based power or conditioned air to the cabin and cockpit; loading and unloading passengers and cargo; and providing cleaning and food and beverage catering services. Today, GSE is largely powered by internal combustion engines (fueled by gasoline, diesel, liquefied petroleum gas, compressed natural gas, or Jet A fuel) or batteries.

GSE is used at major commercial airports, smaller flying fields, air courier services, military facilities, helicopter carriers, hangars, charter services, and air ambulance services. In 2006, there were more than 14,500 such facilities in the United States (Mahadevan et al. 2007). The latest data showing the estimated GSE population in the Unites States (in this case, pushback tractors and baggage tugs) are from 1999, when the U.S. Environmental Protection Agency (EPA) estimated that 2,759 aircraft pushback tractors and 10,505 baggage tugs were in service (U.S. Environmental Protection Agency 1999). Assuming a 4% annual growth, there are at least 4,300 pushback tractors and at least 16,200 baggage tugs in the United States today.

One of the biggest concerns of GSE end users is emissions. With the latest EPA standards on nonroad diesel emissions (15 parts per million sulfur content, effective June 2010), a significant amount of attention has been focused on cleaning up GSE emissions, mainly by using emission control devices or switching to electric motors. Emissions are particularly important in and around airport terminal buildings, where many workers are located. The air quality in those environments directly affects the workers' health and safety. Many airports are located in nonattainment areas, and are either being encouraged or mandated to lower their emissions.

The results in the next section focus on MHE applications because of the lack of GSE available information.

3.1.2 Key Performance Attributes

3.1.2.1 Workshop Results

Table 4. Summary of Onboard Energy Storage Needs for MHE and GSE Workshop Results
(Kurtz et al. 2011a and 2011b)

High-Priority Need	Comments
Fast and convenient filling	• Quick, convenient fueling at no more than 2–3 minutes per fill • Fill time and convenience are more important than continuous run time over a 5–8 hour shift—with quick fills, operators can "opportunity charge" during scheduled breaks • Low-pressure operation would be great but not at the expense of run- or fill-time
Flexibility in storage system design to fit within existing products (weight and volume)	• Today, most fuel cell systems are treated as a retrofit to battery-powered forklifts • Must fit in existing battery spaces (weight, center of gravity, and dimensions) • Fuel cell system weight must be increased approximately four times to make up for counterbalancing provided by heavy batteries • Need to eliminate equipment and control system redundancies in vehicles that have been retrofitted to run on fuel cells
Transparent, simple, safe operations	• Simple is necessary to compete with batteries • Must be easy for operators to use, with user-friendly controls and system diagnostics • Systems must be demonstrated to be safe for operators
Cost of onboard energy system	• Total cost must be competitive with batteries (including costs for fueling, operations, maintenance, and disposal) • Low-cost maintenance requires a simple system that is easy to install, use, and maintain
Onboard energy system lifetime	• Industrial environment requires reliable, easy to retrofit or replace systems that do not require frequent or extensive maintenance • An 8–10 year lifetime is ideal—the ability to refurbish, rather than replace, the energy system is a plus • Hydrogen storage tanks must be capable of high cycling, or many charge/discharge cycles, over a 10-year life span
Certified field support with low maintenance requirements	• Maintenance must not be more frequent than preventative maintenance for incumbent technologies (e.g., 2–3 hours per 500 operation hours)
Meeting power demands	• Customers are demanding vehicles with higher and higher power—the energy system needs to meet the increased power needs without changing its size • Available power must be able to provide multiple 400-inch lift cycles

High-Priority Need	Comments
	• Power should be consistent over the full life of the shift (e.g., no performance degradation at the end of shift or due to extreme hot or cold temperatures) • Power must be available for peak bursts (e.g., lifting or towing) and low use (e.g., driving) • To meet the full range of MHE applications, providers must supply systems with a range of power levels of 3–50 kilowatts
Tolerant to Extreme Environmental Conditions	• Must perform in the full range of MHE environments without performance degradation • Temperatures in freezer, refrigerator, and dry goods storage facilities can range from subfreezing (–30°F) to very hot (> 100°F) • Humidity levels will fluctuate and MHE must be able to withstand condensation caused by moving from cold to hot environments • Must tolerate shock and vibration from rugged use or rough surfaces

3.1.2.2 Kano Results

The Kano results in the MHE category are summarized in Figure 6. The attributes are organized according to the number of “Must-Have” responses to highlight the key performance needs. The following are the top five attributes:

- Shock and vibration
- MTTR
- Reliability/availability
- Greenhouse gas emissions
- Operation temperature.

Fill rate, warranty, and maintenance costs are also important performance needs because of the high count in the “Linear” category. A clear “Exciter” in MHE is storage capacity. Similarly, during workshop discussions, capacity was determined to be important but not a driving factor as long as the system only needed to fill once a shift and could fill quickly (less than five minutes). The greenhouse gas emissions “Must-Have” need is likely related to indoor air quality, as most of the facilities that utilize battery or fuel cell technologies are located indoors.

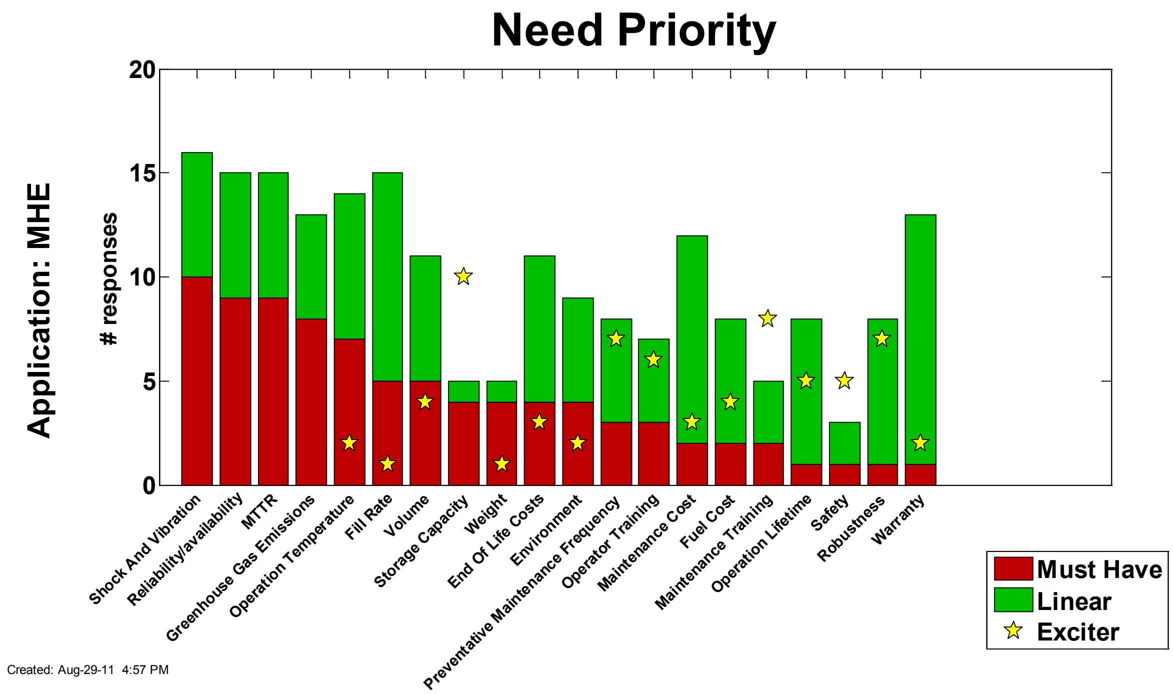


Figure 6. Identification of MHE performance needs by Must-Have, Linear, and Exciter Kano results

With the key performance needs identified, the operation parameters for those needs were determined next. The responses are varied, likely because of the wide variety of MHE facilities and end users, but this information can be summarized in a few statistics to provide a general description of the operation. The average value of the MTTR attribute is 2 hours—for example, in general, end users expect repairs to not take more than 2 hours. The fuel cell MHE sites funded through American Recovery and Reinvestment Act (ARRA) see that 30% of the maintenance events take less than 1 hour (Kurtz et al. 2011f).

The average reliability/availability operation range is 126 hours per week of uptime. Based on the range of answers, the respondents have high-use facilities (where the lowest value is more than 80 hours per week) and have the expectation that systems are rarely down for maintenance. The average range for storage capacity (or continuous runtime) is 8 hours, the average fill rate is 2.6 minutes, and the highest fill rate is less than 5 minutes. Convenient, fast fills are generally more important than continuous run time, according to the end users. Combining the average hours per week with the average continuous run time results in approximately 14 fills per week per unit. This translates into 5,000 to – 10,000 fills over the average operating lifetime of 10 years, which matches the operation lifetime of the truck.

Refer to Table 5 for a complete list of all SV performance needs from the Kano Questionnaire study and workshop discussions. The primary Kano category is also identified as M (Must-Have), E (Exciter), and L (Linear). The values are not specific to a particular truck class and some of the values are for the entire system/vehicle and are not specific to the onboard energy system. Not all attributes received a quantitative response, for instance, there was insufficient data for the greenhouse gas emissions attribute performance range. Refer to Appendix D for a complete set of response data results.

Table 5. Summary of All Performance Needs for SV

Speciality Vehicle[1,2]		Questionnaire Statistics								
Attribute	Units	Mean	Max	Min	75% percentile	25% percentile	Std Dev	Kano	Additional Workshop Information	Comments
Shock and Vibration	g	3 - 15						M		
Reliability/Availability	hours/ w eek	127	160	80	100	150	32	M		Need high up time in w eek (e.g. 2-3 hours for maintenance per 500 operation hours)
MTTR	hours	2	4	1	1	2	1	M		Entire system - 30% maintenance events are < 1 hour long in ARRA MHE demonstrations[5]
Greenhouse Gas Emissions	No quantitative responses							M		kg-CO2 eq/kg-H2 Likely zero emissions required
Operation Temperature (Min)	^oC	-40	120	-40	118	-38		M		
Operation Temperature (Max)	^oC	60	120	-40	118	-38		M		
Fill Rate	minutes	3	5	1	2	3	1	L	2 -3 minutes	Quick and convenience is more important than continuous run time
Warranty	years	3	7	1	2	3	2	L		
Maintenance Costs	$/vehicle/ year	4420	10000	100	775	9250	4699	L		Per vehicle, energy storage is a small percentage
Storage Capacity	hours	9	12	6	8	10	2	E	5 - 8 hours	Continuous run time betw een fills (converts to ~ 5 kg[3,4])
Volume	liters	387	680	49	125	566	251	L		Entire system - assume 30% available for Storage (~1200 Wh/l)[4]
Weight	kg	1190	1814	4	862	1474	570	M		Entire system - assume 50% available for storage (~0.8 w t%)[4]
End of life Costs	$	100	200.0	0.0	0.0	200.0	141	L		
Operation lifetime	years	10	20	5	7	10	5	L	8 - 10 years	Combine availablity hours/w eek w ith continuous run time (capacity) => 14 fills per w eek (5,000 - 10,000 fills over 10 years)
Robustness	No quantitative responses							L		
Fuel Cost	$/MJ (LHV)	0.19	1.11	0.02	0.04	0.06	0.40	L		
Preventative maintenance frequency	days/ vehicle/ month	0.40	1.00	0.00	0.01	1.00	0.48	L		
Environment	No quantitative responses							L		Operating environment includes dirt, humidity, extreme temperatures, rugged use, indoors and outdoors w ith pow er needs of 3 - 50 kW
Maintenance Training	No quantitative responses							E		
Safety	min/operator/ day	6	15	1	2	10	5	E		
Operator Training	hr/operator/ year	27	60	5	9	40	18	E		1-8 hours for dispensing of compressed tanks in DOE MHE sites
Storage System Costs	No quantitative responses							M		
Well to engine efficiency	No quantitative responses							M		WTE Eff. (%)

1. Some values are for entire SV system/vehicle
2. Values are not specific to a certain truck class
3. Assumes 10 kW pow er plant operating at ~ 50% efficiency
4. The capacity in terms of run time w as used to calaculate the amount of fuel needed (~5 kg, 0.8 w t%, 1200 Wh/l).
   The w eight and volume values assumed to be for entire system and estimate 30% w eight and 50% volume available for stoarge
5. CDP-ARRA-MHE-43 http://w w w .nrel.gov/hydrogen/cfm/images/cdparra_mhe_43_maintenancelaborhoursbreakdow n.jpg

3.2 Public Transit

3.2.1 Overview

Public transit buses are large on-road vehicles designed to provide public transportation and carry a large passenger load. The market includes small shuttle-type buses or vanpool buses with a passenger capacity as low as 10-20 people and large commuter buses that can carry as many as 300 passengers. Transit buses traverse both urban and rural routes, and are designed for both long- and short-haul operations.

The major end-users of public transit buses are city or county transit agencies that have a mission to create an accessible, affordable, and useful public transportation infrastructure, including paratransit services for elderly or disabled persons. Other public- and private-sector organizations can also be end users of public transit buses, including airports, military bases, national parks, and schools and universities.

In the United States, bus transit accounted for close to 55% of total public transit trips in 2009, equating to over 4 billion vehicle miles travelled (American Public Transportation Association 2011). In that year, approximately 66,500 public transit buses and 65,800 paratransit vehicles were operating in the United States during peak periods (American Public Transportation Association, 2011, p. Table 9). While the vast majority of transit buses in use today are powered by internal combustion engines operating on diesel fuel or gasoline, alternative fuels are also used, including electricity, compressed natural gas, liquefied natural gas, biofuels, and hydrogen (see Table 5). Because buses are an extremely popular mode of transportation in the United States and globally, it is becoming increasingly important to make them as environmentally friendly and efficient as possible, and the market for alternative fueled buses is growing.

Table 6. Vehicle Power Sources by Mode of Service
(American Public Transportation Association 2011)

Mode	Electricity	Diesel Fuel	Electric and Other (Hybrid)	Gasoline	CNG, LNG and Blends	Other
Bus	0.1%	65.8%	7.0%	0.7%	18.6%	7.8%
Para-transit	--	49.2%	0.5%	42.8%	1.9%	5.6%
Vanpool	--	4.0%	0.3%	93.2%	0.1%	2.4%

3.2.2 Key Performance Attributes

This section summarizes the key energy storage performance needs and capabilities of public transit vehicles, as identified by participants in the workshop discussions and through the Kano questionnaire.

3.2.2.1 Workshop Results

Although three workshops were held to gather information for this analysis, only one included a session specifically addressing public transit vehicles as an end-user application. As shown in Table 6, the participants identified four high-priority needs for the energy storage system, including its cost, weight, lifetime, and capacity (vehicle driving range).

Table 7. Summary of Onboard Energy Storage Needs for PT Workshop Results
(Kurtz et al. 2011a)

High-Priority Need	Comments
Onboard Energy System Cost	• The low weight requirement drives the hydrogen storage tank material to be carbon fiber, which is very expensive • The storage system is typically designed each time, but repetition in tank system design could help reduce cost
Bus Weight	• A fuel cell bus should weigh the same as or less than a diesel hybrid bus because of transit agencies' weight and size limits, as well as potential U.S. Department of Transportation weight limits • Space for onboard energy storage may be better optimized to decrease weight
Energy Storage System Lifetime	• Operation lifetime should match that of the bus (12 years/500,000 miles or ~ 5,000 tank cycles). Current compressed hydrogen storage technology meets this goal, but alternative technologies may not
Driving Range	• 200–250 miles per day and one fill per day

3.2.2.2 Kano Results

The Kano results in the public transit category are summarized in Figure 7. The attributes are organized according to the number of "Must-Have" responses in order to highlight the key performance needs. The following are the top five attributes:

- Environment (e.g. snow, rain, ice, dirt, humidity, extreme temperatures)
- Storage capacity
- Fill rate
- Shock and vibration
- Operation lifetime.

Maintenance cost is also a key attribute based on the high number of "Linear" responses, along with a series of attributes relating to operation and maintenance (specifically Reliability/Availability, Preventative Maintenance Frequency, and MTTR). There were not sufficient "Exciter" responses for a detailed investigation into the "Exciter" attributes.

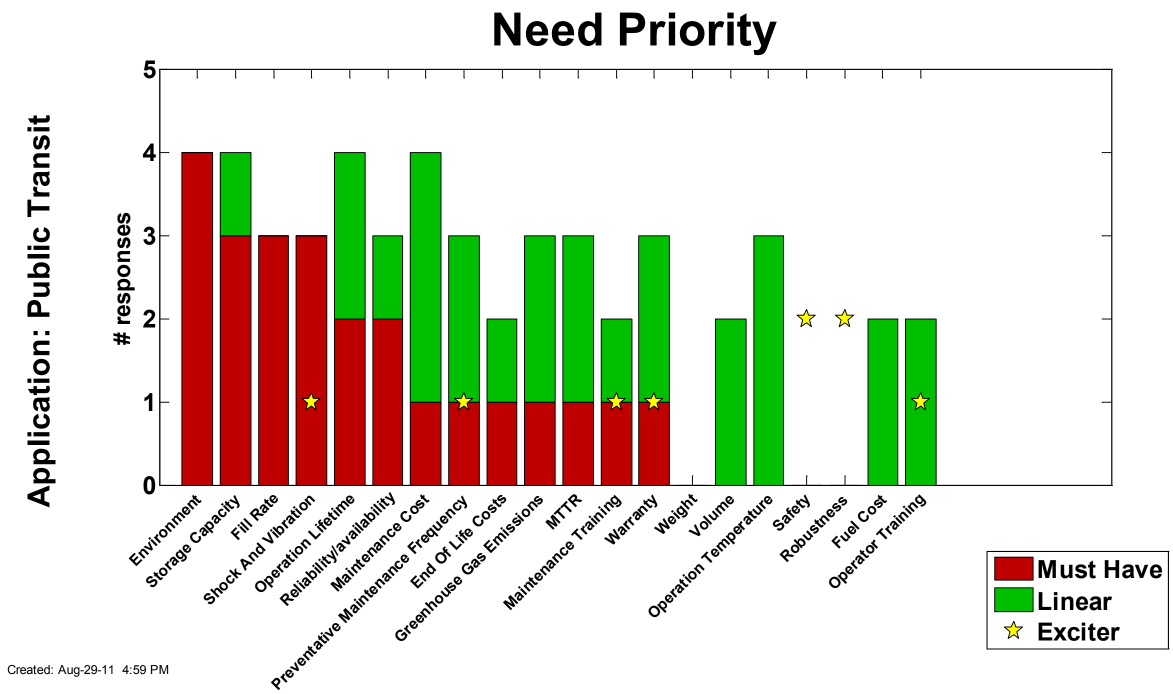


Figure 7. Identification of PT performance needs by Must-Have, Linear, and Exciter Kano results

With the key performance needs identified, the operation parameters for those needs were determined next. The operating environment for public transit applications includes a variety of air quality challenges. Additionally, the systems used in these applications are expected to operate 8–12 hours continuously before refueling and average between 200 and 250 miles per day. The average fill rate is 7 minutes, and all responses came in at less than 10 minutes. Another important aspect of filling buses is the ability to quickly fill many buses back-to-back. The respondents identified an operation period of 8–12 years, matching the operation period of the bus. When the hours per week are combined with at least 1 fill per day, it results in approximately 5,000 fills over the operation lifetime. The average MTTR is around 2 hours, which is similar to the MHE group's findings. Likewise, the end-user requirement for a reliable system that is available 85–140 hours per week is also similar to the MHE group's results.

Refer to Table 8 for a complete list of all PT performance needs from the Kano Questionnaire study and workshop discussions. The primary Kano category is also identified as M (Must-Have), E (Exciter), and L (Linear). The values are not specific to a particular bus class and some of the values are for the entire system/vehicle and are not specific to the onboard energy system. Not all attributes received a quantitative response; for instance, there was insufficient data for the greenhouse gas emissions and shock and vibration attributes performance ranges. Refer to Appendix E for a complete set of response data results.

Table 8. Summary of All Performance Needs for Public Transit

Public Transit[1,2]		Questionnaire Statistics								
Attribute	Units	Mean	Max	Min	75% percentile	25% percentile	Std Dev	Kano	Additional Workshop Information	Comments
Shock and Vibration	No quantitative responses							M	Road driving	Road shock and vibration conditions ~ 3 - 5 g
Reliability/Availability	hours/ w eek	112	140	84	84	140	40	L		Need high up time in w eek, as bus is likely routinely utilized
MTTR	hours	3	4	2	2	3.5	1	L		
Greenhouse Gas Emissions	No quantitative responses							L		
Operation Temperature (Min)	°C	-33	160	-100	140	-60	46/51	L		
Operation Temperature (Max)	°C	103	160	-100	140	-60	46/51	L		
Fill Rate	minutes	7	10	3	4	10	4	M		Need fast back to back fills
Warranty	years	8	12	6	6.2	10.7	3	L		
Maintenance Costs	$/vehicle/ year	14250	26000	2500	2500	26000	16617	L		Per vehicle, energy storage is a small percentage
Storage Capacity	hours	9	12	8	8	11	2	M		Continuous run time betw een fills (~50 kg[3,4]), 200 - 250 miles per day
Volume	No quantitative responses							L		
Weight	No quantitative responses							M	Low w eight	Weight the same as or less than a diesel hybrid bus (~45,000 lbs curb w eight 50+ passanger capacity FOOTNOTE)
End of life Costs	No quantitative responses									
Operation lifetime	years	11	12	8	9	12	2	M		Combine availability hours/w eek w ith 1 fill per day for ~ 5,000 fills over lifetime
Robustness	No quantitative responses							E		
Fuel Cost	$/MJ (LHV)	0.029	0.03	0.02	0.02	0.03	0.006	L		
Preventative maintenance frequency	days/ vehicle/ month	3	8	0	0	6	5	L		
Environment	No quantitative responses							M		Operating environment includes dirt, humidity, extreme temperatures, snow , and rain
Maintenance Training	No quantitative responses							M		
Safety	No quantitative responses									
Operator Training	hr/operator/ year	40	40	40	40	40	0	L		
Storage System Costs	No quantitative responses							M		On par w ith diesel hybrid costs, $500,000 - $700,000
Well to engine efficiency	No quantitative responses							M		WTE Eff. (%)

1. Some values are for entire SV system/vehicle
2. Values are not specific to a certain public transit option
3. Assumes 100 kW pow er plant operating at ~ 50% efficiency
4. The capacity in terms of run time w as used to calaculate the amount of fuel needed (~50 kg).

3.3 Autonomous Vehicles (AV)

3.3.1 Overview

AVs are powered vehicles that operate via remote operator control or autonomously, via "self-directed" computer programming. There are three primary types of AVs: aerial, ground, and maritime. AVs have numerous uses, including battlefield reconnaissance; battlefield targeting and decoy; autonomous combat; de-arming bombs and munitions; search and rescue/recovery; remote sensing; border patrol; commercial surveillance (e.g., pipeline monitoring, crop and livestock monitoring, wildfire mapping, weather monitoring, highway patrol, etc.); oil, gas and mineral exploration; cargo transport; equipment maintenance and repair; and scientific research in hostile or extreme environments.

The success of AVs in performing these various missions and services has fostered a rapidly growing global industry. The Federal Aviation Administration estimates that in the United States alone there are more than 50 companies, universities, and government organizations actively involved in developing and producing approximately 155 autonomous aircraft designs (Federal Aviation Administration 2010). As of April 2009, the U.S. military was developing or producing 311 autonomous systems (93 air, 171 ground, and 47 maritime) (U.S. Department of Defense 2009).

The power source for AVs varies depending on the application. According to the DOD, current energy sources are insufficient to support future military expectations for long-duration employment of autonomous systems, and they have defined a need to move to "next generation power resources." that will provide enhanced, smaller, and more robust power sources (U.S. Department of Defense 2009, p. 41 and 167). Today, small AV systems are typically powered by battery-operated motors or gasoline engines. Larger systems are typically powered by engines fueled by diesel, AVGAS, MOGAS, JP-5, JP-8, and Jet-A. Future power sources being considered include advanced engines and batteries, fuel cells, solar arrays, or biomass gasifier reactors.

3.3.2 Key Performance Attributes

Key performance attributes for all AVs include operating range, durability, reliability, ability to operate increasingly autonomously, without human control or intervention; and low acoustic, thermal, visual and communication signatures (particularly for military applications). Other performance attributes depend on the application, including speed, maneuverability, performance at altitude/depth, load carrying capacity, load lifting capacity, and ability to handle harsh or extreme environmental conditions such as rugged/bumpy terrain, high gravitational forces, rapid drops in air pressure, high humidity, and salt, dust, mud or sand. Autonomous ground vehicles may be required to operate in buildings or in urban environments busy with pedestrians, so low emissions is also important.

The section below describes results from the Kano questionnaire distributed for this analysis. The workshops did not attract participants from the AV industry, so no workshop results are presented.

3.3.2.1 Kano Results

The Kano results in the AV category are summarized in Figure 8. The results for the AV market are difficult to summarize clearly because of the low number of responses, small market size, and a developing market. The attributes are organized according to the number of "Must-Have" responses in order to highlight the key performance needs. The following are the top five attributes:

- Storage capacity
- End-of-life costs
- Reliability/availability
- Shock and vibration
- MTTR.

Fill Rate, Operation Temperature, Maintenance Cost, Preventative Maintenance Frequency, and Warranty are also important attributes because of the number of "Linear" responses.

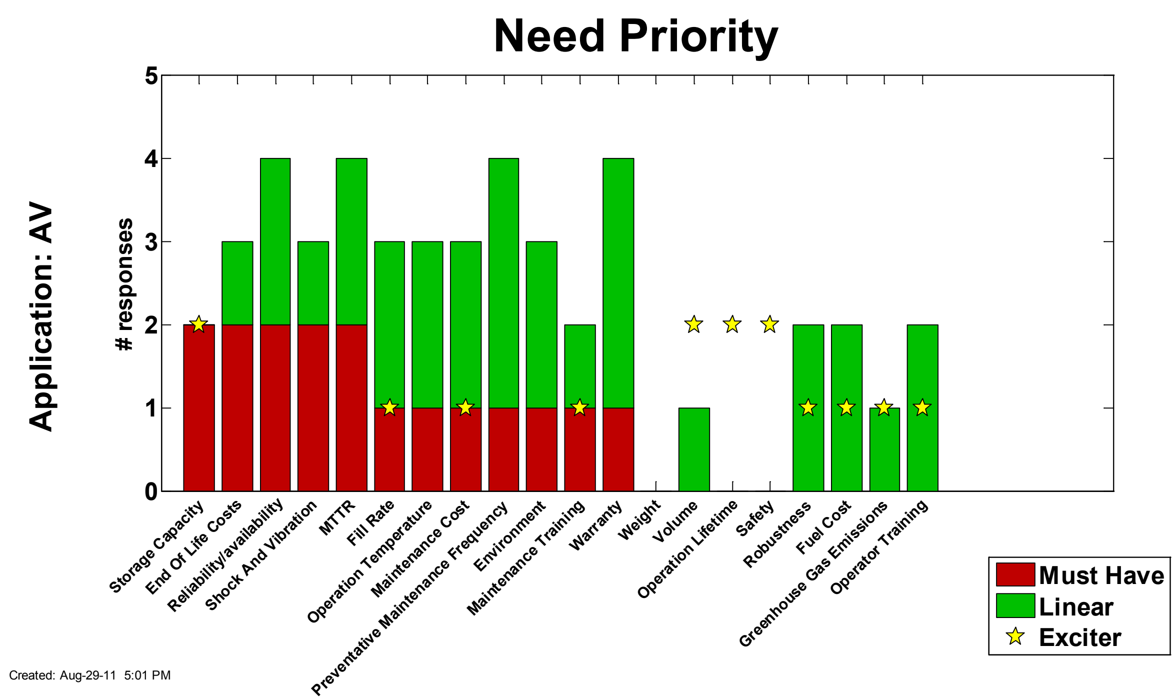


Figure 8. Identification of AV performance needs by Must-Have, Linear, and Exciter Kano results

With the key performance needs identified, the operation parameters for those needs were determined next. There is significant variability in the attribute operation ranges because there are many variations in the types of AV systems and missions. For instance, storage capacity is 8–24 hours of continuous operation, but a longer continuous runtime presents other mission possibilities. The acceptable fill rate is higher for AVs because the expected operation hours per week (20–160) are less than in the MHE and public transit groups. Weight is more important for aerial AVs than underwater AVs, and volume is likely critical in all AVs.

Refer to Table 9 for a complete list of all PT performance needs from the Kano Questionnaire study. The values are not specific to a particular AV system, such as aerial, and some of the values are for the entire system/vehicle and are not specific to the onboard energy system. Not all attributes received a quantitative response, for instance, there was insufficient data for the greenhouse gas emissions attribute performance range. Refer to Appendix F for a complete set of response data results.

Table 9. Summary of All Performance Needs for Autonomous Vehicle

Autonomous Vehicle[1,2]		Questionnaire Statistics							
Attribute	Units	Mean	Max	Min	75% percentile	25% percentile	Std Dev	Kano	Comments
Shock and Vibration	No quantitative responses							M	
Reliability/Availability	hours/ w eek	84	168	16	40	160	64	M	
MTTR	hours	28	120	2	3.5	36	52	M	
Greenhouse Gas Emissions	No quantitative responses							L	
Operation Temperature (Min)	°C	-0.8/111	140	-40	120	-25	36/22	L	
Operation Temperature (Max)	°C	-0.8/111	140	-40	120	-25	36/22	L	
Fill Rate	minutes	15	30	5	5	25	10	L	
Warranty	years	5	15	2	2	7.5	6	L	
Maintenance Costs	$/vehicle/ year	3900	10000	500	675	7800	5294	L	Per system, energy storage is a small percentage
Storage Capacity	hours	11	24	8	8	12	6	M	Continuous run time betw een fills (~34 kg[3,4])
Volume	liters	637	1359	170	311	963	509	L	Entire system - assume 1800 Wh/l needed[3,4]
Weight	No quantitative responses								
End of life Costs	$	300	500	100	100	500	283	M	
Operation lifetime	No quantitative responses								
Robustness	No quantitative responses							E	
Fuel Cost	$/MJ (LHV)	0.09	0.17	0.03	0.03	0.14	0.07	L	
Preventative maintenance frequency	days/ vehicle/ month	63	250	0.5	0.75	125.5	125	L	
Environment	No quantitative responses							L	
Maintenance Training	No quantitative responses							L	
Safety	No quantitative responses								
Operator Training	hr/operator/ year	32	40	2	30.5	40	17	L	
Storage System Costs	No quantitative responses							M	
Well to engine efficiency	No quantitative responses							M	WTE Eff. (%)

1. Some values are for entire SV system/vehicle
2. Values are not specific to a certain autonomous vehicle
3. Assumes 50 kW pow er plant operating at ~ 50% efficiency
4. The capacity in terms of run time w as used to calaculate the amount of fuel needed (~34 kg 1800 Wh/l).

3.4 Hydrogen Technologies Comparisons with Performance Needs

Metal hydrides, chemical hydrides, sorbents, compressed, liquid, and cryo-compressed hydrogen storage technologies were all included in comparing current hydrogen storage technologies to the market performance needs. General performance attributes were assigned to each category even though there are many variations within each category.

Table 10 through Table 12 show key performance needs by application, operation values, and how a storage technology is able to satisfy the operation expectation. There are a number of entries marked "TBD," which is an indication of little or no data to support whether the storage technology can meet the operation need.

The commercially available hydrogen storage technology that is most commonly used today is compressed storage at ambient temperature. In addition to gravimetric and volumetric capacity potentials being limited to close to present values, the major issue is hydrogen storage system cost. Another issue is the high cost and low reliability of compressing the hydrogen to relatively high pressures of 350–700 bar. However, compressed hydrogen provides rapid fill and delivery of high-purity hydrogen that can be stored indefinitely. In addition, steel tanks are used in some applications where weight is not an issue (e.g., MHE), meaning tank costs can be substantially reduced compared to applications where composites are needed for lighter weight.

Lower temperatures can be used to increase volumetric capacities further, but they require cryogenics. For example, liquid hydrogen storage at ~20 K and near atmospheric pressures enables ~30 g/L and ~6 wt % hydrogen storage systems, but dormancy and the relatively large amount of energy needed for liquefaction are critical issues. Recent work at Lawrence Livermore National Laboratory has led to the design of cryo-compressed hydrogen storage systems that combine very low temperatures (e.g., ~35 K) with high pressures (e.g., 300–700 bar) to substantially increase volumetric capacities to ~45 g/L and gravimetric capacities to ~7 wt %. However, these systems still require liquid hydrogen for fueling and have limited dormancy.

Sorbents with very high specific surface areas and nominal hydrogen isosteric heats of adsorption can increase volumetric and gravimetric capacities at any temperature and lower pressures compared to compressed hydrogen alone. In such cases, hydrogen is adsorbed on the surfaces of the material, and any interstitial volume is filled with compressed gas. Volumetric system capacities of ~35 g/L can be achieved with sorbents—higher than what is possible with liquid hydrogen—at a storage temperature of ~100 K. If cooler temperatures of ~35 K were used, sorbent systems would have capacities well in excess of cryo-compressed systems. However, the increased isosteric heats of adsorption at all temperatures must be removed during filling and nominal amounts of heat must be provided during delivery to remove the hydrogen from the sorbent. These added issues must be balanced against the increased capacities obtained with sorbents, along with the similar dormancy and hydrogen cost issues associated with cryogenic temperatures.

To enable higher capacities at temperatures near ambient, the hydrogen must be bound more strongly. Metal and chemical hydrides achieve this by forming chemical bonds with atomic hydrogen (compared to the molecular hydrogen typically associated with compressed, liquid, or sorbent storage systems). Metal hydrides typically dissociate molecular hydrogen and release heat during filling. Thus, some metal hydrides can be refilled onboard the vehicle; however, higher capacity generally requires stronger binding and more heat has to be removed during fueling. In addition, metal hydride kinetics near ambient temperature may be slow and require substantial times for refueling. Also, metal hydrides may require temperatures higher than 200°C to deliver hydrogen. Other metal hydrides such as alanes must be regenerated off-vehicle because they require high pressures and temperatures. Chemical hydrides are generally regenerated off-vehicle because complex chemical processes are typically involved. Off-vehicle regeneration requires technologies to fill the tank and remove the spent products. Shipping of the hydrides and spent materials requires additional costs and technology as well. In addition, chemical hydrides typically release heat and contaminants when hydrogen is delivered, both of which impact storage system capacity and costs.

Table 10. Comparison of Hydrogen Storage Technologies Capabilities to Key Performance Needs for MHE

Need	Mean	Units	Metal Hydrides	Chemical Hydrides	Sorbents	Compressed	Liquid H_2	Cryo-compressed	Reference	Comments
Shock and Vibration	3 - 15	g	TBD	TBD	TBD		TBD	TBD		
Reliability/Availability	127	hours/ week	TBD	TBD	TBD	TBD	TBD	TBD		Need high up time in week (e.g. 2-3 hours for maintenance per 500 operation hours)
MTTR	2	hours	TBD	TBD	TBD		TBD	TBD		
Greenhouse Gas Emissions			14	63	20	14	20-40	20	2	kg-CO2 eq/kg-H2 Likely zero emissions required
Operation Temperature (Min)	-40	^oC								
Operation Temperature (Max)	60	^oC								
Fill Rate	3	minutes	3 to 10	<2	<2	<2	<2	<2	2	Assume a fill of 2 kg for a fill rate of 0.7 kg/min
Warranty	3	years	TBD	TBD	TBD		TBD	TBD		
Maintenance Costs	4420	$/vehicle /year	TBD	TBD	TBD	TBD	TBD	TBD		Per vehicle, energy storage is a small percentage
Storage Capacity	9	hours								
Volume	387	liters	800 Wh/l	1700 Wh/l	1200 Wh/l	700 Wh/l	800 Wh/l	1400 Wh/l	1, 2, 3	Value for entire system - Assume 30% available for Storage (~1200 Wh/l) Liquid vol capacity better if dormancy is not an issue
Weight	1190	kg	~2 wt%	~5 wt%	~6 wt%	~5 wt%	~6 wt%	5 to 9 wt%	1,2, 3	Value for entire system - assume 50% available for storage (~0.8 wt%) Liquid wt% better if dormancy is not an issue
Storage System Costs		$/kWh	8	5	12	12	5	8	4	
Well to engine efficiency		%	10 to 45	10 to 20	40	55	22	40	2	WTE Eff. (%)

1. Assumes 10 kW power plant operating at ~ 50% efficiency
2. Compilation of results primarily from ST001 presentation by R. Ahluwalia for light duty vehicles at the DOE 2011 Fuel Cell Technology Program Review, May 9-13, 2011; may not be representative for technologies developed specifically for a SV market.
3. The weight and volume values assumed to be for entire system and estimate 30% weight and 50% volume available for stoarge
4. Compilation of results primarily from ST002 presentation by K. Law for light duty vehicles at the DOE 2011 Fuel Cell Technology Program Review, May 9-13, 2011; may not be representative for technologies developed specifically for a SV market.

Table 11. Comparison of Hydrogen Storage Technologies Capabilities to Key Performance Needs for Public Transit

Need	Mean	Units	Metal Hydrides	Chemical Hydrides	Sorbents	Compressed	Liquid H_2	Cryo-compressed	Reference	Comments
Environment			TBD	TBD	TBD	TBD	TBD	TBD		
Storage Capacity	9	hours								
Fill Rate	7	minutes	6 - 80	6 - 12	6 - 12	6 - 12	6 - 12	6 - 12	2	Assume 30 kg onboard for a fill rate of ~ 4 kg/min
Shock and Vibration			TBD	TBD	TBD	TBD	TBD	TBD		
Operation Lifetime	11	years	TBD	TBD	TBD		TBD	TBD		
Maintenance Costs	14250	$/vehicle /year	TBD	TBD	TBD	TBD	TBD	TBD		
Reliability/Availability	112	hours/ week	TBD	TBD	TBD		TBD	TBD		1 fill per day, assumed 5,000 fills over lifetime
Preventative Maintenance Frequency	3	day/vehicle/ month	TBD	TBD	TBD		TBD	TBD		
MTTR	3	hours	TBD	TBD	TBD		TBD	TBD		
Weight										
Storage System Costs		$/kWh	8	5	12	12	5	8	3	
Well to engine efficiency		%	10 to 45	10 to 20	40	55	22	40	2	WTE Eff. (%)

1. Assumes 100 kW power plant operating at ~ 50% efficiency
2. Compilation of results primarily from ST001 presentation by R. Ahluwalia for light duty vehicles at the DOE 2011 Fuel Cell Technology Program Review, May 9-13, 2011; may not be representative for technologies developed specifically for a PT market.
3. Compilation of results primarily from ST002 presentation by K. Law for light duty vehicles at the DOE 2011 Fuel Cell Technology Program Review, May 9-13, 2011; may not be representative for technologies developed specifically for a PT market.

Table 12. Comparison of Hydrogen Storage Technologies Capabilities to Key Performance Needs for AV

Need	Mean	Units	Metal Hydrides	Chemical Hydrides	Sorbents	Compressed	Liquid H_2	Cryo-compressed	Reference	Comments
Storage Capacity	11	hours							1, 3	~34 kg
End-of-Life Costs	300	$	TBD	TBD	TBD	TBD	TBD	TBD		
Reliability/Availability	84	hour/ week	TBD	TBD	TBD	TBD	TBD	TBD		
Shock and Vibration		g	TBD	TBD	TBD	TBD	TBD	TBD		
Volume	637	liters	800 Wh/l	1700 Wh/l	1200 Wh/l	700 Wh/l	800 Wh/l	1400 Wh/l	1, 2, 3	Entire system - assume 1800 Wh/l needed[3,4]
MTTR	28	hours	TBD	TBD	TBD	TBD	TBD	TBD		
Storage System Costs		$/kWh	8	5	12	12	5	8	4	
Well to engine efficiency		%	10 to 45	10 to 20	40	55	22	40	2	WTE Eff. (%)

1. Assumes 50 kW power plant operating at ~ 50% efficiency
2. Compilation of results primarily from ST001 presentation by R. Ahluwalia for light duty vehicles at the DOE 2011 Fuel Cell Technology Program Review, May 9-13, 2011; may not be representative for technologies developed specifically for a SV market.
3. The capacity in terms of run time was used to calaculate the amount of fuel needed (~34 kg 1800 Wh/l).
4. Compilation of results primarily from ST002 presentation by K. Law for light duty vehicles at the DOE 2011 Fuel Cell Technology Program Review, May 9-13, 2011; may not be representative for technologies developed specifically for a SV market.

3.4.1 Specialty Vehicles

The results from the questionnaires of whether the storage technologies will meet the must-have attributes of shock and vibration, reliability/availability, and MTTR are all inconclusive. Additional testing is needed to understand if a particular technology is more suited for the MHE environment, with the exception of compressed storage tanks. The MHE market does have experience with fuel cell and hydrogen technologies, primarily with onboard compressed hydrogen storage.

The need for reliability and availability was given in the number of hours per week the system is expected to be operational. Using this value (127 hours/week) along with the continuous runtime requirement of 9 hours and operation lifetime of 10 years, the onboard storage systems could experience 7,000 fill cycles. This number could be even higher if a runtime of 4–5 hours between fills is used for the estimate, based on feedback from the workshop discussions on MHE needs. Each technology may have different strategies to meet the required reliability and availability; for example, chemical hydrides may need to be replaced or replenished offsite periodically or the high number of cycles may require multiple recertification over the operation period of the onboard storage system.

An attribute that is closely connected to reliability is MTTR. The expectation for MTTR is 2 hours, so special considerations for repairing storage technologies (if necessary) are whether repairs can be made onsite or offsite, system complexity, and special handling requirements such as material safety procedures, toxicity, flammability, and pyrophoricity.

Another must-have MHE attribute is greenhouse gas emissions, which are assumed to be zero, particularly for indoor MHE facilities. Factors impacting the well-to-engine emissions include how the hydrogen is produced, transported, compressed, stored, and regenerated, as well as individual storage technology efficiencies. Most of these factors do not relate directly to the onboard energy storage system capabilities. The linear attribute of warranty is another example where there is a need for additional information, specifically with respect to reliability and preventative maintenance needs of the different storage technologies.

The operation temperature requirement range is –40°C to 60°C. The hydrides need additional testing to understand how these extreme low and high operation temperatures would impact performance. This is another attribute for which different operation strategies can be implemented to ensure operation.

Most of the storage technologies can be engineered to meet the fast fill times. Metal hydride is the only technology for which the fill rate is dominated by the material properties. The fill times per storage technology were calculated based on a fill amount of 5 kg, but the fill amounts for MHE will likely be 2.5 kg or less. Fill rate is not likely a major hurdle for the storage technologies for MHE.

The other linear attribute of maintenance cost is provided as cost per entire vehicle. The available maintenance cost for onboard storage from the total is likely to be a very small percentage and connected to the expectation of high reliability and low preventative maintenance for the storage systems. Maintenance features that may add to the cost include regeneration of metal hydrides, toxic gas and purity filters for chemical hydrides, and regeneration of sorbents.

An attribute that was not included in the Kano question set, but is a known key attribute, is capital and operation costs. The end user is unlikely to distinguish between energy storage costs and the entire drive system costs, so low equipment cost is important. An annualized cost of ownership analysis for the ARRA and Defense Logistics Agency (DLA) MHE demonstrations indicates that per lift the cost of infrastructure for fuel cell MHE is more than 2.5 greater than for a battery MHE in class I or II (Kurtz et al. 2011d).

Hydrides have low equipment costs compared with compressed and sorbents technologies but higher fuel costs. Fuel cost is also a key need for the daily operation of these systems, but most of the factors affecting fuel costs, except for well-to-drive system efficiency, are not influenced by the type of storage technology.

Another important aspect of cost is the availability of commercial off the shelf products. None of the fuel cell system original equipment manufacturers (OEMs) present at the workshops expressed an interest in designing a storage system that involves any basic research or extensive engineering time. Compressed gas cylinders have an advantage in that they may be purchased on the open market today.

3.4.2 Public Transit

The results of whether the storage technologies will meet the must-have attributes of shock and vibration, reliability/availability, maintenance, operation lifetime, and MTTR are all inconclusive. Additional testing is needed to understand if a particular technology is more suited for the public transit environment, with the exception of compressed storage tanks. The public transit market does have experience with fuel cell and hydrogen technologies, primarily with onboard compressed hydrogen storage (carbon fiber tanks). Refer to the discussion in Section 3.5 for detailed discussion on the different performance needs as there is significant overlap between the public transit and MHE performance needs.

3.4.3 Autonomous Vehicles

Due to the low number of responses and varied operation conditions, the market-specific performance needs are not clearly identified. Some general performance metrics overlap with MHE and public transit performance needs, but few conclusions about the comparison of hydrogen storage technology capabilities and the performance needs of the AV market can be made.

3.5 Summary

The questionnaire and workshop results show some common performance needs, a few application specific needs, and operation ranges that are very application specific. The top five must-have attributes (along with a few key linear attributes) are summarized in Table 13.

Table 13. Summary of Key Performance Attributes by Application

MHE	Public Transit	AV
Shock and vibration	Environment	Storage capacity
MTTR	Storage capacity	End-of-life costs
Reliability/availability	Fill rate	Reliability/availability
Greenhouse gas emissions	Shock and vibration	Shock and vibration
Operation temperature	Operation lifetime	MTTR
Fill rate, maintenance costs, and storage capacity	Maintenance costs, reliability/availability, preventative maintenance frequency, and MTTR	Fill rate, operation temperature, maintenance cost, preventative maintenance frequency, and warranty

Refer to Figure 9 through Figure 13 for the operation range of the key performance metrics by application. These figures identify the mean, maximum, minimum, and 25th and 75th percentiles for the responses in each application.

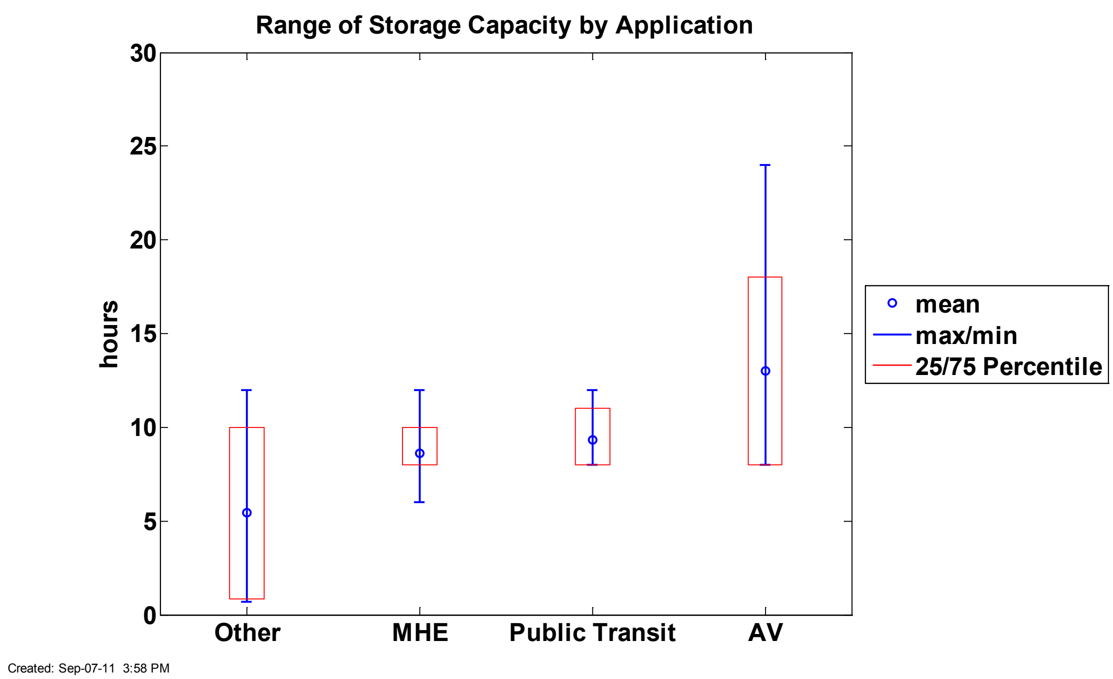


Figure 9. Continuous runtime between fill by application

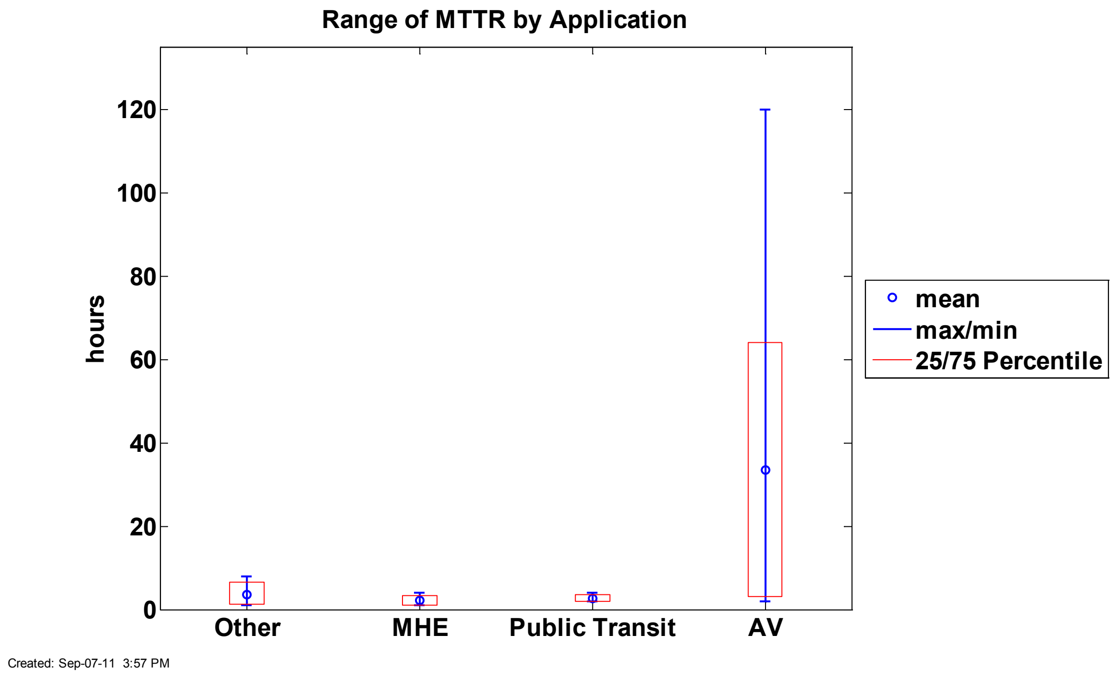


Figure 10. Range of MTTR by application

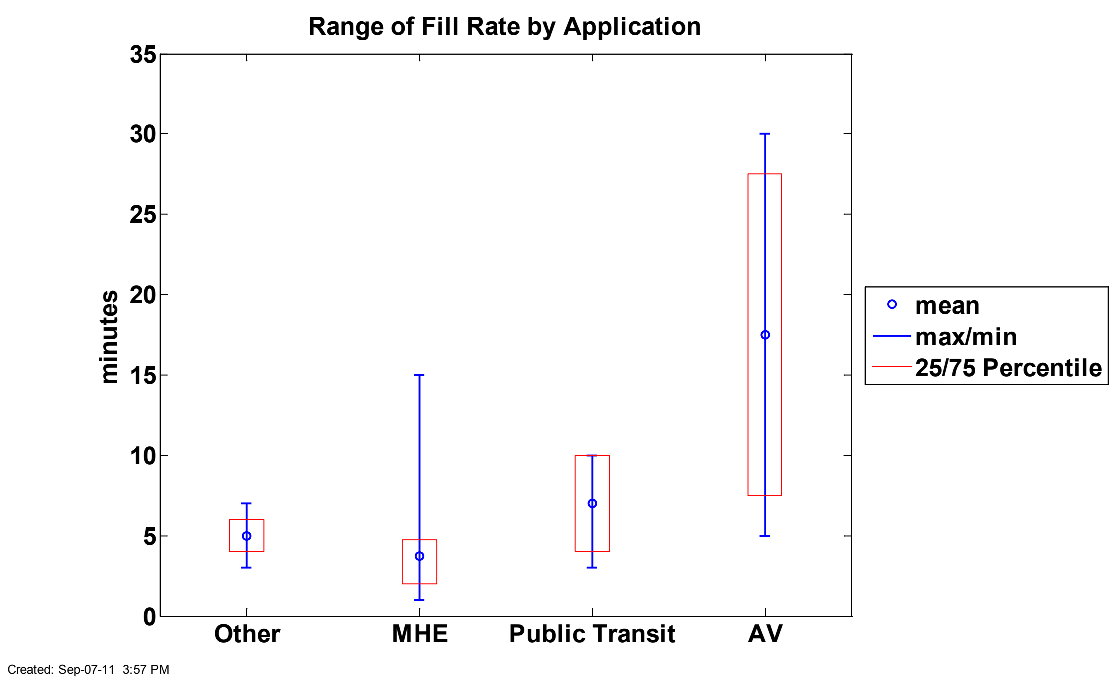


Figure 11. Fill rate ranges by application

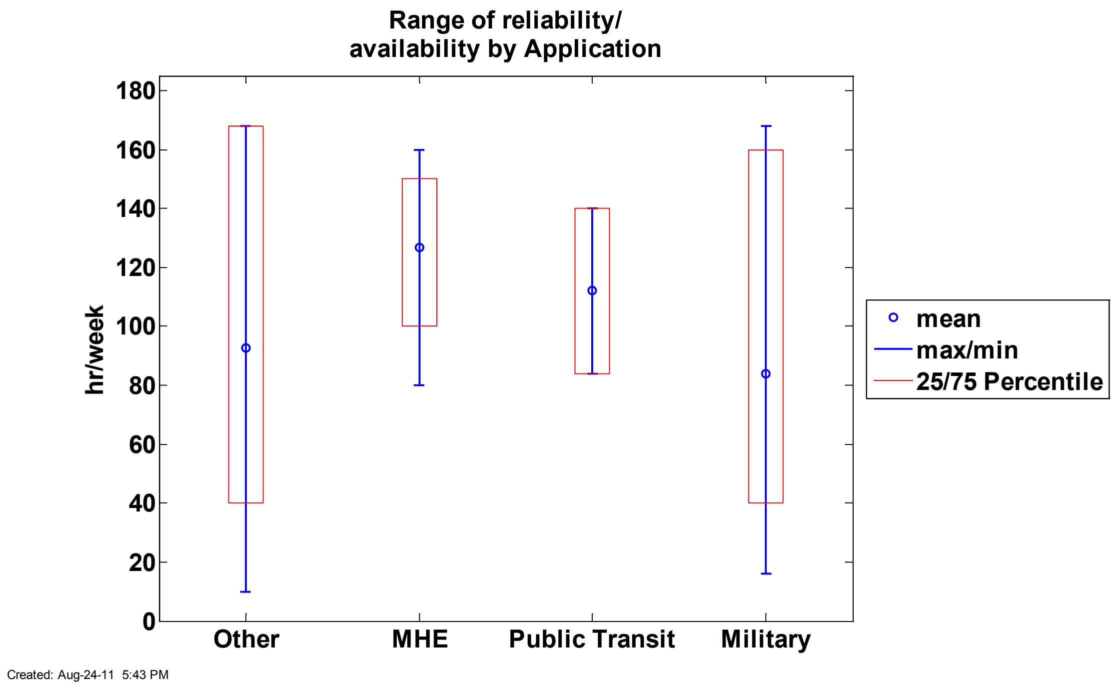


Figure 12. Operation hours per week by application

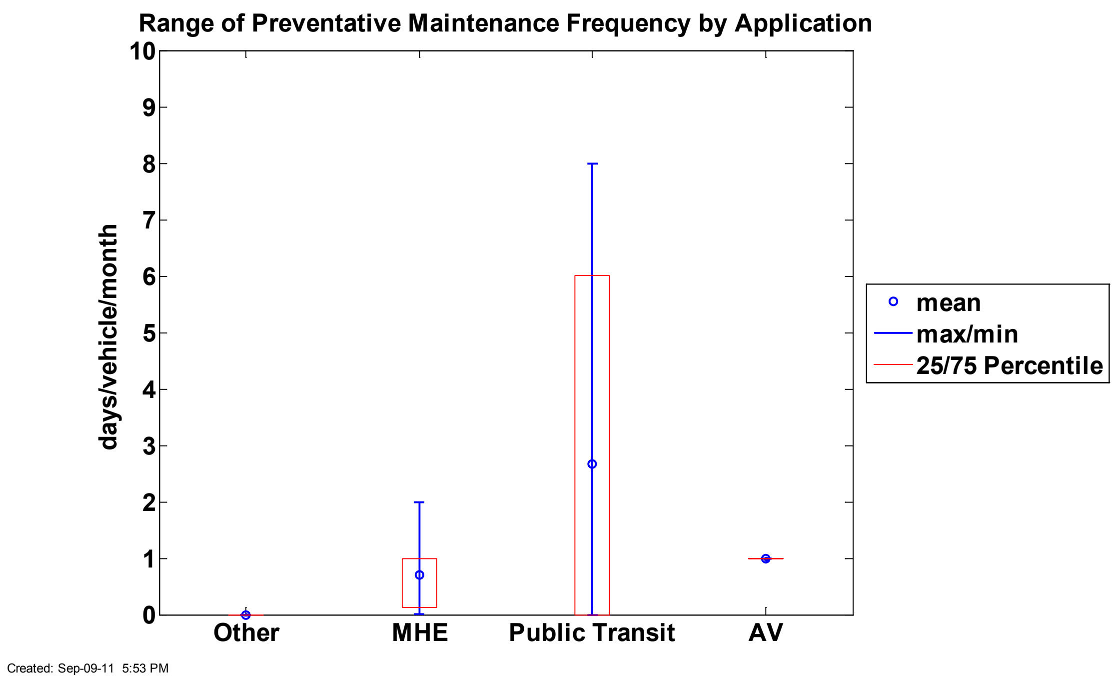


Figure 13. Range of preventative maintenance frequency by application

4 Recommendations

A few common topics across the applications were either discussed in the workshops or identified as key performance needs in the Kano results. One of the common topics focused on the incumbent technologies in MHE and public transit markets. These markets have incumbent technologies that are well established, familiar, and generally simple. If an alternative technology is to compete in those markets, it must have similar or better performance capabilities than the incumbent. Simple, flexible, safe, low capital and operation costs, and robustness were all used to describe how an alternative technology must operate to compete in these well-established markets. These markets generally operate on thin profit margins and tend to be risk averse. Therefore, any onboard storage technology should meet the end user's expectations that are based on experience with incumbent technologies. Particular attention should be given to onboard storage technologies that, from the operator's perspective, are easy to use, safe, simple, and effective.

Another topic that came up frequently is how hydrogen infrastructure cost and complexity can hinder market acceptance of hydrogen fuel cell technologies in markets because a site with a small fleet size may not see a benefit with the high capital cost (Kurtz et al. 2011d). Challenges for high-pressure (~200 bar and higher) hydrogen infrastructure include hydrogen compression, storage, frequent fills in rapid succession, reliability, and capital and operation costs. Particular attention should be given to onboard storage technologies that could decrease infrastructure complexity and cost (e.g., near ambient pressure hydrogen storage options) and still satisfy the other end user performance needs.

These near-term markets, end users, and technology OEMs are not interested in long, involved product development cycles on equipment with low technology readiness levels or low manufacturing readiness levels. Compressed hydrogen storage tanks (steel and carbon fiber) are meeting many of the performance needs for these markets. However, one reason compressed tanks are the most commonly used onboard storage system is that no other validated hydrogen storage technology is readily available. Consideration should also be given to onboard storage technologies with overlap across the different markets to leverage R&D investments. The close relationship to the fuel cell system should not be overlooked. Collaboration between fuel cell OEMs and storage OEMs could result in integration gains with overall weight and volume.

4.1 Specialty Vehicles

Compressed tanks are capable of satisfying many of the performance needs of the MHE market, and a number of DOE funded projects have hydrogen fuel cell MHE utilizing steel and carbon fiber tanks (250–350 bar) in field demonstrations. However, there is potential for performance gains by developing alternative hydrogen storage technologies to

- Lower storage system costs
- Simplify infrastructure with the potential for no compressor without much additional training and safety procedures compared to compressed tanks.

Key performance attributes that require R&D include high cycling, MTTR, preventative maintenance, and shock and vibration. Many of these would be best validated in real-world operation.

The DOE funded fuel cell MHE projects provide a reference for the current hydrogen technology capabilities. The performance status results supplement the questionnaire and workshop results for a more complete picture of the SV performance needs. (Refer to http://www.nrel.gov/hydrogen/proj_fc_market_demo.html for all publications and results.) For example, the current systems store between 0.5 and 2 kilograms of hydrogen for Class I, II, and III forklifts. Class III are the lowest power and smallest onboard hydrogen amounts. The average fill rate is 0.3 kg/min from 86,016 fill events (see Figure 14) where the average fill amount is 0.5 kg and just under 2 minutes for filling. The maximum continuous run time capability is dependent on the fuel cell system efficiency, amount of stored hydrogen, and operating conditions. Figure 15 depicts operation time between fills with the distribution of all fills and the average of just over 5 hours between fills. The insert graph highlights the range of averages per site from greater than 3 hours to less than 8 hours.

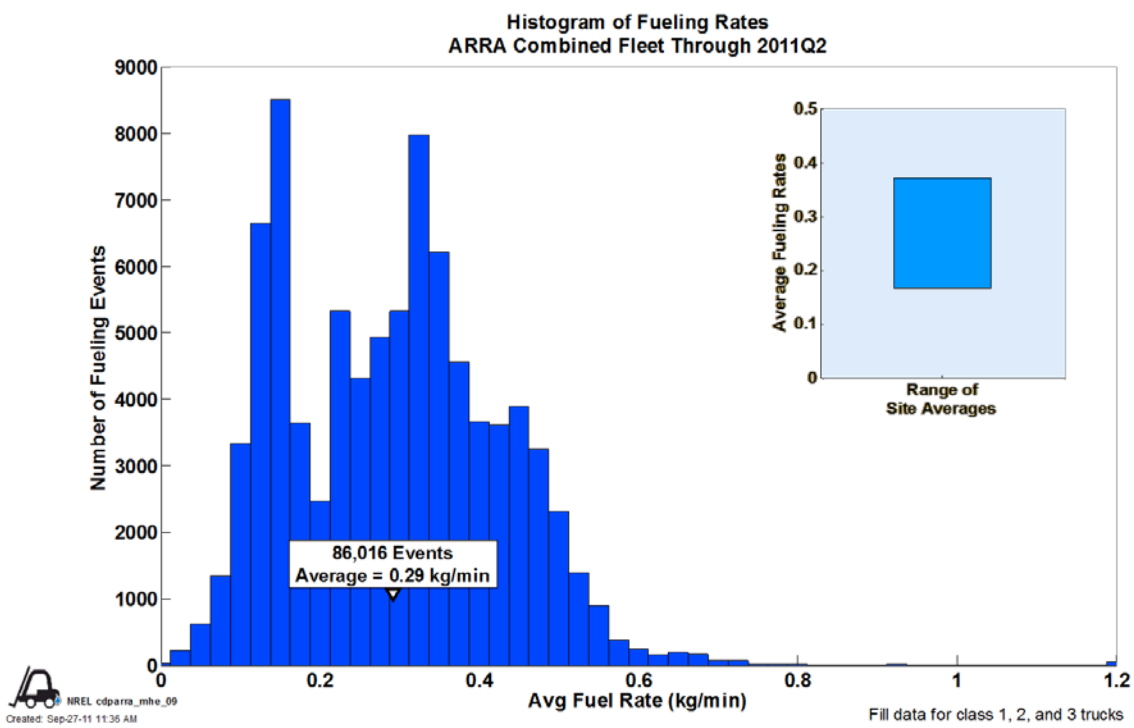


Figure 14. Histogram of fueling rates for MHE units
(Kurtz et al. 2011e)

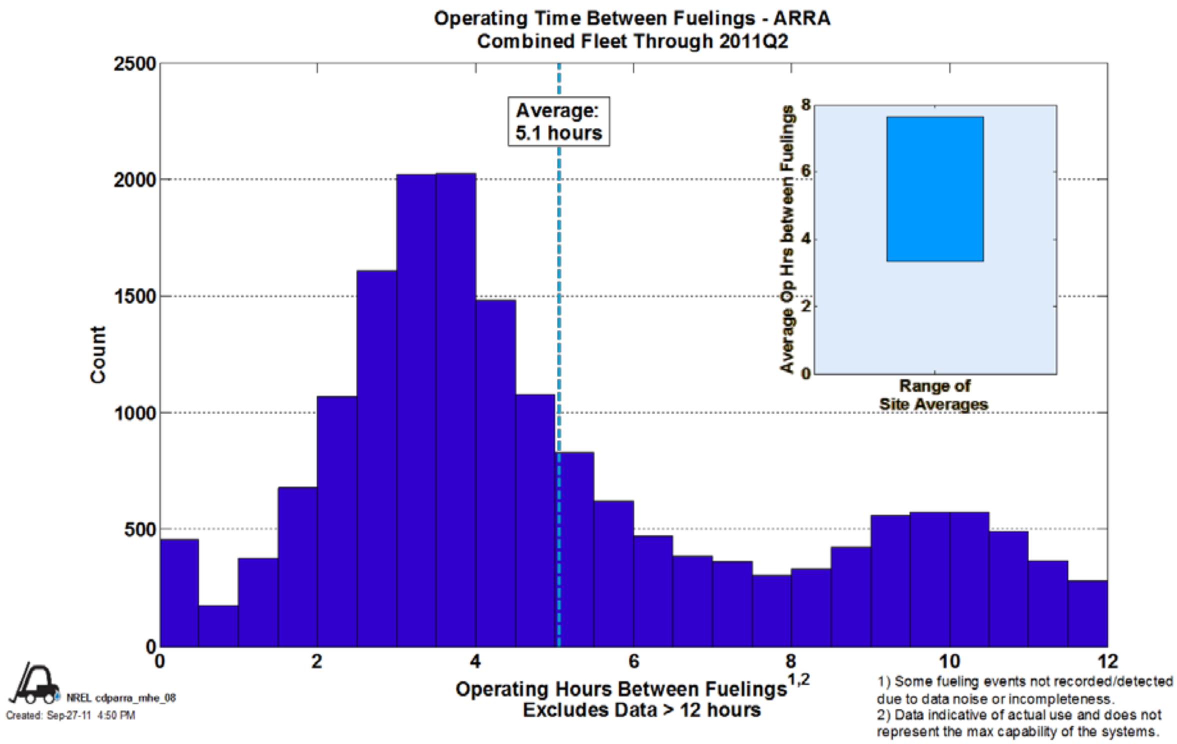


Figure 15. Operating hours between fuelings
(Kurtz et al. 2011g)

The average operation time between fills fits with the average daily operation for the fleets, which range from approximately 3 to 8 hours. Most fleets average one fill per day per system (see Figure 16). The kilograms dispensed per day is dependent on the fleet size and ranges from 10 to 40 kilograms.

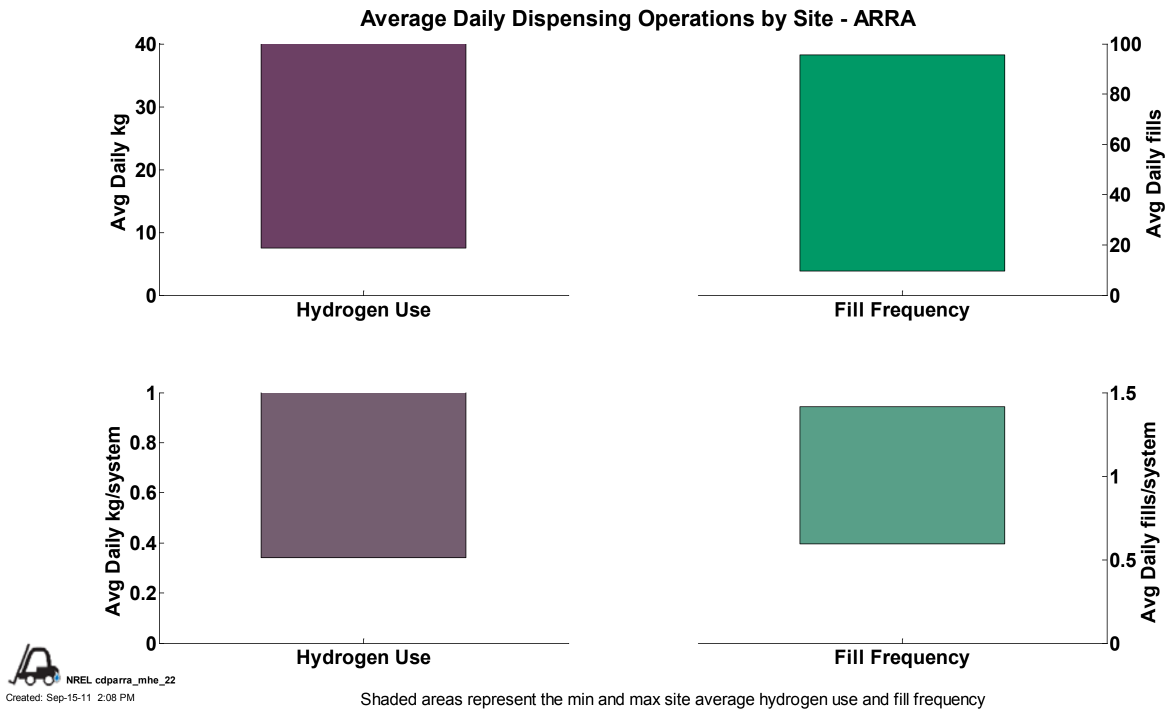
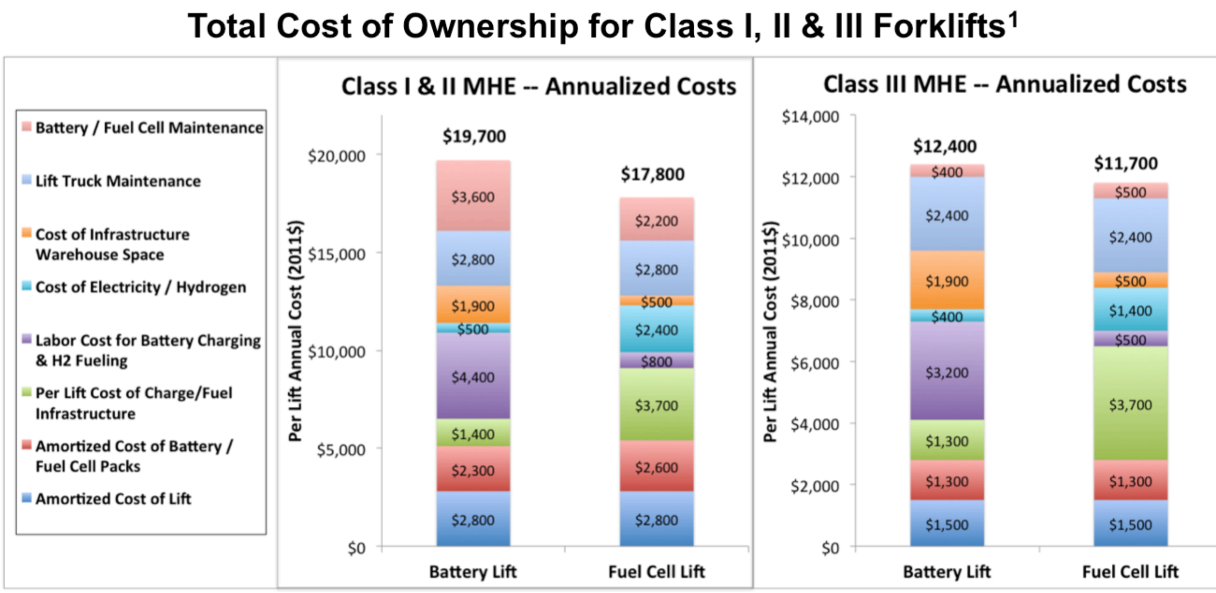


Figure 16. Range of average daily kilograms of hydrogen fill frequency and amount dispensed for the fleets
(Kurtz et al. 2011c)

A cost of ownership analysis of the facilities operating fuel cell MHE indicates there is a strong relationship between fleet size and hydrogen demand to the cost benefits of fuel cell MHEs over battery MHEs. Cost benefits depend on fleet size and utilization, primarily due to amortization of infrastructure costs based on different levels of hydrogen usage. Current data (see Figure 17) already shows a strong advantage of fuel cell MHE to battery-powered MHE in high use facilities. The cost of ownership analyses breakdown major cost components and reflect many parameters, such as maintenance and productivity improvements due to reduced labor time for hydrogen filling versus a battery change out. Infrastructure cost differential between battery and fuel cells increases as the number of units in a fleet decreases making the capital cost of hydrogen infrastructure a limiting factor for fleets with only a few MHEs.



(1) Total cost represents the annualized cost of ownership of Class I, II, and III forklifts on a net present value basis, accounting for capital, operating, and maintenance costs of forklifts, power packs, and infrastructure (labor costs for maintenance and for charging or fueling are included, but labor costs of forklift material handling operations are excluded). Costs are calculated assuming that the material handling operations are ongoing, with equipment replacements made as necessary. Capital, operating, and maintenance costs are assumed to remain constant in real-dollar terms, and capital purchases are discounted using a discount rate representing the time value of money. Fuel cell system costs reflect the current fuel cell tax credit of $3,000/kW or 30% of purchase price. Analysis does not consider the potential productivity increases resulting from the constant power output of fuel cell systems, which may be significant. Costs of ownership of Class II forklifts are expected to be similar for Class I forklifts, though the cost of the lift itself is expected to be higher.

NREL cdp_mhe_58
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Costs are based on information provided by deployment host partners (end-users) based on a questionnaire developed by NREL, supplemented with data provided by project partners, and are reflective of the material handling operations of these deployments. Where appropriate, fuel cell deployment data were used in place of end-user questionnaire data; in particular, data from CDPs 1, 6, 8, 14, and 22 were used. Cost assessment will be further refined as additional data are available.

Figure 17. Annualized cost of ownership for battery and fuel cell forklifts with the breakdown of major cost components
(Kurtz et al. 2011d)

Table 14 summarizes key performance needs for the SV market using a combination of workshop, questionnaire, and demonstration performance data.

Table 14. SV Performance Needs

Need	Value	Comments
Volume	<120 liters	0.5–2 kg current onboard capacity for fuel cell MHE units (Class I, II, and III) ~ 1,200 Wh/L
Cycles (operation life)	5,000–10,000 fills	~10 years
Fill rate	<0.7 kg/min	3 min fills
Shock and vibration	3–15 g	
Ambient temperature	-40°C to 60°C	
Operation temperature		Safe for close proximity to operators
Reliability/Availability		Need high up time in week (e.g. 2–3 hours for maintenance per 500 operation hours)
Environment		Operating environment includes humidity, dirt, air and floor particles
Cost		See Figure 17 for annualized system costs

4.2 Public Transit

Compressed (carbon fiber) tanks are capable of satisfying many of the performance needs of the public transit market. A number of DOE/U.S. Department of Transportation funded projects have hydrogen fuel cell buses in field demonstrations. However, there is potential for performance gains by developing alternative hydrogen storage technologies to

- Lower storage system costs
- Simplify infrastructure with the potential for no compressor without much additional training and safety procedures than compressed tanks
- Improve relatively good volumetric capacity and weight (and therefore increased passenger capacity and route capability)
- Increase scalability (ability to fills of multiple buses sequentially without a decrease in fill amount or time).

Key performance attributes that require R&D include high cycling, MTTR, preventative maintenance, and shock and vibration. Many of these would be best validated in real world operation.

4.3 Autonomous Vehicles

The AV market is smaller and not as well established as the other two markets analyzed in this report and the market-specific performance needs are not as clearly identified. Some general performance metrics overlap with MHE and public transit performance needs, so the AV market may be able to capitalize on the development of advanced hydrogen storage technologies developed for other early market applications.

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Appendix A. Workshop Agendas

Workshop: Onboard Energy Storage Performance Needs for Material Handling Equipment

Wednesday, February 16, 2011 — Gaylord National Hotel and Conference Center, National Harbor, MD

Agenda

Afternoon Session

1:00-1:20 pm	**Introduction** (with lunch)
1:20-2:30 pm	**BREAKOUT SESSION 1: How does onboard energy storage impact an application's key performance needs?** MHE, Public Transit, and Other
2:30-2:50 pm	***Break and Questionnaire***
2:50-3:40 pm	**BREAKOUT SESSION 2: What are the key gaps and opportunities to improve onboard energy storage technologies?** MHE, Public Transit, and Other
3:50-4:15 pm	**Breakout Session Summary**
4:15-4:55 pm	**End User and Expert Panel Q&A** Panel Members (TBD) from public transit, military, MHE, hydrogen storage, and DOE
4:55-5:00 pm	**Wrap-up**
5:00 pm	***Adjourn***

Organized by the National Renewable Energy Laboratory and the U.S. Department of Energy

In conjunction with 2011 Fuel Cell and Hydrogen Energy Conference

Workshop: Onboard Energy Storage Performance Needs for Material Handling Equipment

March 21, 2011 McCormick Place South • Chicago Illinois

Agenda

Morning Session

8:15 am ***Registration/Check-in and coffee, Room 501 B/C***

8:45 am **Workshop Overview**

Chris Ainscough, National Renewable Energy Laboratory

9:15 am **Breakout Discussion Session:**

- **Focus Question 1:** What are the key performance needs for your material handling equipment?
- **Focus Question 2:** How could advanced onboard energy storage technology improve the performance of your vehicles or operations?
- **Energy Storage Questionnaire**

11:15 am ***Break***

11:30 am

LUNCH *(provided, for both morning and afternoon session participants)*

Expert Panel Presentations and Q&A

- **Brian Nowicki,** Nuvera Fuel Cells
- **Eric Jensen,** Crown Equipment Corporation
- **Frank Devlin,** The Raymond Corporation
- **Sanjiv Malhotra,** Oorja Protonics

1:30 pm ***Adjourn***

Sponsored by the National Renewable Energy Laboratory (NREL) of the US Department of Energy

In conjunction with ProMat 2011

Workshop: Onboard Energy Storage Performance Needs for Material Handling Equipment

March 21, 2011 McCormick Place South • Chicago Illinois

Agenda

Afternoon Session

11:15 am ***Registration/Check-in, Room 501 B/C***

11:30 am ***LUNCH*** *(provided, for both morning and afternoon session participants)*

Expert Panel Presentations and Q&A

- **Brian Nowicki,** Nuvera Fuel Cells
- **Eric Jensen,** Crown Equipment Corporation
- **Frank Devlin,** The Raymond Corporation
- **Sanjiv Malhotra,** Oorja Protonics

1:30 pm ***Break***

1:45 pm

Workshop Overview

Chris Ainscough, National Renewable Energy Laboratory

2:15 pm

Breakout Discussion Session:

- **Focus Question 1:** What are the key performance needs for your material handling equipment?
- **Focus Question 2:** How could advanced onboard energy storage technology improve the performance of your vehicles or operations?
- **Energy Storage Questionnaire**

4:30 pm ***Adjourn***

Sponsored by the National Renewable Energy Laboratory (NREL) of the US Department of Energy

In conjunction with ProMat 2011

Appendix B. Questionnaires Developed by NREL in Cooperation with Sandia National Laboratories

B-1. Expert Questionnaire

Energy Storage Questionnaire

Revision B

NATIONAL RENEWABLE ENERGY LABORATORY

INSTRUCTIONS: Please answer the following questions to the best of your ability. If a question does not apply to you, or you do not have specific information on a topic, please leave the field blank, or check "N/A" as appropriate. If you have information on multiple applications, or materials, please feel free to complete a separate form for each.

About You

A. Which of the following categories best describes your organization?

- ◯ Vehicle OEM
- ◯ H2 Storage Technology Provider
- ◯ Vehicle Service Organization
- ◯ Vehicle Parts Supplier
- ◯ Government/National Lab
- ◯ Vehicle Sales Organization
- ◯ Codes & Standards Body
- ◯ University/Education
- ◯ Fuel Cell Supplier
- ◯ Systems Integrator

Other ____________

B. Which market does your organization primarily service?

- ◯ Material Handling
- ◯ Public Transit
- ◯ Military
- ◯ Airport

Other ____________

C. Which of the following best describes your responsibilities within the organization?

- ◯ Vehicle Operator
- ◯ General Management
- ◯ Fleet Maintenance
- ◯ Energy Storage Researcher
- ◯ Information Technology
- ◯ Operations Management
- ◯ Engineeering
- ◯ Legal
- ◯ Environmental Health & Safety
- ◯ Facility Management
- ◯ Consultant

Other ____________

Tell us about your energy sources.

D. What do you use today?

- ◯ Gasoline
- ◯ Propane
- ◯ Hydrogen
- ◯ Diesel
- ◯ Battery
- ◯ Bus Bar
- ◯ Natural Gas
- ◯ Methanol
- ◯ Ethanol/E85

Other ____________ ☐ N/A

E. What would you prefer to use?

- ◯ Gasoline
- ◯ Propane
- ◯ Hydrogen
- ◯ Diesel
- ◯ Battery
- ◯ Bus Bar
- ◯ Natural Gas
- ◯ Methanol
- ◯ Ethanol/E85

Other ____________ ☐ N/A

F. What mix of vehicles do you have in your fleet, and how much power do they need? How many Class I, II, and III lifts, buses, GSE, etc. What are typical peak power rating for the engines/motors?

☐ N/A ◯ kW ◯ HP

	Qty.	Power
Class I Lift		
Class II Lift		
Class III Lift		

	Qty.	Power
Tugs		
Other GSE		
Other		

	Qty.	Power
Transit Bus ~40ft		
Coach Bus		
Para Transit		

NATIONAL RENEWABLE ENERGY LABORATORY

Energy Storage Supplier/Expert Questionnaire

1) Please select the hydrogen storage technology you are most familiar with, or is most commercially viable. Please answer the rest of this form for that particular technology.

   - ( ) 350 Bar Cyl
   - ( ) CryoCompress
   - ( ) Metal Hydride
   - ( ) Sorbent
   - ( ) 700 Bar Cyl
   - ( ) Liquid
   - ( ) Chemical Hydride
   - ( ) Other

   What particular technology will you answer this form for (e.g. MgH2, TiFeH2, Type 3 cylinders, clathrate hydrates, etc.)

As an expert in hydrogen storage technologies, how would you rate the technology in you described in Question 1 in the following areas.

2) At what stage of production is this technology?

   - ( ) Lab Based
   - ( ) Prototype Systems Available
   - ( ) Low Rate Initial Production
   - ( ) Prototype Components Available
   - ( ) Pilot Production Demonstrated

3) How many units are produced each year?

4) Does your production environment represent your predicted full-rate production?

   - ( ) Yes
   - ( ) No

For all of the remaining questions, please answer considering a complete system with balance of plant, not just the storage medium itself.

5) How do you rate the technology's ability to meet:

a)	1.5 wt%	( ) Meets	( ) Likely	( ) Possible	( ) Unlikely	( ) Will not meet
b)	2.5 wt%	( ) Meets	( ) Likely	( ) Possible	( ) Unlikely	( ) Will not meet
c)	3.5 wt%	( ) Meets	( ) Likely	( ) Possible	( ) Unlikely	( ) Will not meet
d)	4.5 wt%	( ) Meets	( ) Likely	( ) Possible	( ) Unlikely	( ) Will not meet
e)	5.5 wt%	( ) Meets	( ) Likely	( ) Possible	( ) Unlikely	( ) Will not meet
f)	7.5 wt%	( ) Meets	( ) Likely	( ) Possible	( ) Unlikely	( ) Will not meet

6) What is the maximum achievable weight % of this hydrogen storage technology?

7) What limits the maximum gravimetric capacity?

8) How would you rate the technology's volumetric capability greater than:

a) 30 g-H_2/L

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) 40 g-H_2/L

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) 70g-H_2/L

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

9) What is the maximum achievable volumetric density (g-H_2/L)?

10) What limits the maximum volumetric density?

11) How would you rate the technology's ability to fill the system in:

a) 30 minutes

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) 10 minutes

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) 3 minutes

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

12) What H_2 pressure is required for filling (psi or bar)?

◯ psi ◯ bar

13) Are there other requirements for filling (cooling, offboard regen, etc.)?

14) What is the limiting fill rate?

15) How would you rate the technology's ability to deliver H_2 at 0.25 g/sec/kg H_2 stored?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

16) What limits the delivery rate?

17) How would you rate the technology's ability to last:

a) 500 fill/discharge cycles?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) 1000 fill/discharge cycles?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) 5000 fill/discharge cycles?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

18) What factors are limiting the cycle life?

[ ]

19) How would you rate the technology's ability to deliver H_2:

a) Without impurities that degrade fuel cells and may be toxic

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) With impurities that can be removed with appropriate filtering

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) Without toxic or other impurities that affect the fuel cell

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

20) What are the impurities?

[ ]

21) What are the technology's temperature ranges?

a) What is the ambient temperature range over which the technology can operate?

[ ] to [ ] ◯ °F ◯ °C

b) What are the internal temperatures in the system during operation?

[ ] to [ ] ◯ °F ◯ °C

c) At what temperatures can a filled system be stored at?

[ ] to [ ] ◯ °F ◯ °C

22) Why are higher temperatures needed to operate the storage system?

23) What temperature is required to deliver 95% of the hydrogen?

◯ °F ◯ °C

24) Why are lower temperatures needed?

25) How would you rate the technology's ability to:

a) Not produce toxic or dangerous by-products

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

26) Other than H_2, is the storage system free of pyrophoric or toxic chemicals?

◯ Yes ◯ No

27) What kind of toxic materials may be produced?

28) What kind of pyrophoric or toxic chemicals are present?

29) How would you rate the storage system's ability to have O&M costs at:

a) Less than $5/fill

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) Less than $1/fill

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) Is ~ $0/fill

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

30) What type of maintenance is required?

31) What is the annual maintenance cost per system?

32) What is the annual preventative maintenance cost per system?

33) How would you rate the technology system costs?

a) Less than \$1000/kg-H_2 delivered

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) Less than \$500/kg-H_2 delivered

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) Less than \$250/kg-H_2 delivered

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

34) How much does a comparable energy storage system using the incumbent technology cost?

35) What would be required for a hydrogen storage system to meet this cost level?

36) What are the primary cost drivers?

37) How do you rate the technology's end of life disposal system costs?

a) Less than 20% of original system costs

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) Less than 10% of original system costs

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) Less than 1% of original system costs

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

38) What are the disposal issues at end of life?

39) What are the disposal costs ($ per system)?

40) Is the technology nearly always available when needed?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

41) Does the technology operate at or slightly beyond the edge of its specification for long periods?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

42) How often does a storage system break while in use (number of failures per month)?

43) What components are most susceptible to failure? How much do they cost to repair ($ per failure)?

44) How would you rate the technology's ability to withstand large shock and vibration loads?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

45) What are typical shock and vibration loads in your industry (Gs at Hz)?

Gs ____ at Hz ____

46) How would you rate the technology's well-to-tank efficiency from H_2 generation to fuel cell?

a) Higher than 40%

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) Higher than 60%

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) Higher than 75%

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

47) What is the primary cause of efficiency loss?

48) How much does the technology increase greenhouse gas (CO_2) emissions?

a) Less than 30 kg-CO@/kg H_2 stored/delivered

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

b) Less than 20 kg-CO@/kg H_2 stored/delivered

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

c) Less than 10 kg-CO@/kg H_2 stored/delivered

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

49) What is the major cause of CO emissions?

50) Can the technology achieve storage loses (due to dormancy) less than 0.1 g/h/kg H2 stored?

◯ Meets ◯ Likely ◯ Possible ◯ Unlikely ◯ Will not meet

51) How long can a system be unused without losing some of its capacity (days)?

B-2. End User Questionnaire

Energy Storage Questionnaire

Revision 8

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

INSTRUCTIONS: Please answer the following questions to the best of your ability. If a question does not apply to you, or you do not have specific information on a topic, please leave the field blank, or check "N/A" as appropriate. If you have information on multiple applications, or materials, please feel free to complete a separate form for each.

About You

A. Which of the following categories best describes your organization?

- ◯ Vehicle OEM
- ◯ H2 Storage Technology Provider
- ◯ Vehicle Service Organization
- ◯ Vehicle Parts Supplier
- ◯ Government/National Lab
- ◯ Vehicle Sales Organization
- ◯ Codes & Standards Body
- ◯ University/Education
- ◯ Fuel Cell Supplier
- ◯ Systems Integrator

Other ______

B. Which market does your organization primarily service?

- ◯ Material Handling
- ◯ Public Transit
- ◯ Military
- ◯ Airport

Other ______

C. Which of the following best describes your responsibilities within the organization?

- ◯ Vehicle Operator
- ◯ General Management
- ◯ Fleet Maintenance
- ◯ Energy Storage Researcher
- ◯ Information Technology
- ◯ Operations Management
- ◯ Engineeering
- ◯ Legal
- ◯ Environmental Health & Safety
- ◯ Facility Management
- ◯ Consultant

Other ______

Tell us about your energy sources.

D. What do you use today?

- ◯ Gasoline
- ◯ Propane
- ◯ Hydrogen
- ◯ Diesel
- ◯ Battery
- ◯ Bus Bar
- ◯ Natural Gas
- ◯ Methanol
- ◯ Ethanol/E85

Other ______ ☐ N/A

E. What would you prefer to use?

- ◯ Gasoline
- ◯ Propane
- ◯ Hydrogen
- ◯ Diesel
- ◯ Battery
- ◯ Bus Bar
- ◯ Natural Gas
- ◯ Methanol
- ◯ Ethanol/E85

Other ______ ☐ N/A

F. What mix of vehicles do you have in your fleet, and how much power do they need? How many Class I, II, and III lifts, buses, GSE, etc. What are typical peak power rating for the engines/motors?

☐ N/A ◯ kW ◯ HP

	Qty.	Power
Class I Lift		
Class II Lift		
Class III Lift		

	Qty.	Power
Tugs		
Other GSE		
Other		

	Qty.	Power
Transit Bus ~40ft		
Coach Bus		
Para Transit		

For each question below, consider how you would feel if the energy storage device used in your vehicles had each of the following attributes. Additionally there are follow-up questions asking you for more information about what values of certain attributes you would consider acceptable. The energy storage device is that which provides the primary source of energy for the vehicle, such as a gasoline or propane tank, battery, hydrogen tank, and the associated hardware such as filling nozzles, fuel pumps, charging receptacles, etc.

1. What is an acceptable O&M cost ($ per vehicle per year)?

   [ ]

2. How would you feel if the energy storage system in your vehicles took little time to repair when in the shop for service?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

3. How would you feel if the energy storage system in your vehicles had residual (scrap, recycling or core credit) value at end of life?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

4. How would you feel if the energy storage system in your vehicles were often not available when you need it?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

5. How would you feel if the energy storage system in your vehicles could withstand large shock and vibration loads?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

6. How would you feel if the energy storage system in your vehicles substantially increased greenhouse gas emissions?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

7. How would you feel if the energy storage system in your vehicles required frequent preventative maintenance?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

8. How would you feel if the energy storage system in your vehicles could operate in a snowy, muddy, dirty, wet, cold, hot or otherwise extreme conditions?

   ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

9. How much space does energy storage take up today (L, ft^3 or in^3)?

   [ ] ◯ L ◯ ft^3 ◯ in^3

10. How would you feel if the energy storage system in your vehicles had little or no warranty coverage?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

11. How would you feel if the energy storage system in your vehicles what types of harsh environmental conditions exist at your facility? (check each that is appropriate)

☐ mud ☐ snow ☐ dirt ☐ dust ☐ rain ☐ ice ☐ cold ☐ hot ☐ wind

☐ Hazardous (Classified per NEC Articles 500 or 505)

12. How would you feel if the energy storage system in your vehicles could not operate in a snowy, muddy, dirty, wet, cold, hot or otherwise extreme environment?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

13. What are typical shock and vibration loads in your industry?

Gs ☐ at Hz ☐

14. How would you feel if the energy storage system in your vehicles had no effect on your site emissions of regulated air pollutants (Not including CO_2)?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

15. How would you feel if the energy storage system in your vehicles could be fueled quickly?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

16. How would you feel if the energy storage system in your vehicles required the vehicle to be larger?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

17. How would you feel if the energy storage system in your vehicles cost little for operations and maintenance (O&M)?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

18. How would you feel if the energy storage system in your vehicles took a long time to repair when in the shop for service?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

19. What is an appropriate level of education for a service technician in your industry? (check all that apply)

☐ High School ☐ Some College ☐ Bachelor's Degree

☐ On-the-job Training ☐ Annual Seminar ☐ Apprenticeship

20. How much training would you consider acceptable (hours per operator per year)?

☐

21. How would you feel if the energy storage system in your vehicles had little to no impact on greenhouse gas emissions?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

22. How long should a vehicle last before being retired (years)?

[ ]

23. How would you feel if the energy storage system in your vehicles worked in a narrow temperature range?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

24. How would you feel if the energy storage system in your vehicles worked in a wide temperature range?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

25. How would you feel if the energy storage system in your vehicles had little to no impact on fuel costs?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

26. How would you feel if the energy storage system in your vehicles required extensive training to operate safely and reliably?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

27. Is the amount of down time you currently experience due to energy storage devices acceptable?

○ Yes ○ No

28. What is an acceptable fuel cost?

[ ] ○ $/gal (liquid fuel) ○ $/kWh (electric) ○ $/kg (hydrogen) ○ $/therm (Nat. Gas)

29. How would you feel if the energy storage system in your vehicles were nearly always available when you need it?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

30. What would you consider to be heavy, with respect to an energy storage system (lb or kg)?

[ ] ○ lb ○ kg

31. What would you consider to be quick fueling (minutes)?

[ ]

32. How would you feel if the energy storage system in your vehicles were covered by a long warranty?

○ Like it ○ Expect It ○ Don't Care ○ Live With It ○ Dislike It

33. How would you feel if the energy storage system in your vehicles were heavy?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

34. How would you feel if the energy storage system in your vehicles required extensive training or new personnel to service?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

35. How would you feel if the energy storage system in your vehicles took a long time to fuel?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

36. How would you feel if the energy storage system in your vehicles required minimal procedural controls to be safe?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

37. How would you feel if the energy storage system in your vehicles cost money to dispose of at end of life?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

38. How would you feel if the energy storage system in your vehicles could be serviced by your existing service technicians?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

39. How would you feel if the energy storage system in your vehicles were light?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

40. How would you feel if the energy storage system in your vehicles had to be recertified or replaced several times with in a vehicle's lifetime?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

41. How would you feel if the energy storage system in your vehicles substantially increased the cost of the fuel for storage?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

42. How would you feel if the energy storage system in your vehicles were able to operate at or slightly beyond the edge of its specification for long periods of time?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

43. How would you feel if the energy storage system in your vehicles took up less space than energy storage does today?

◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

44. How would you feel if the energy storage system in your vehicles required operator compliance procedures to be safe?

- ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

45. How would you feel if the energy storage system in your vehicles had to be filled more than once during your shift or standard operation time?

- ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

46. How much does it cost to dispose of energy storage systems? If the existing system has residual salvage value please provide that value instead. ($ per system)?

[ ] ◯ Disposal Cost ◯ Salvage Value

47. How much time dedicated to procedural controls and checklists would you consider to be acceptable (minutes per operator per day)?

[ ]

48. What would you consider to be a wide operating temperature range?

[ ] to [ ] ◯ °F ◯ °C

49. How would you feel if the energy storage system in your vehicles lasted as long as the vehicle's lifetime?

- ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

50. How long is a typical shift or standard operation time (hours)?

[ ]

51. How often is equipment in the shop today for preventative maintenance (PM) for energy storage issues? (days per vehicle per month)

[ ]

52. How much does an energy storage system cost today ($ per vehicle)?

[ ]

53. How long do you consider an acceptable warranty to be? (fill in one)

[ ] ◯ Miles ◯ Years ◯ Hours

54. How would you feel if the energy storage system in your vehicles required little training to operate safely and reliably?

- ◯ Like it ◯ Expect It ◯ Don't Care ◯ Live With It ◯ Dislike It

55. How would you feel if the energy storage system in your vehicles had high O&M costs?

- Like it
- Expect It
- Don't Care
- Live With It
- Dislike It

56. How many hours per week to you require your equipment to be available?

57. How would you feel if the energy storage system in your vehicles were rarely in the maintenance shop for preventative maintenance?

- Like it
- Expect It
- Don't Care
- Live With It
- Dislike It

58. What is a reasonable repair time (hours)?

59. How would you feel if the energy storage system in your vehicles had a run time that lasted for your entire shift or standard operation time?

- Like it
- Expect It
- Don't Care
- Live With It
- Dislike It

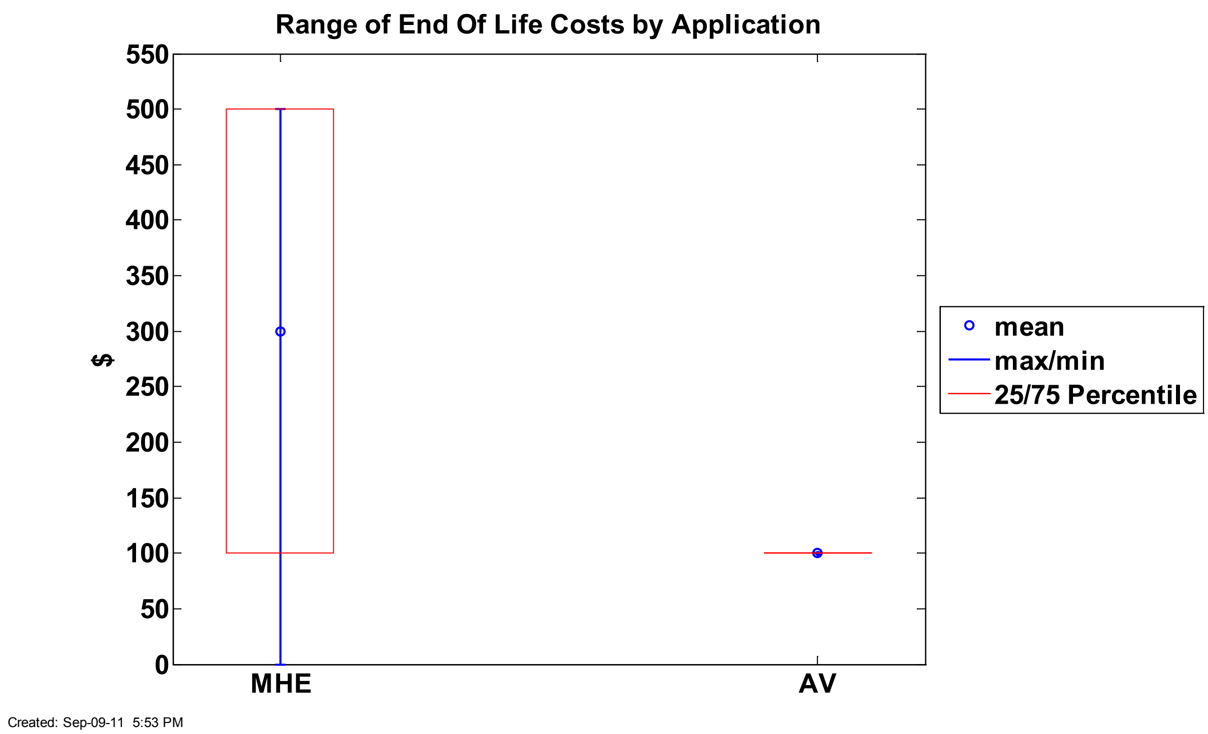
60. How would you feel if the energy storage system in your vehicles required strict operator discipline to remain within its designed performance envelope?

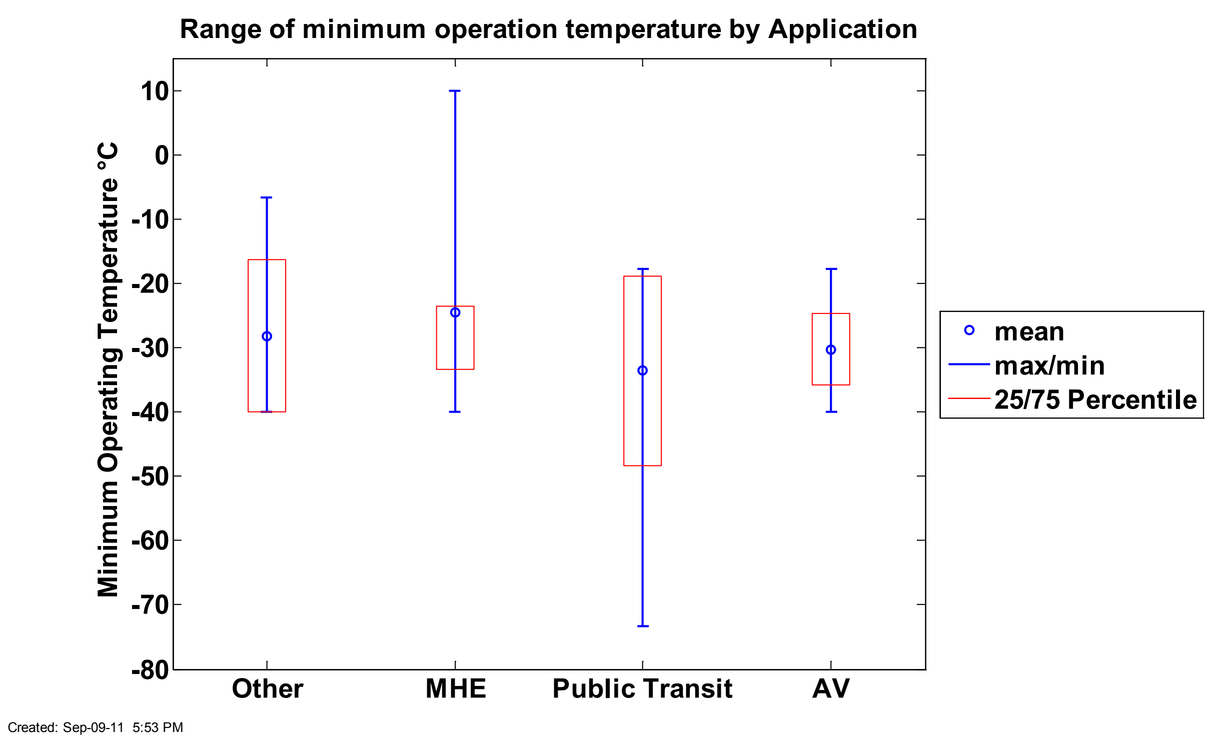
- Like it
- Expect It
- Don't Care
- Live With It
- Dislike It

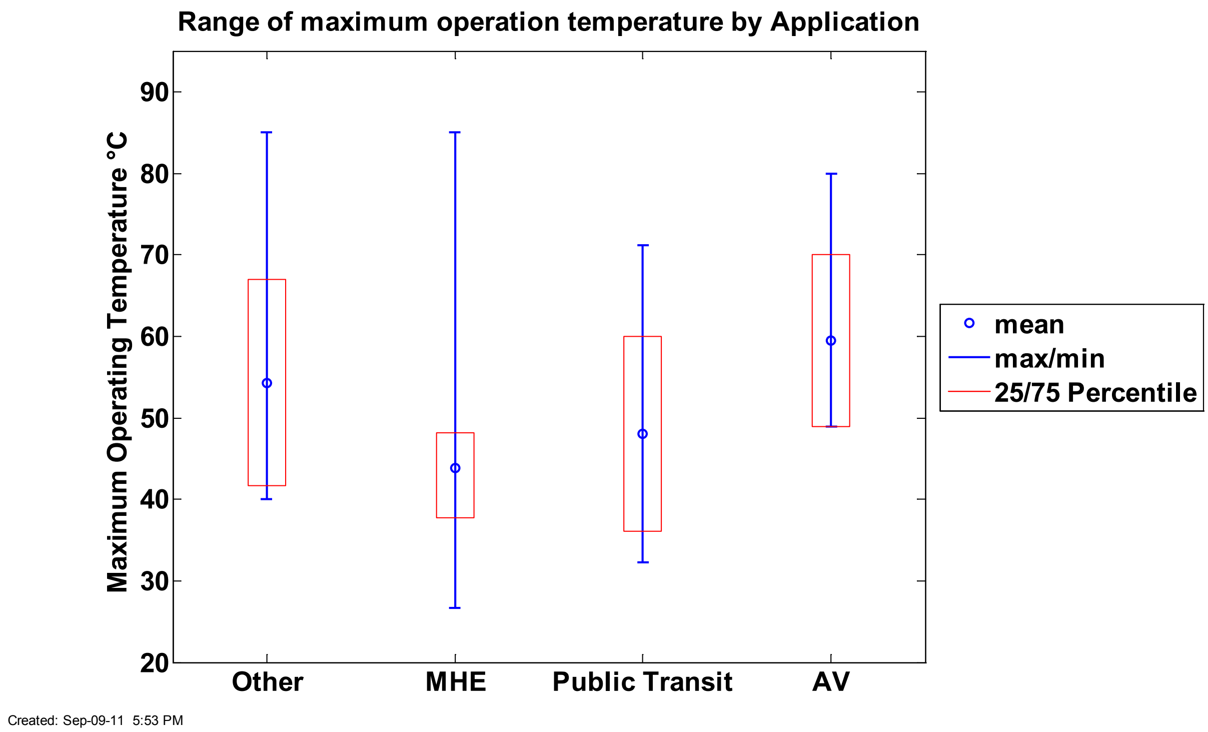
61. How would you feel if the energy storage system in your vehicles had to be treated gently to minimize vibration damage?

- Like it
- Expect It
- Don't Care
- Live With It
- Dislike It

Appendix C. Detailed Results by Application and Questionnaire Topic






Range of maximum operation temperature by Application
Maximum Operating Temperature °C
90
80
70
60
50
40
30
20
Other
MHE
Public Transit
AV
mean
max/min
25/75 Percentile
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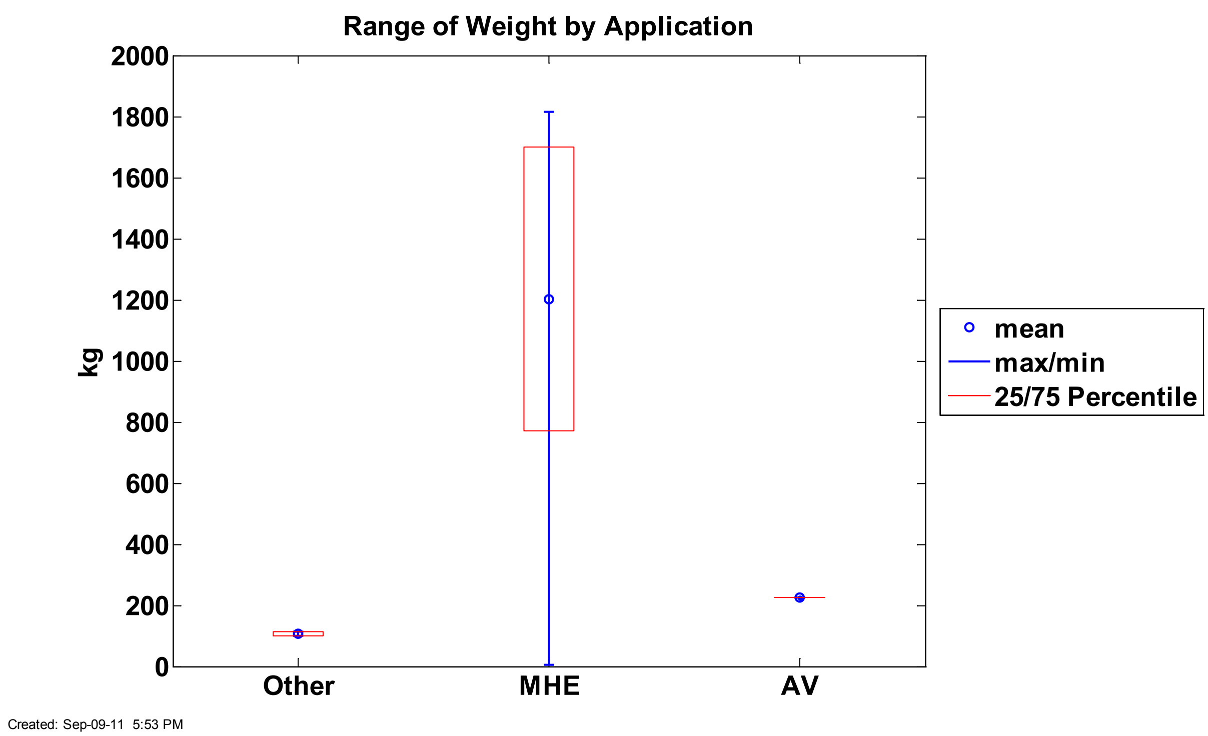
Range of Weight by Application
kg
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Other
MHE
AV
mean
max/min
25/75 Percentile
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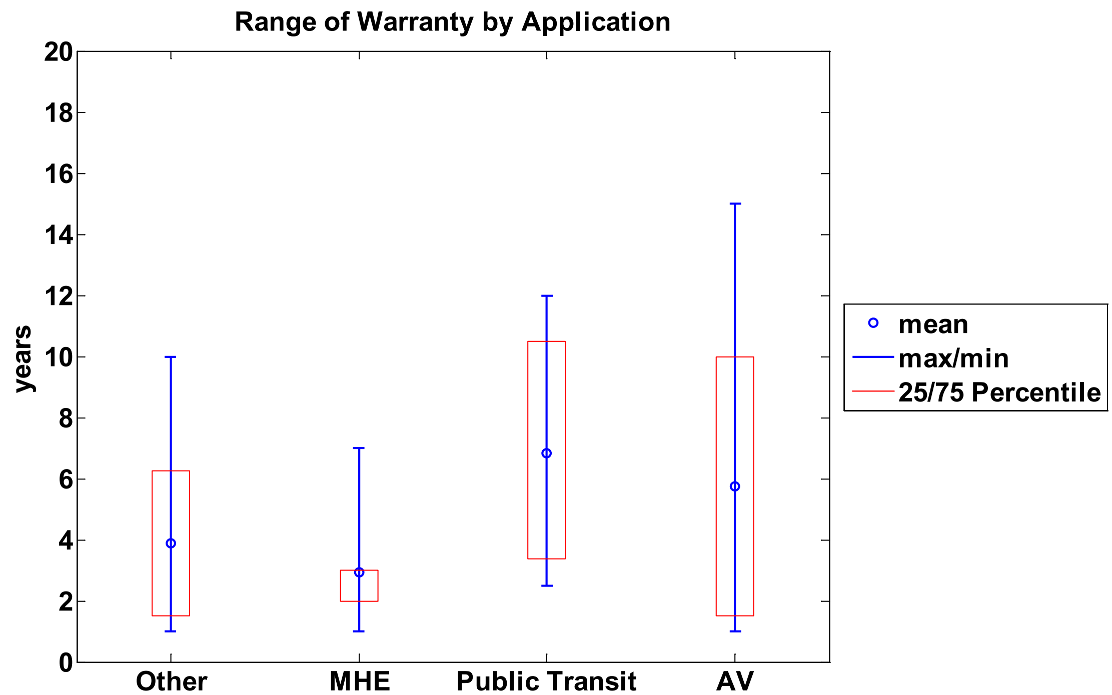

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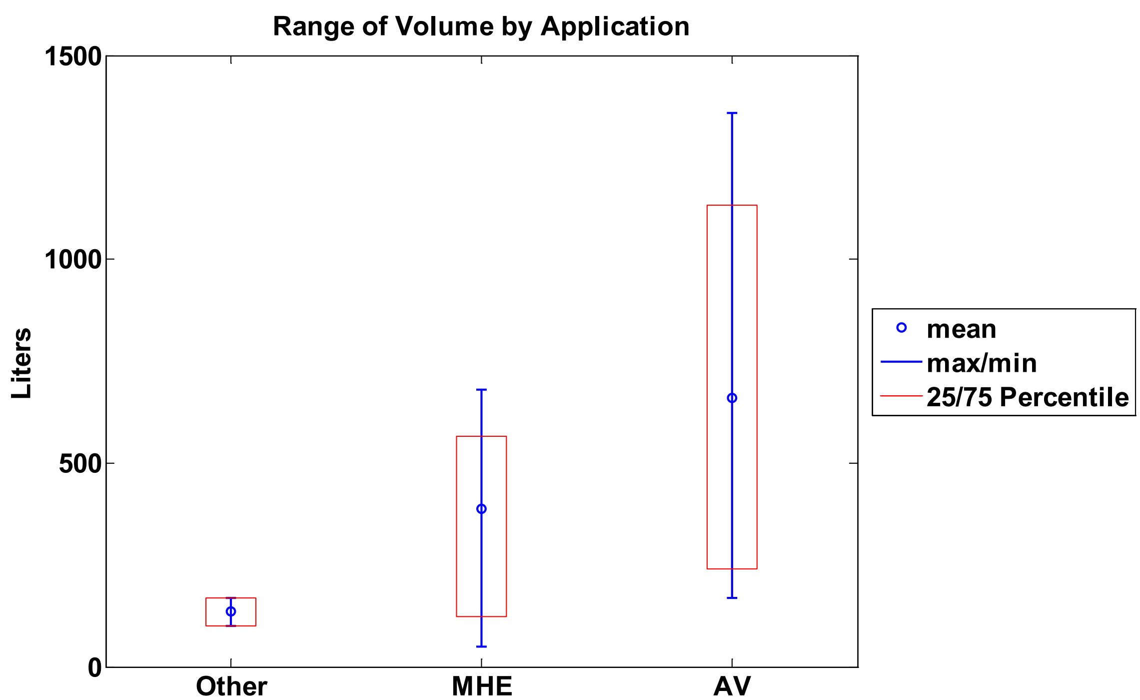

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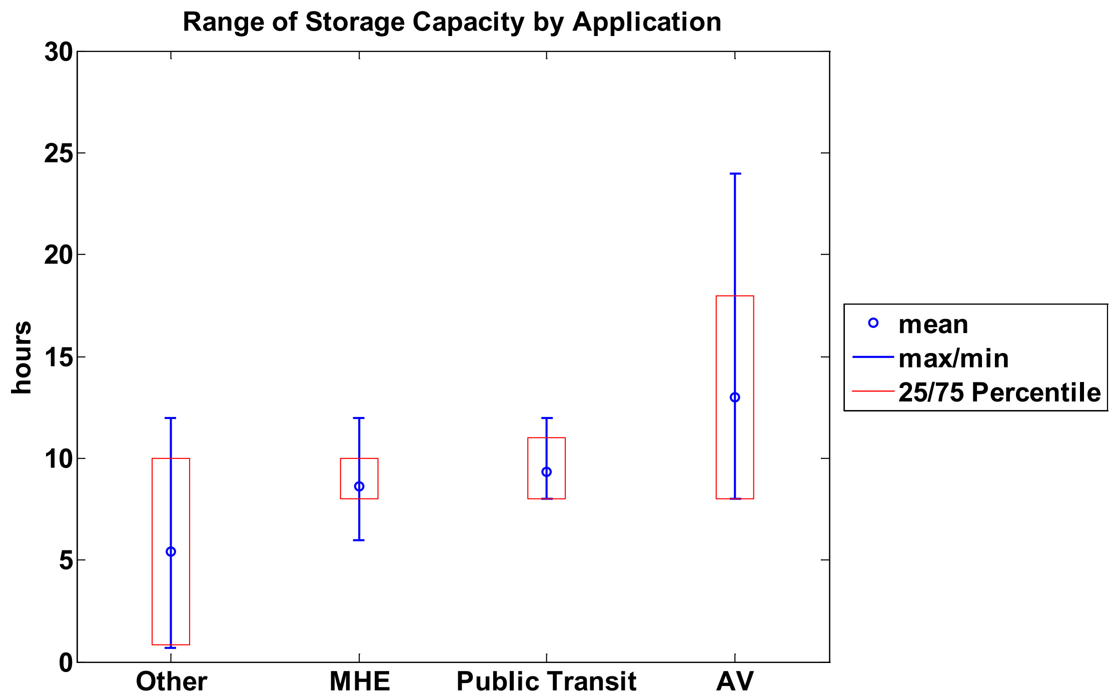

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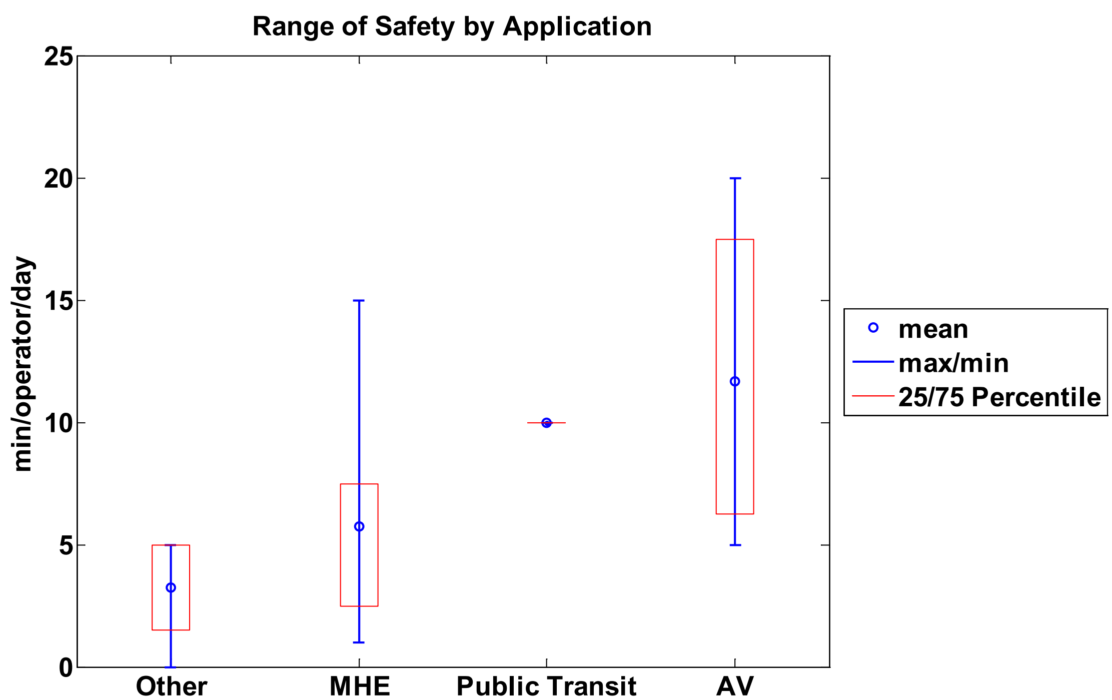

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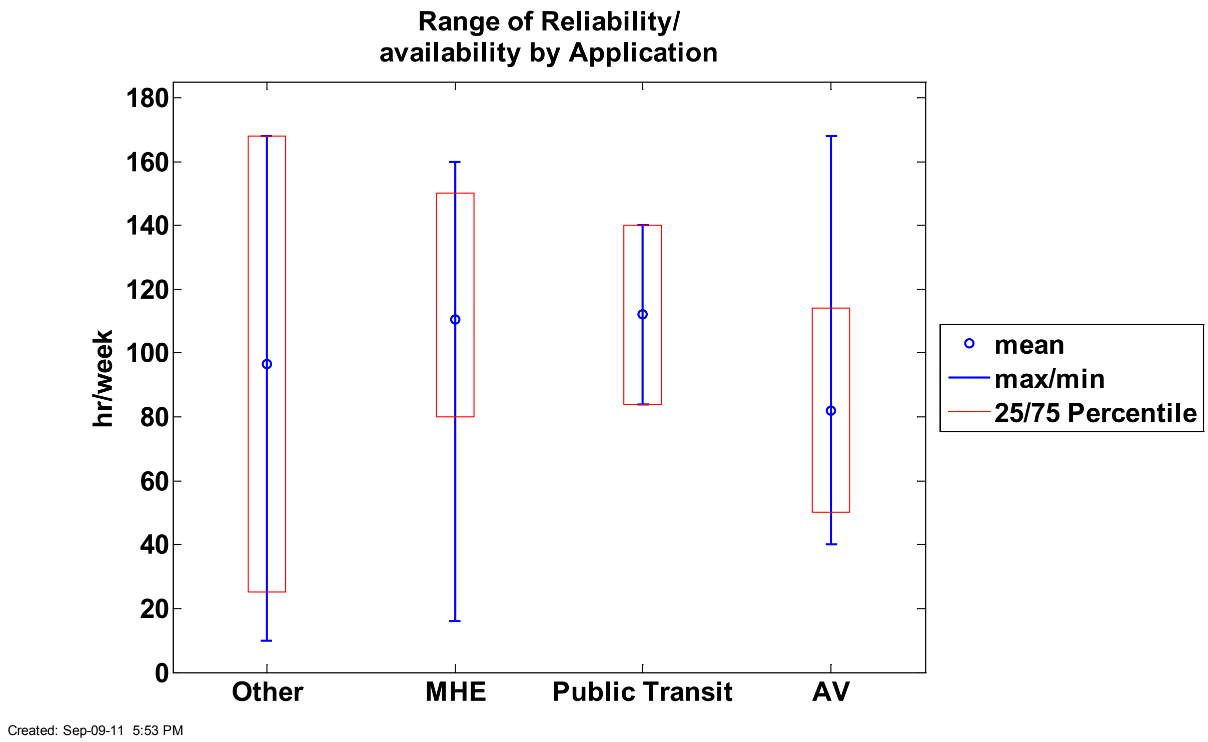
Range of Reliability/
availability by Application
hr/week
180
160
140
120
100
80
60
40
20
0
Other
MHE
Public Transit
AV
mean
max/min
25/75 Percentile
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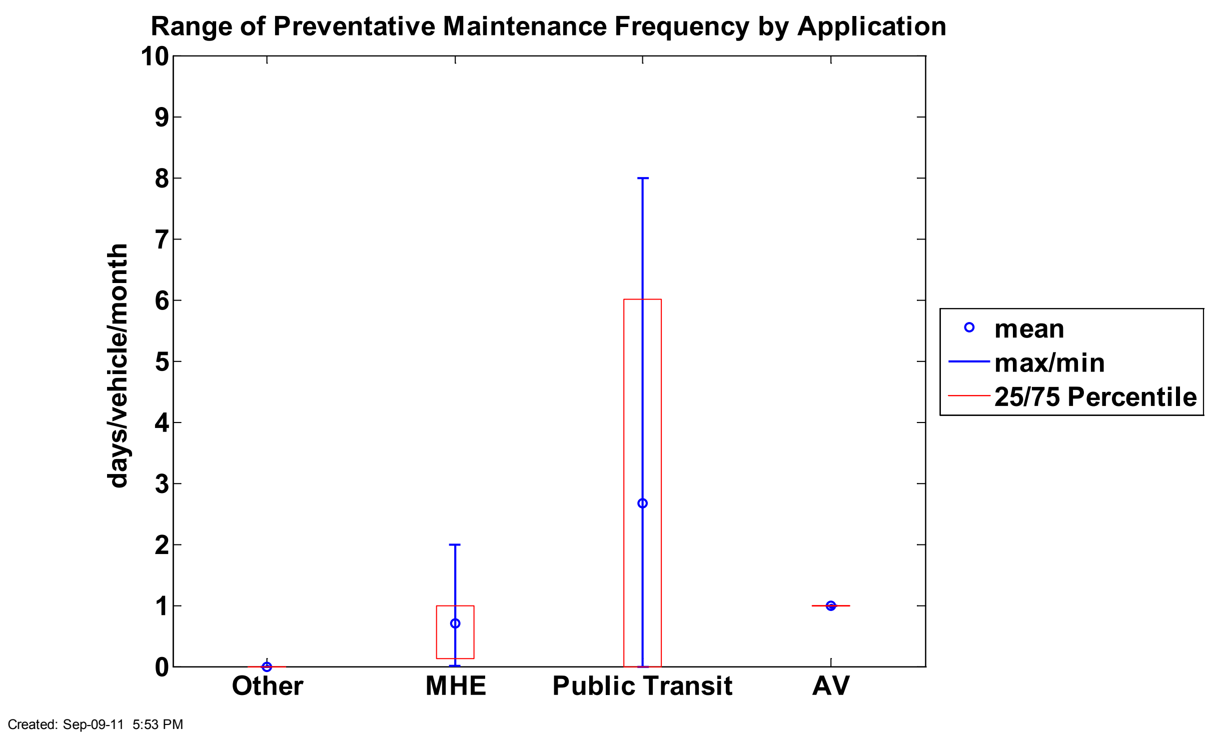
Range of Preventative Maintenance Frequency by Application
days/vehicle/month
10
9
8
7
6
5
4
3
2
1
0
Other
MHE
Public Transit
AV
mean
max/min
25/75 Percentile
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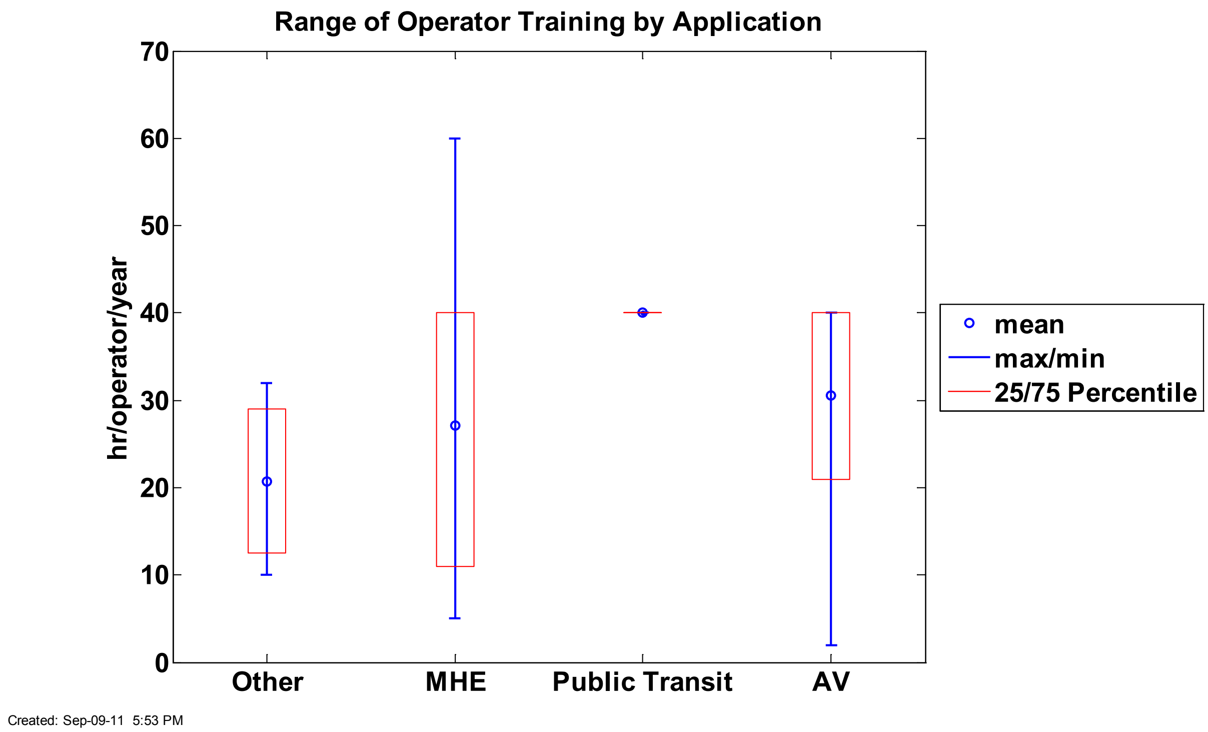
Range of Operator Training by Application
hr/operator/year
70
60
50
40
30
20
10
0
Other
MHE
Public Transit
AV
mean
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25/75 Percentile
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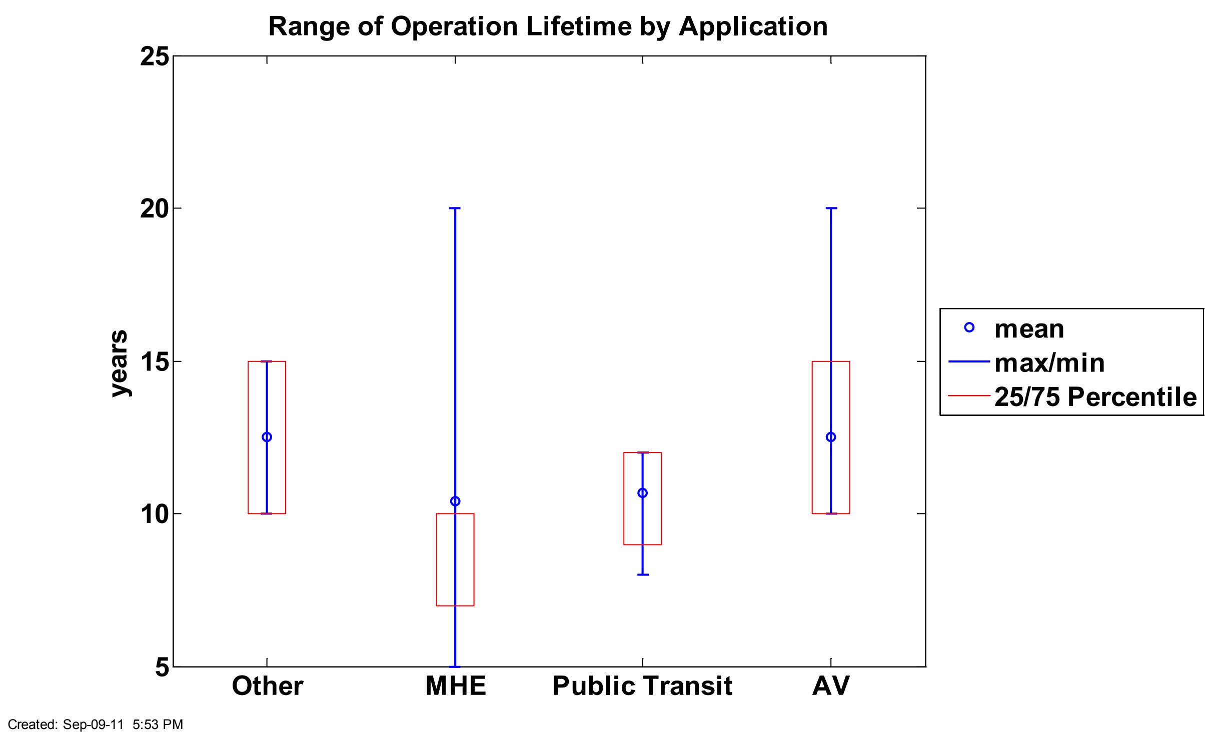
Range of Operation Lifetime by Application
years
25
20
15
10
5
Other
MHE
Public Transit
AV
mean
max/min
25/75 Percentile
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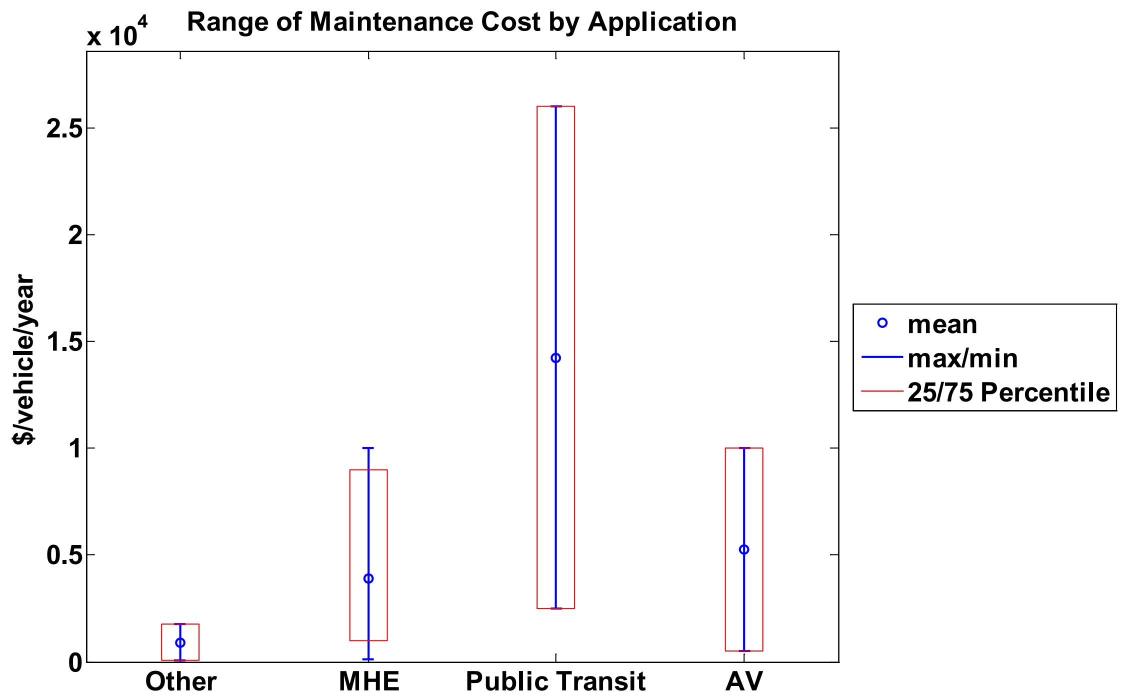

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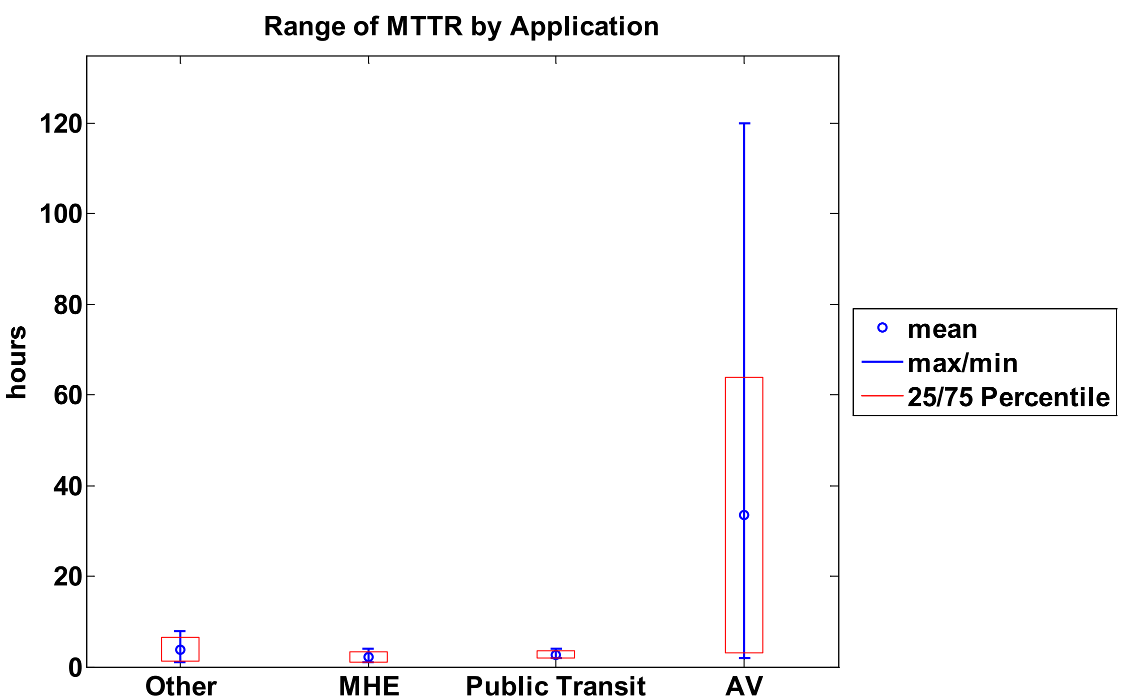

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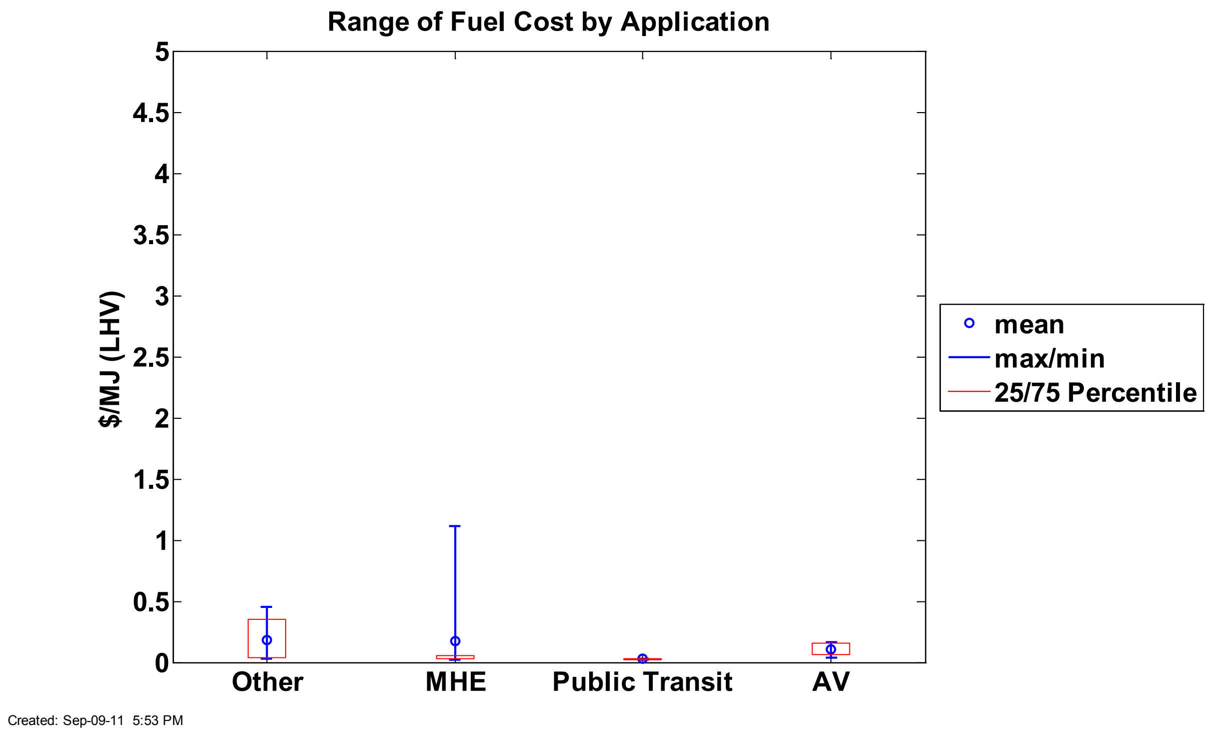
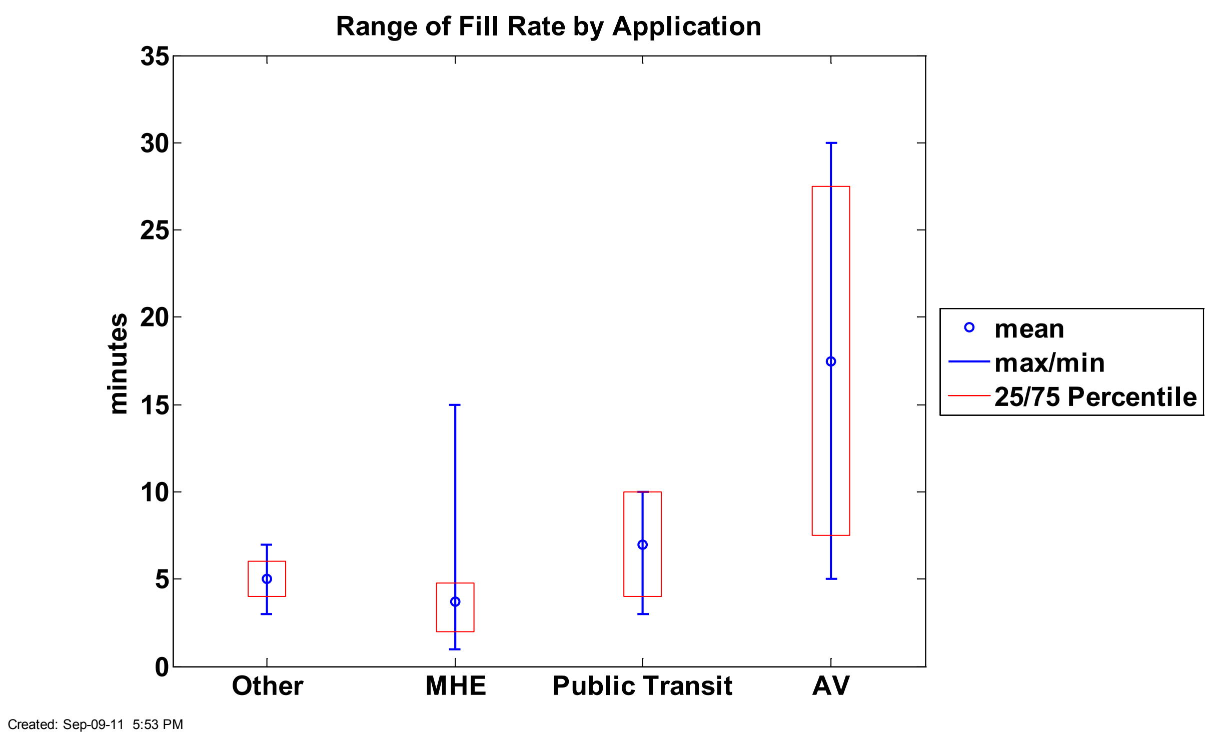

Range of Fuel Cost by Application
$/MJ (LHV)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Other
MHE
Public Transit
AV
mean
max/min
25/75 Percentile
Created: Sep-09-11 5:53 PM


Range of Fill Rate by Application
minutes
35
30
25
20
15
10
5
0
Other
MHE
Public Transit
AV
mean
max/min
25/75 Percentile
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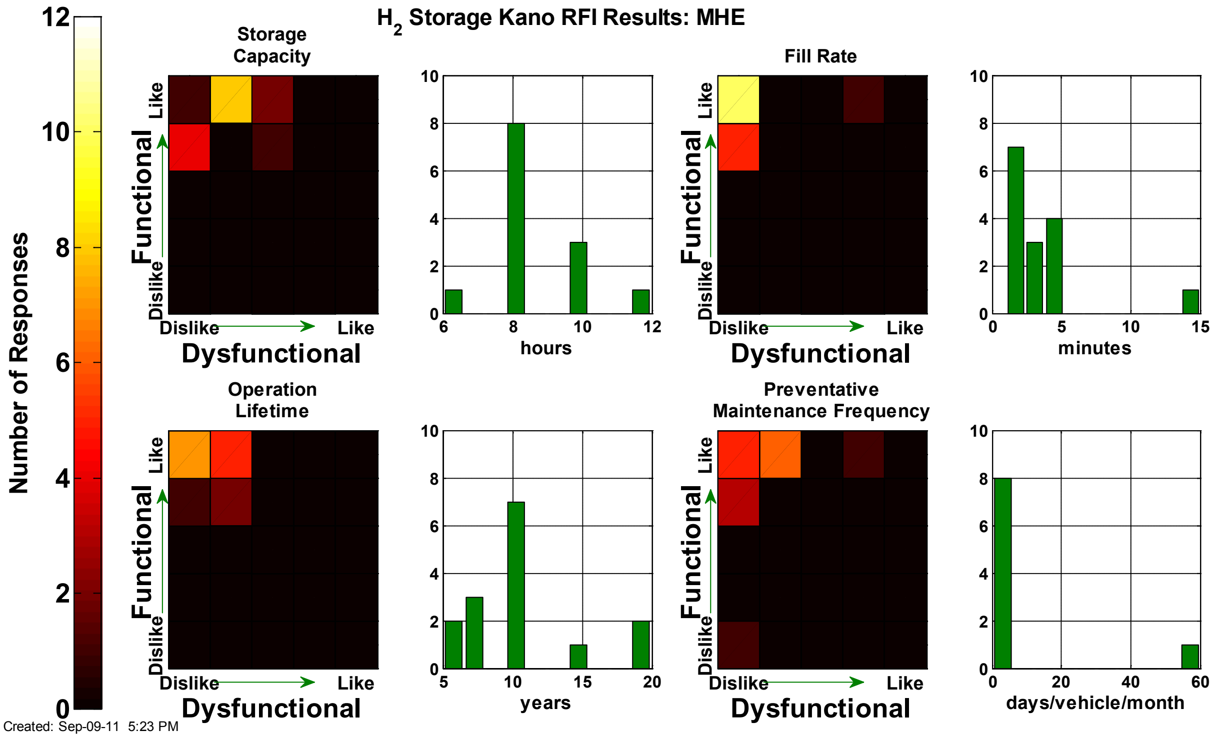
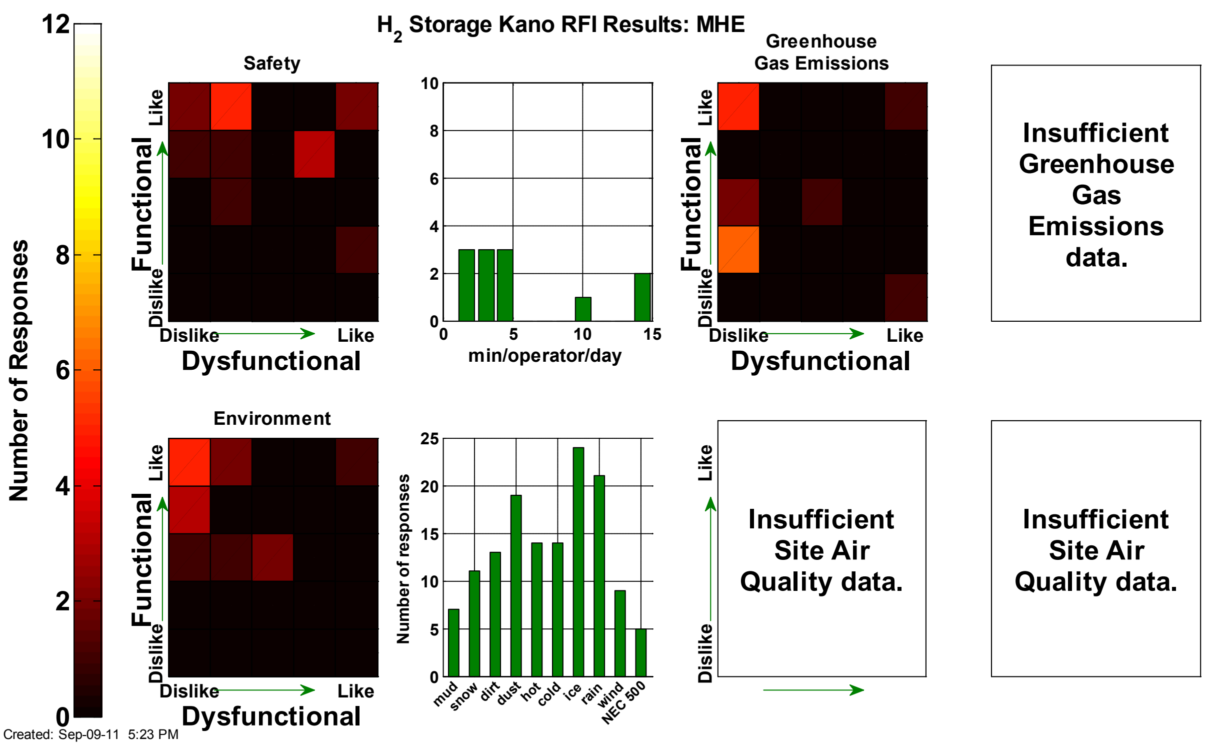
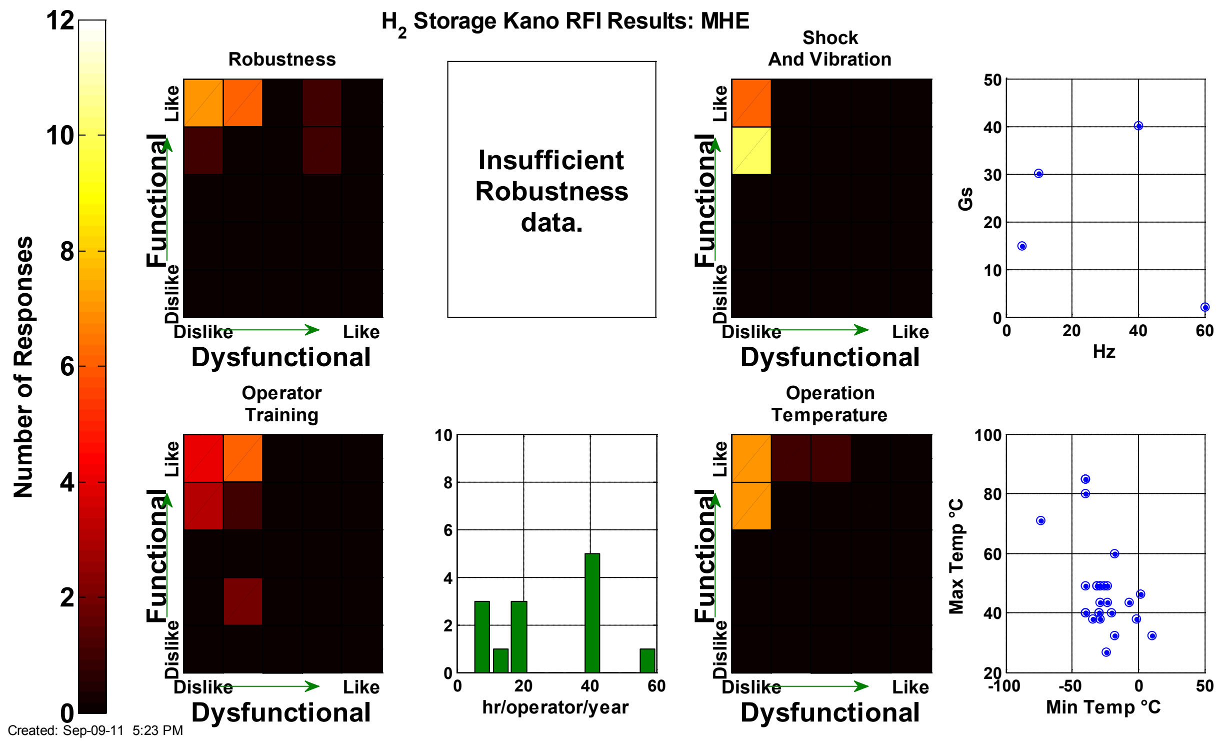
Appendix D. Specialty Vehicle Attributes Results






H2 Storage Kano RFI Results: MHE
Number of Responses
Robustness
Insufficient Robustness data.
Shock And Vibration
Gs
Hz
Operator Training
hr/operator/year
Operation Temperature
Max Temp °C
Min Temp °C
Functional
Dysfunctional
Dislike
Like
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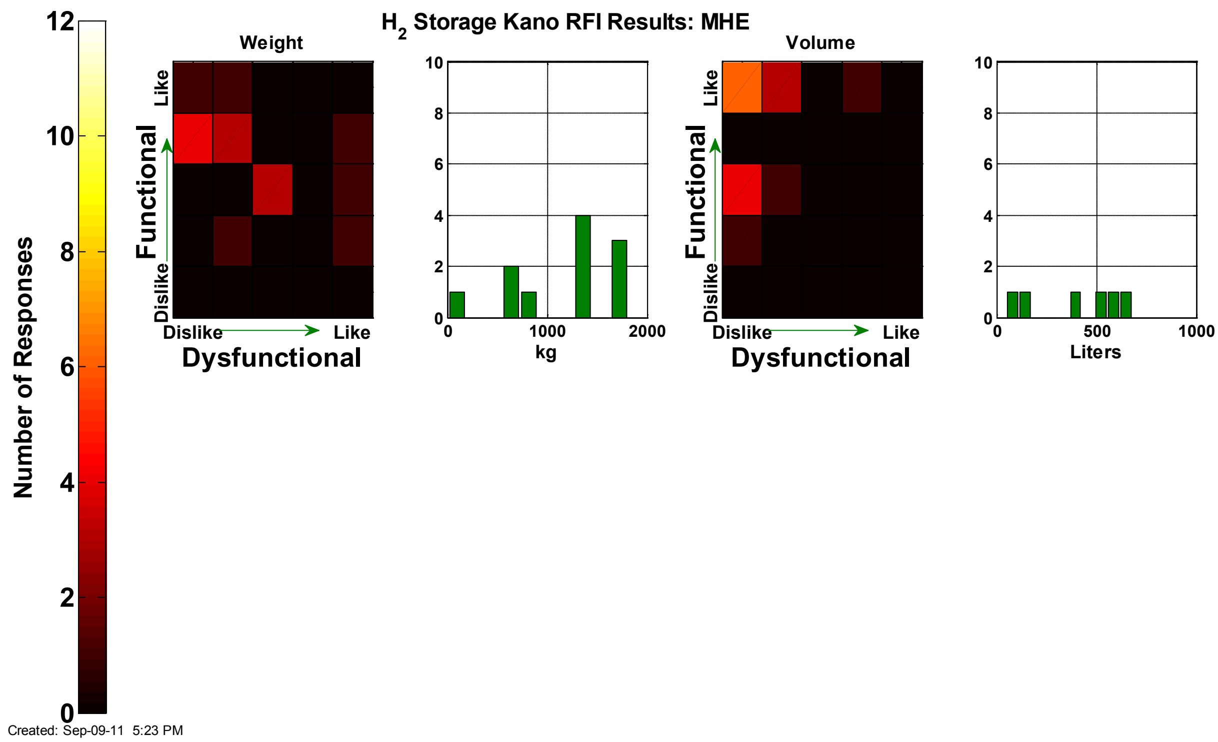
H2 Storage Kano RFI Results: MHE
Number of Responses
Weight
kg
Volume
Liters
Functional
Dysfunctional
Dislike
Like
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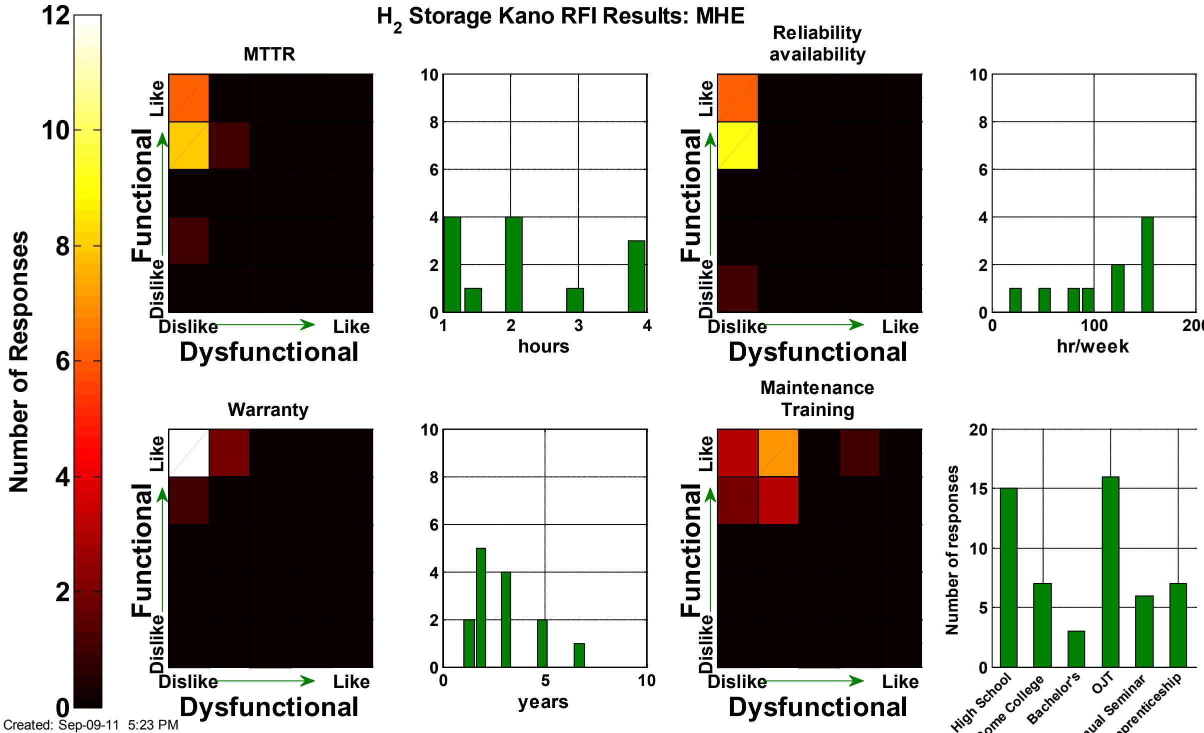
H$_2$ Storage Kano RFI Results: MHE
Number of Responses
MTTR
Functional
Dysfunctional
Dislike
Like
hours
Reliability availability
hr/week
Warranty
years
Maintenance Training
Number of responses
High School
Some College
Bachelor's
OJT
Annual Seminar
Apprenticeship
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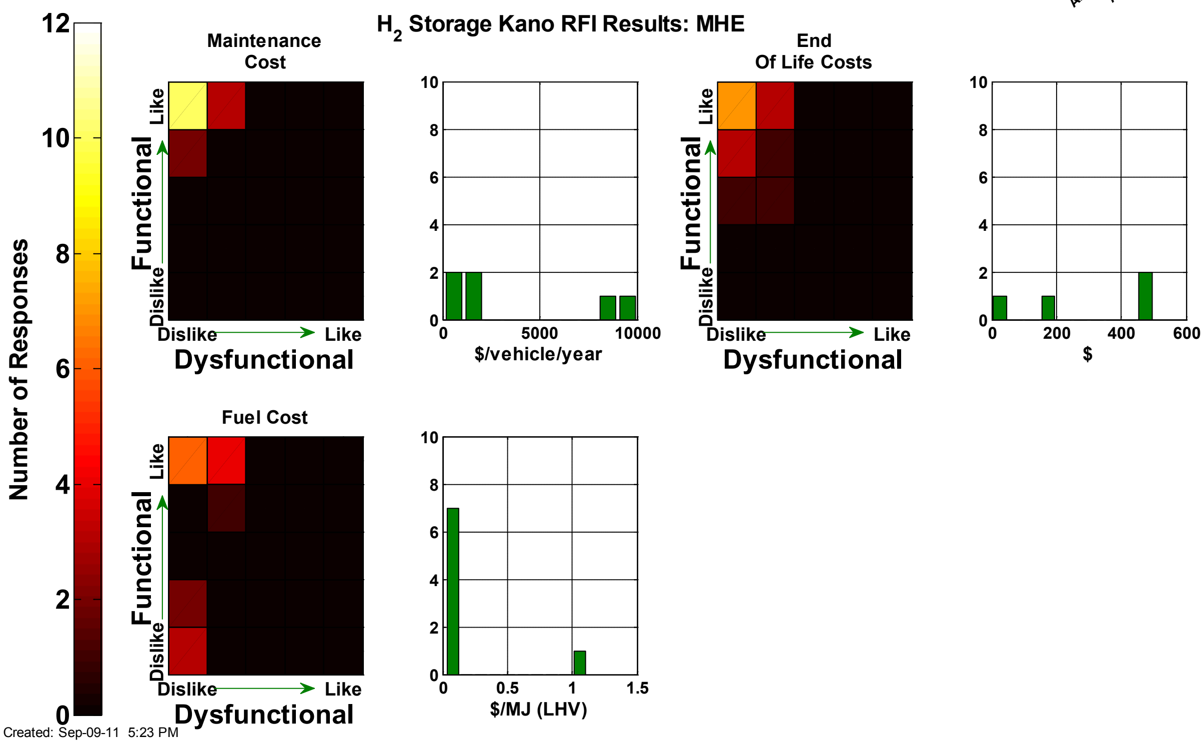
H$_2$ Storage Kano RFI Results: MHE
Number of Responses
Maintenance Cost
Functional
Dysfunctional
Dislike
Like
$/vehicle/year
End Of Life Costs
$
Fuel Cost
$/MJ (LHV)
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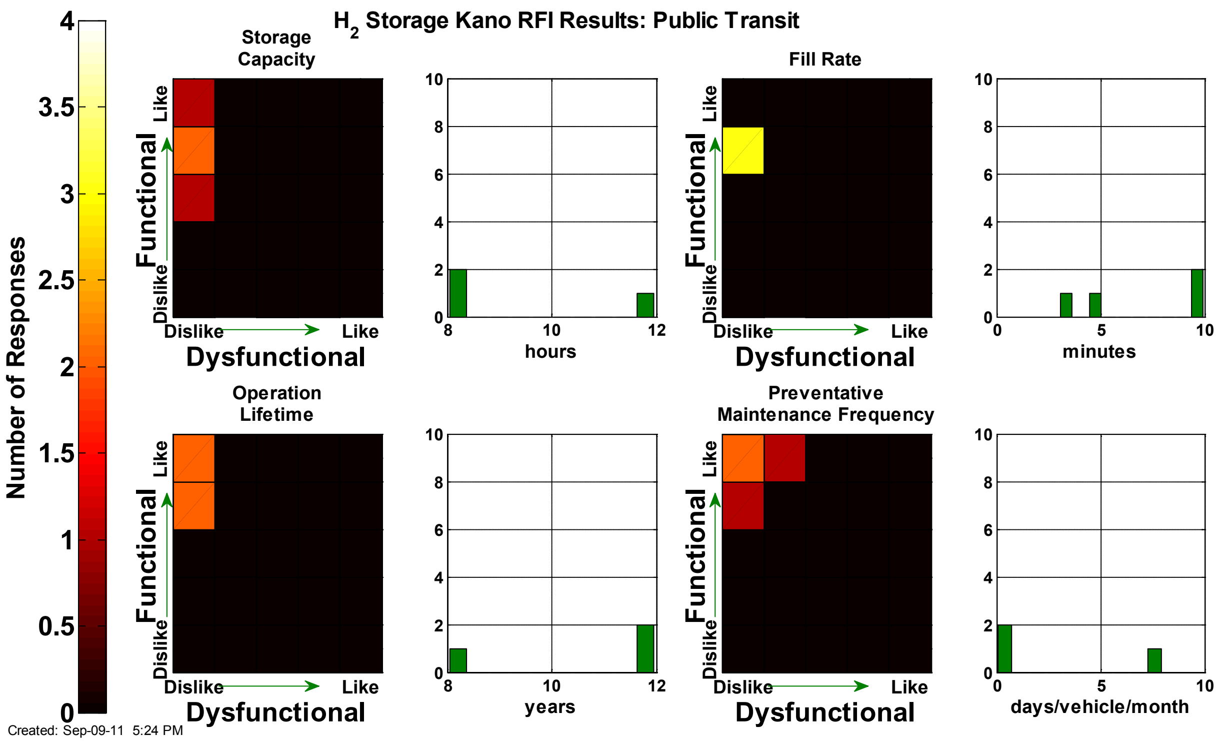
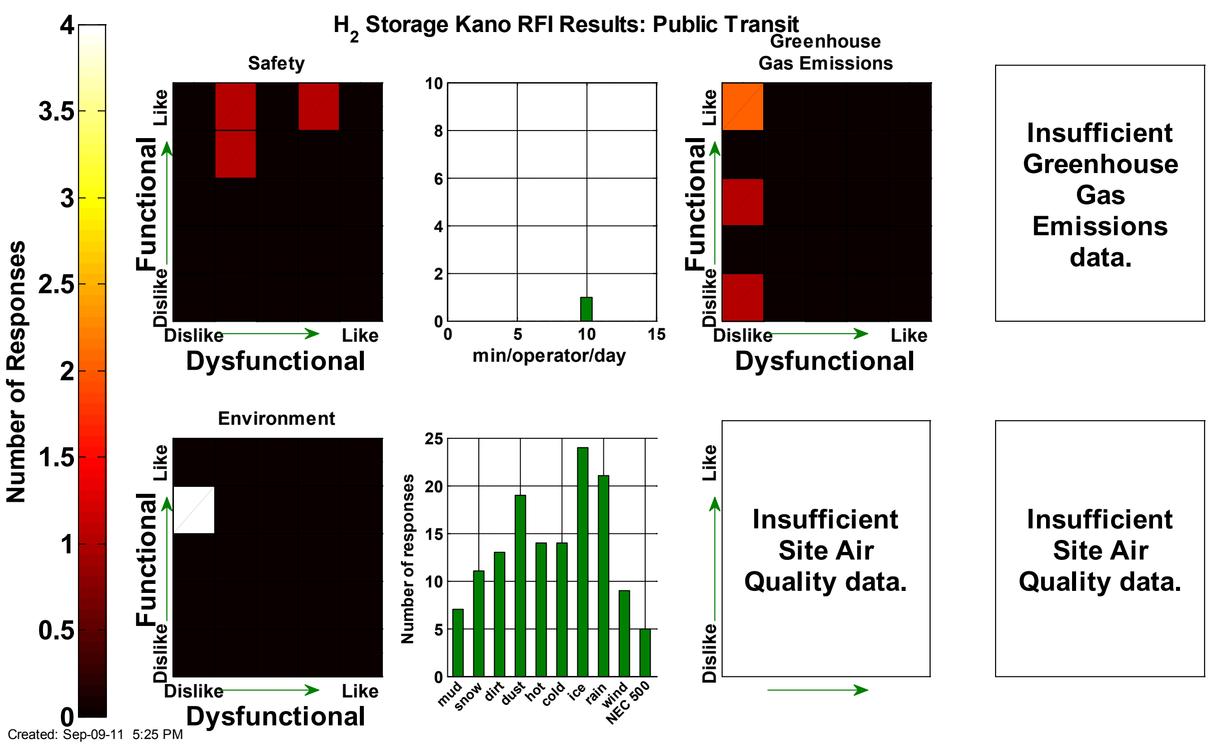
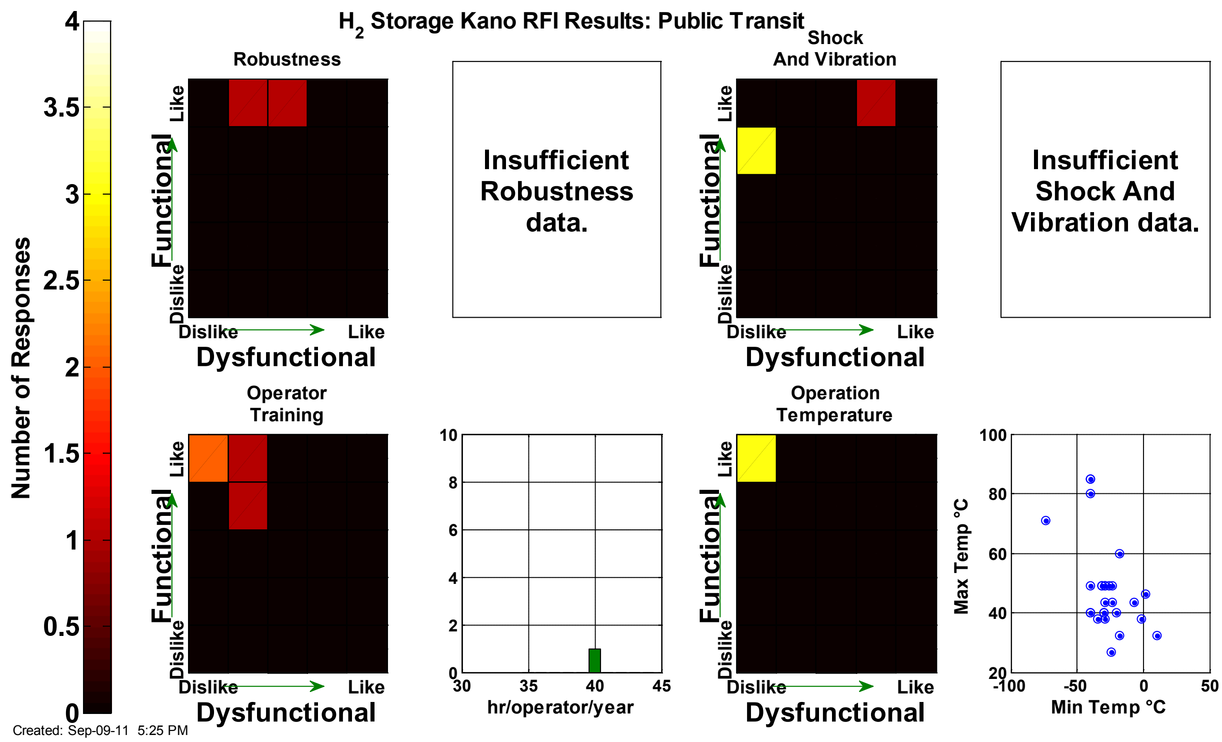
Appendix E. Public Transit Attributes Results






H2 Storage Kano RFI Results: Public Transit
Number of Responses
4
3.5
3
2.5
2
1.5
1
0.5
0
Robustness
Insufficient Robustness data.
Shock And Vibration
Insufficient Shock And Vibration data.
Operator Training
10
8
6
4
2
0
30
35
40
45
hr/operator/year
Operation Temperature
100
80
60
40
20
-100
-50
0
50
Max Temp °C
Min Temp °C
Functional
Dislike
Like
Dysfunctional
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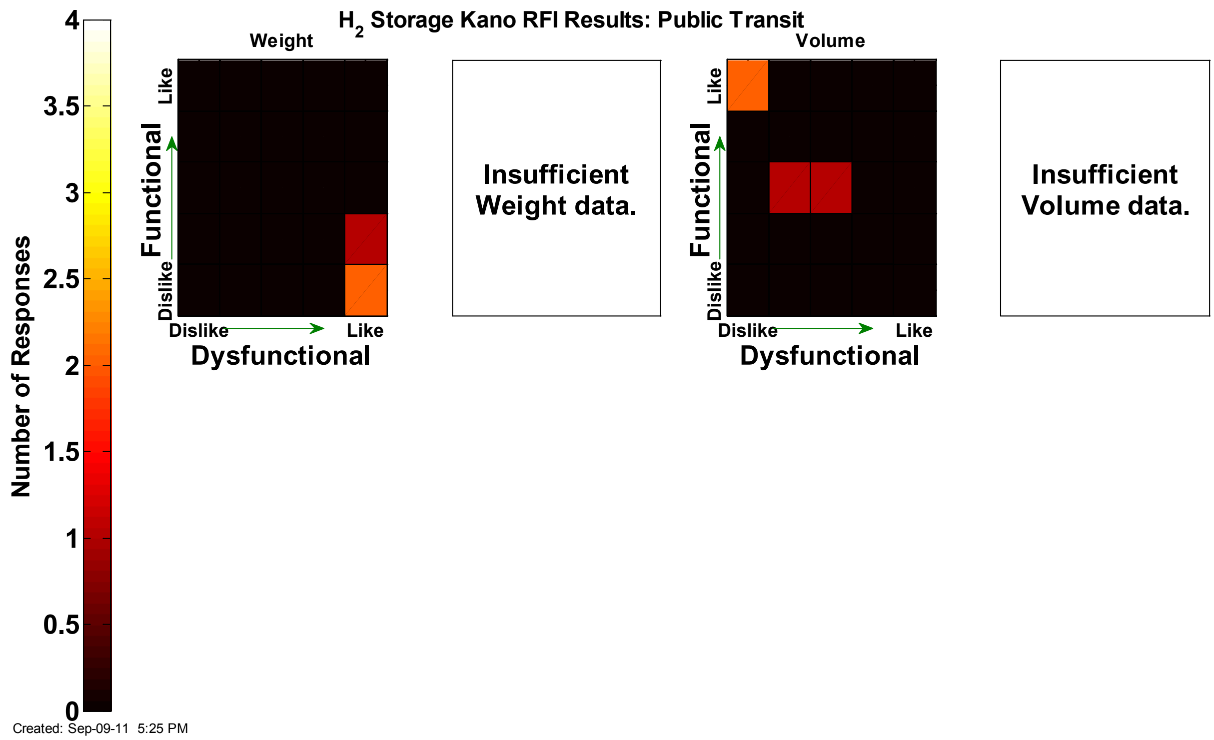
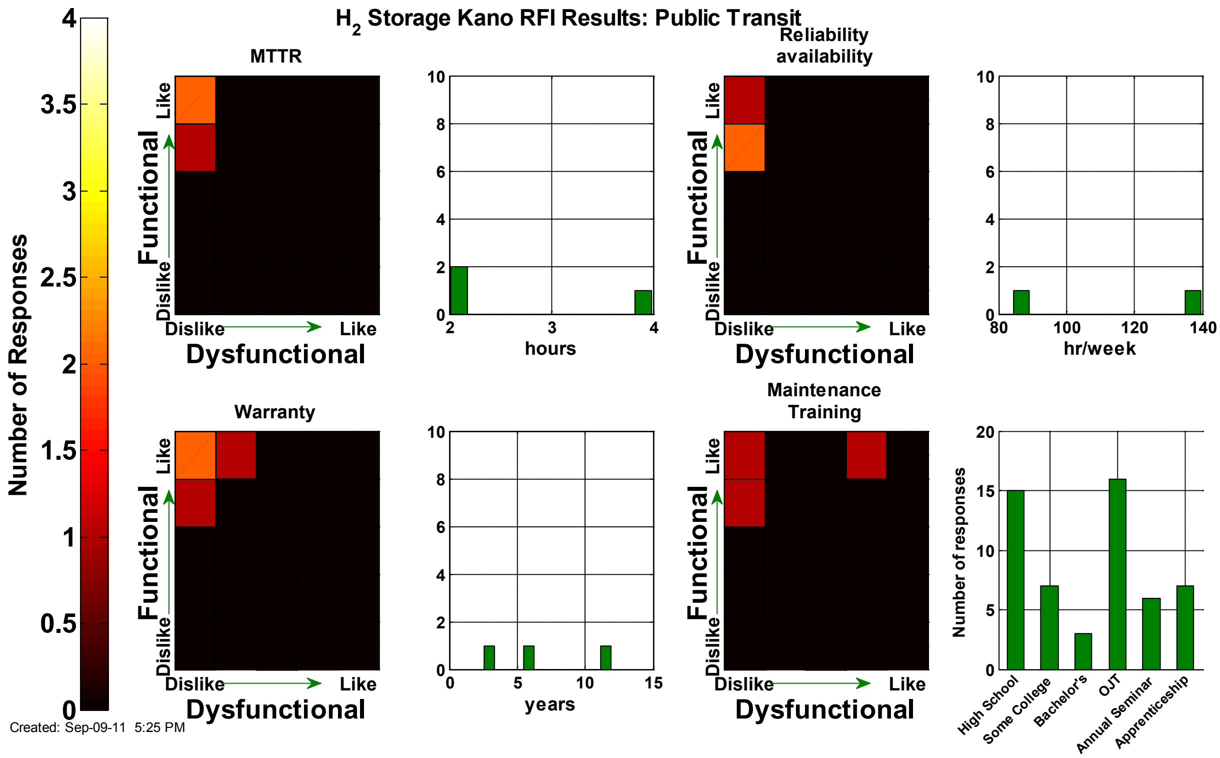
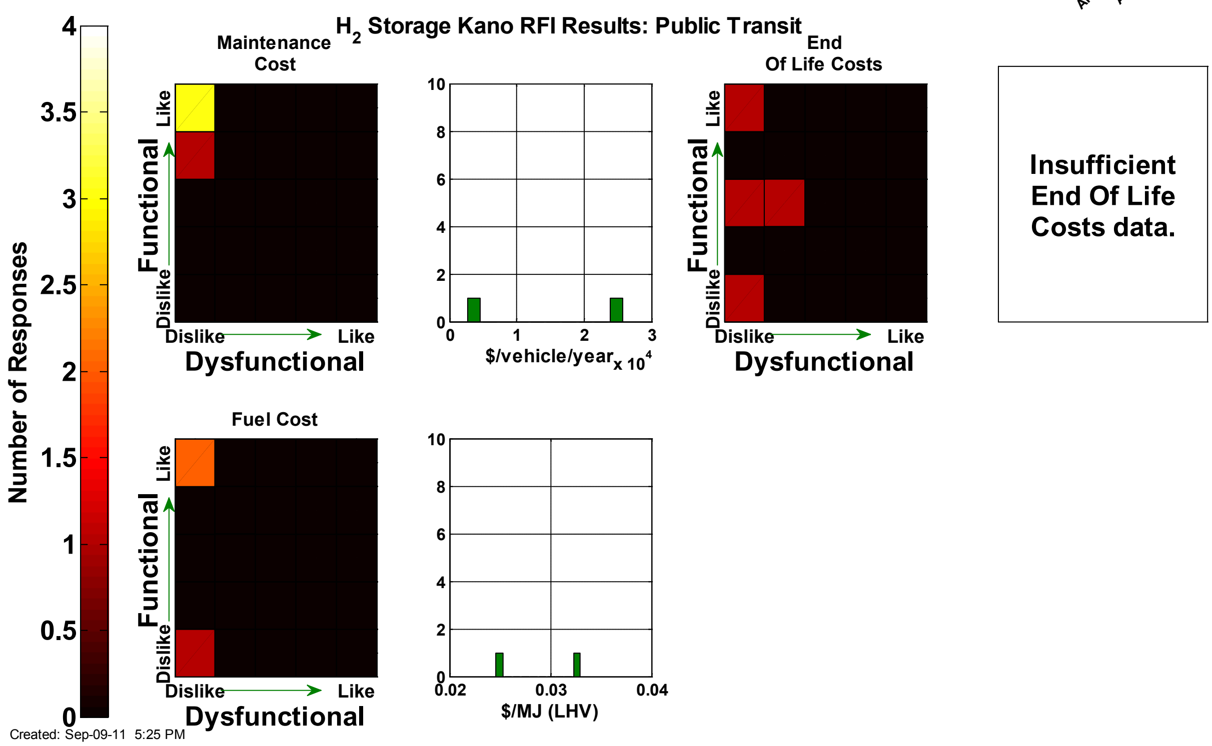

H2 Storage Kano RFI Results: Public Transit
Number of Responses
4
3.5
3
2.5
2
1.5
1
0.5
0
Weight
Insufficient Weight data.
Volume
Insufficient Volume data.
Functional
Dislike
Like
Dysfunctional
Created: Sep-09-11 5:25 PM

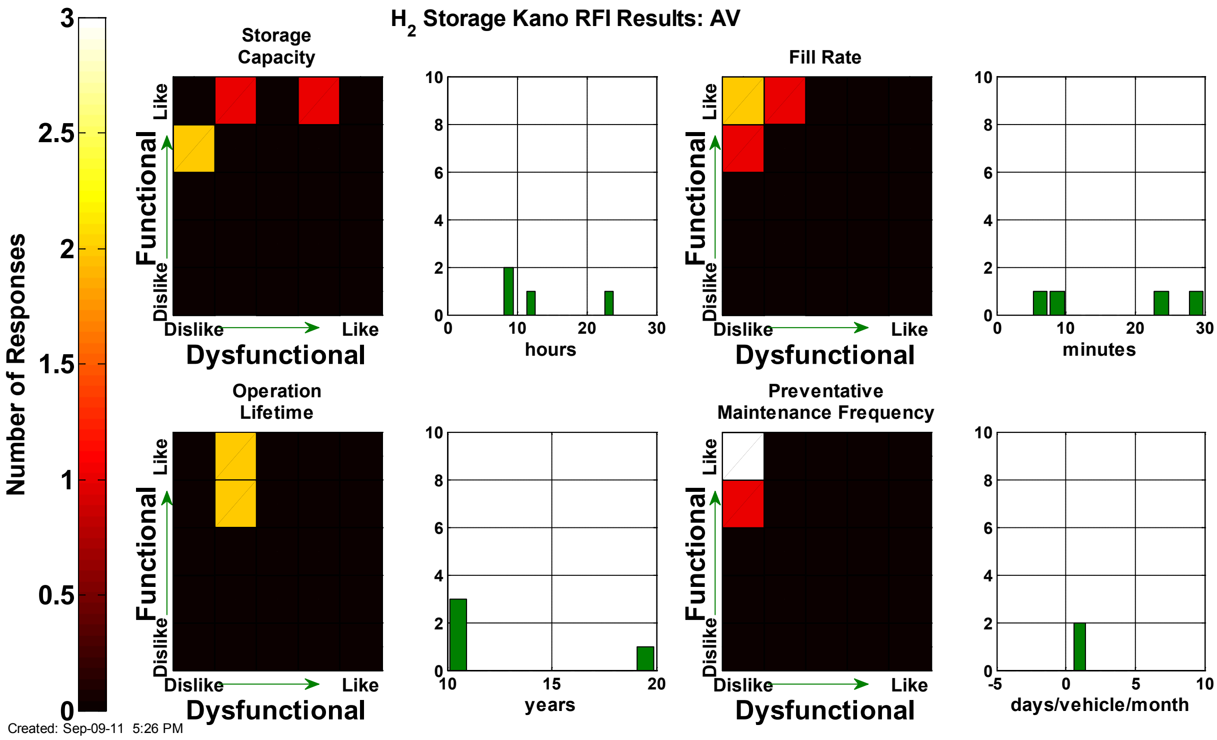


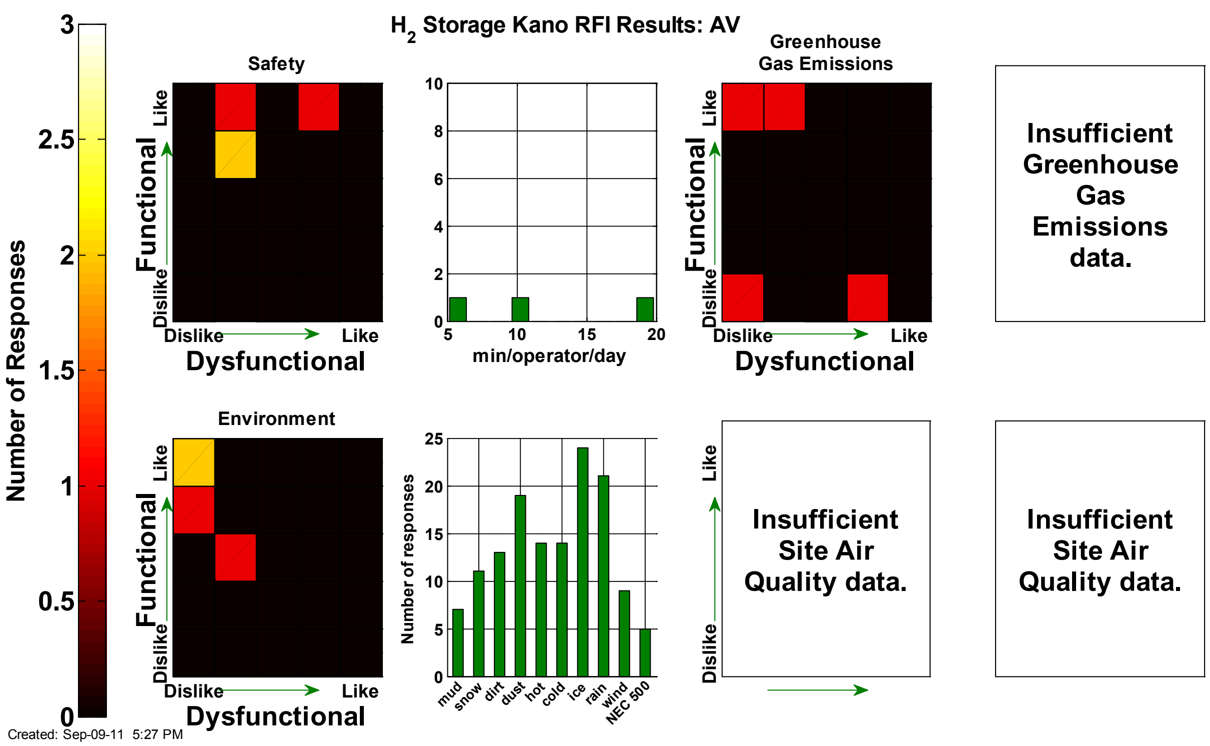
H2 Storage Kano RFI Results: Public Transit
Number of Responses
MTTR
Reliability availability
Warranty
Maintenance Training
Functional
Dysfunctional
Dislike
Like
hours
hr/week
years
Number of responses
High School
Some College
Bachelor's
OJT
Annual Seminar
Apprenticeship
Created: Sep-09-11 5:25 PM

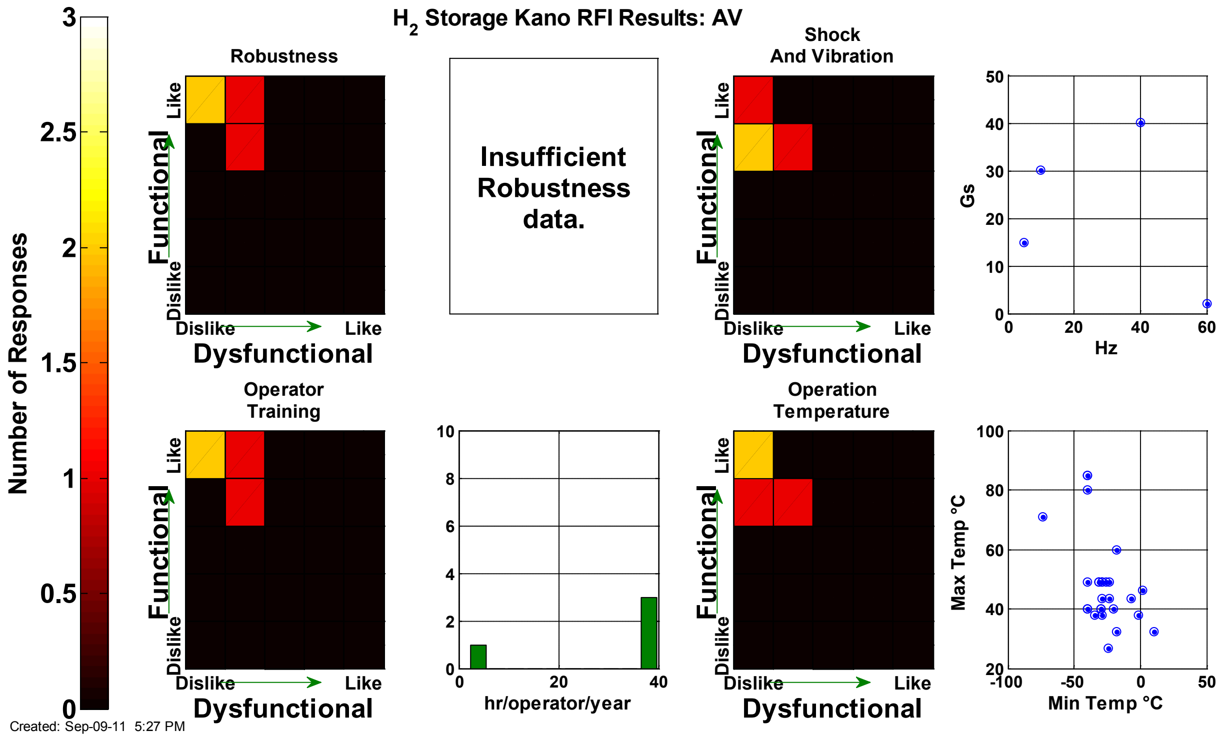


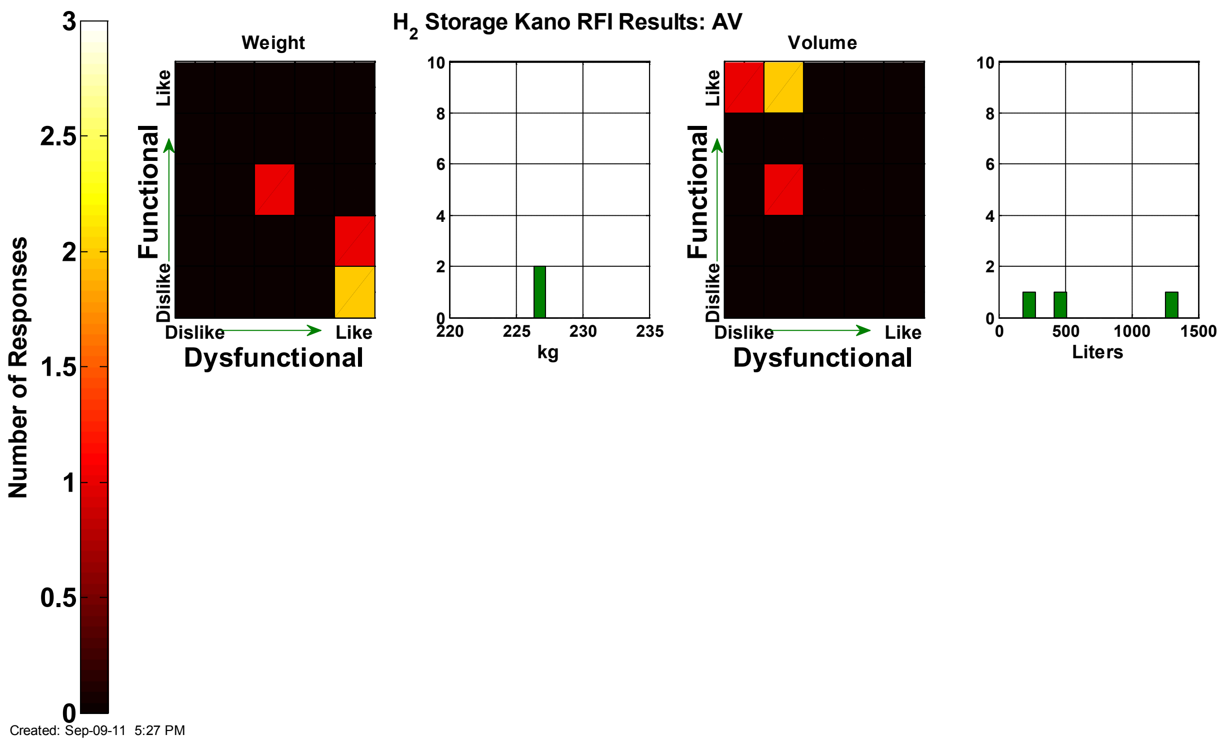
H2 Storage Kano RFI Results: Public Transit
Number of Responses
Maintenance Cost
End Of Life Costs
Fuel Cost
Functional
Dysfunctional
Dislike
Like
$/vehicle/year x 10^4
$/MJ (LHV)
Insufficient End Of Life Costs data.
Created: Sep-09-11 5:25 PM

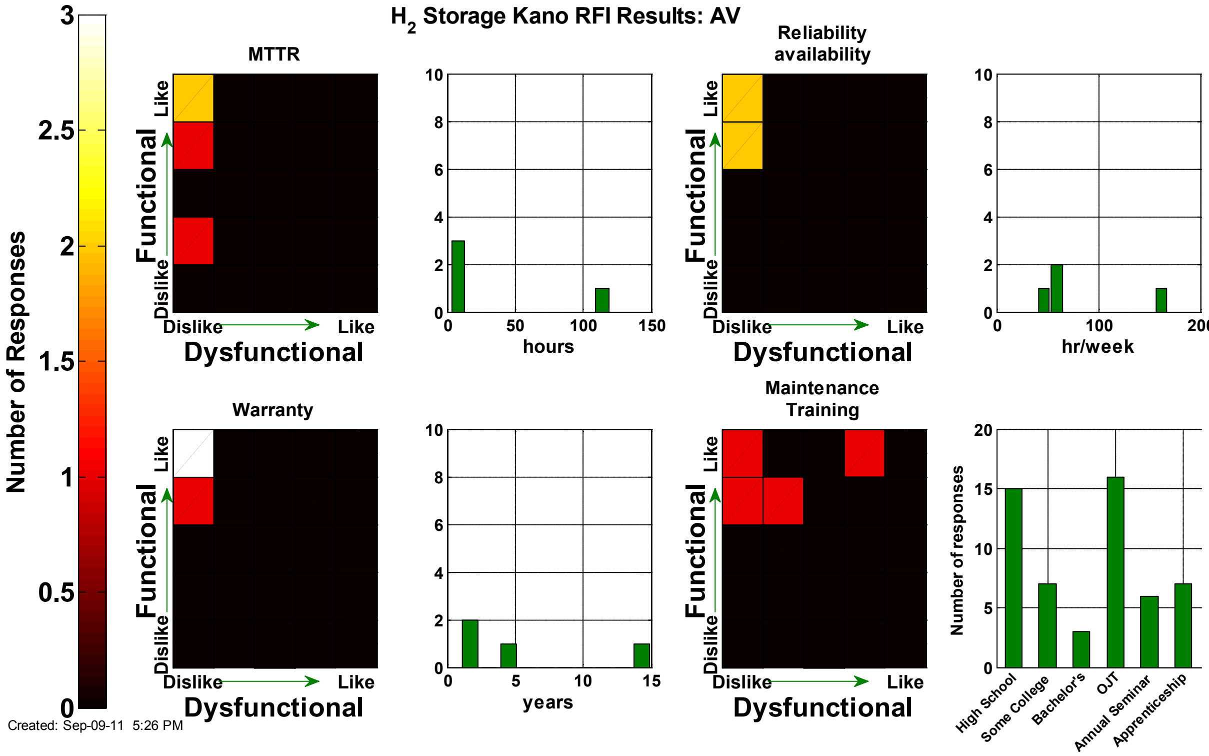
Appendix F. Autonomous Vehicle Attributes Results

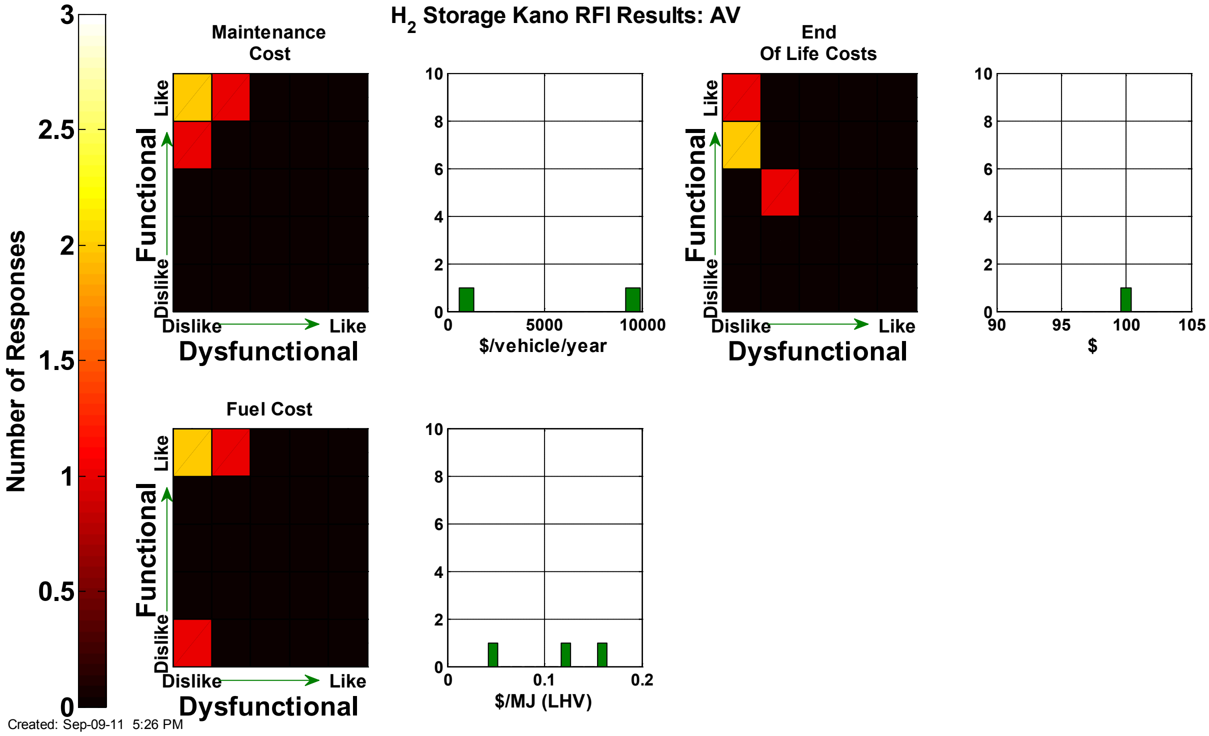





H2 Storage Kano RFI Results: AV
Number of Responses
Robustness
Insufficient Robustness data.
Shock And Vibration
Gs
Hz
Operator Training
hr/operator/year
Operation Temperature
Max Temp °C
Min Temp °C
Functional
Dysfunctional
Dislike
Like
Created: Sep-09-11 5:27 PM


H2 Storage Kano RFI Results: AV
Number of Responses
Weight
kg
Volume
Liters
Functional
Dysfunctional
Dislike
Like
Created: Sep-09-11 5:27 PM


H$_2$ Storage Kano RFI Results: AV
Number of Responses
MTTR
Functional
Dysfunctional
Dislike
Like
hours
Reliability availability
hr/week
Warranty
years
Maintenance Training
Number of responses
High School
Some College
Bachelor's
OJT
Annual Seminar
Apprenticeship
Created: Sep-09-11 5:26 PM


H$_2$ Storage Kano RFI Results: AV
Number of Responses
Maintenance Cost
Functional
Dysfunctional
Dislike
Like
$/vehicle/year
End Of Life Costs
$
Fuel Cost
$/MJ (LHV)
Created: Sep-09-11 5:26 PM