ABSTRACT

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This thesis considers fire hazards in the existing vehicle fleet and uses failure modes and effects analyses of three generic designs to identify and rank potential fire hazards in the Emerging Fuel Vehicle (EFV) fleet. A statistics based predictive quantitative risk assessment framework and estimated uncertainty analysis is presented to predict risk of EFV fleets. The analysis also determines that the frequency of fire occurrence is the greatest factor that contributes to risk of death in fire. These preliminary results predict 420±14 fire related deaths per year for a fleet composed entirely of gasoline-electric hybrid vehicles, 910±340 for compressed natural gas vehicles, and 1300±570 for hydrogen fuel-cell vehicles relative to the statistical record of 350 for traditional fuel vehicles. The results are intended to provide vital fire safety information to the traveling public as well as to emergency response personnel to increase safety when responding to EFV fire hazards.

FIRE SAFETY IN TODAY'S AND TOMORROW'S VEHICLES

By

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Chapter 1: Introduction

Fires involving highway vehicles pose a significant hazard to the traveling public and emergency responders. In a typical year in the U.S. there are 266,000 highway vehicle fires, which are associated with 350 deaths, 1230 injuries, and $959 million in property damage. (Ahrens, 2005a) Fire hazards of gasoline and diesel fueled vehicles are relatively well understood, but Emerging Fuel Vehicles (EFVs) may introduce new and unanticipated fire hazards.

Owing to economic and regulatory pressures, vehicles fueled by emerging fuels are appearing in greater numbers on U.S. highways. The registration of 392,000 new hybrids in the U.S. between 2000 and 2006 indicates how EFVs are becoming increasingly prevalent (Polk, 2006). The Energy Policy Act (EPAct) of 1992 requires that 75% of the light-duty vehicles acquired by most government agencies in metropolitan areas be fueled by alternative fuels, i.e., fuels not derived from petroleum. The EPAct (eere.gov, 2006) was updated in 2005. Some extra requirements have been added, such as requiring that all vehicles capable of running on alternative fuels do so 100% of the time, whereas before they were only required to do so 51% of the time.

Several studies have been conducted to assess hazards of accidents involving EFVs. One such study sought to identify these risks before the vehicles were widely used, thus ensuring public acceptance of the new systems (Purdue University, 1978). Two significant conclusions were drawn. First, to gain rapid acceptance by the public, operating procedure information needs to be widely distributed. And, second, to evaluate statistics, accident data needs to be well documented on a large scale. This study is 30 years old and does not reflect current EFV technologies.

The objective of a more recent study sought to analyze not only fire hazards associated with accidents involving alternative vehicles but also the infrastructure and regular operation of such vehicles (Plotkin, 2000). This study determined that properties of a fuel, vehicle storage, and refueling are also significant contributing factors to the fire hazards of EFVs. This study named many of the hazards of fuels and gave some comparison to traditional fuels assuming generic designs. However several fuels and the determination of what fire hazards are of the most concern were left for future research.

The reporting of accident data, such as by Ahrens (2005a), helps to quantify and track the frequency of accidents and deaths involving highway vehicle fires. By evaluating fuel system hazards quantitatively, such as was done for compressed natural gas buses by Chamberlain et al. (2005), risk comparisons between fuel systems can be made. But before a quantitative analysis can take place, the hazards need to be comprehensively identified and this information alone can provide useful safety information.

The EPAct (eere.gov, 2006) provides a list of Alternative Fuels. EFVs are defined here to be vehicles fueled by Alternative Fuels as well as gasoline-electric hybrid vehicles. The emerging fuels and systems considered here are:

- Gasoline-electric hybrids
- Natural gas and liquid fuels domestically produced from natural gas
- Hydrogen
- Liquefied petroleum gas (propane)
- Ethanol, methanol, and other alcohols
- Blends of 85% or more of alcohol with gasoline
- Coal-derived liquid fuels

- Electricity
- Biodiesel (B100)
- P-Series fuel

The objectives of this work are to:

1. Identify the fire hazards associated with emerging fuel vehicle systems.
2. Create a Failure Modes and Effects Analysis (FMEA) for three generic designs of selected vehicle types. The selected vehicle types include:
    a. Gasoline-Electric Hybrid
    b. Compressed Natural Gas (CNG)
    c. Hydrogen Fuel-Cell
3. Create a predictive quantitative risk analysis for the same vehicle types.
4. Identify important vehicle fire research issues

Chapter 2: Fire Hazards of Emerging Fuel Vehicles

This chapter begins with a discussion of fuel property hazards of EFVs. Following this, a discussion of other possible hazards identified from previous history and expert interviews is presented. The chapter concludes with suggestions for future research inspired by this research.

2.1 *Fuel Property Hazards*

2.1.1 Gasoline-Electric Hybrid

Because gasoline-hybrids are powered by combustion and electricity, they have many of the same hazards as gasoline powered vehicles. In addition to gasoline hazards, hybrid vehicles can have additional, electrical fire hazards owing to the higher voltages they employ.

2.1.2 Natural Gas

Vehicle compressed natural gas (CNG) tanks involve high pressures. Exceeding the rated pressure can result in tank failure or explosion. In addition, fire can weaken tanks that may then cause them to rupture.

Companies such as American Honda and FuelMaker have designed a refueling mechanism that can be installed in a consumer's home. The appliance, called "Phill," is costly, but it can perform a slow fill, refueling a vehicle overnight (South Coast AQMD, 2005). Having a CNG fuel line in the home increases some fire risks, such as the possibility of having accumulated vapors that can explode.

Due to its positive Joule-Thompson coefficient, expanding CNG can lower the temperature below the freezing point of water. This freezing can block check valves in the open position, allowing for a blow-back scenario where the fueling nozzle can be expelled with a pressure of up to 25,000 kPa (250 bars or about 3626 psi).

Liquefied natural gas (LNG) refueling requires training and cannot generally be performed by consumers owing to exposure concerns. Certain substances, such as liquid water from condensation, can pose a fire/explosive hazard. This hazard is referred to as Rapid Phase Transition (RPT). If liquid water enters a LNG pool, the LNG can undergo a RPT, potentially leading to a fire or explosion (Orion, 2006; WMATA, 2006; epa.gov, 2002).

2.1.3 Hydrogen

Hydrogen involves several unusual fire risks. One such risk is that compressed hydrogen vehicles use gas at high pressure and have hazards related to using pressure vessels. Hydrogen leaks easily due to its small molecular size and ignites easily. It has wide flammability limits, a high flame speed, and low ignition energy. To prevent static discharge from igniting hydrogen fuel during refueling the vehicles need to be grounded to eliminate the buildup of electrical charge. Additionally, hydrogen flames are not easily visible under daytime illumination.

2.1.4 Propane

Refueling a propane vehicle parallels refueling a gasoline vehicle. The refueling stations pump at about the same rate (about 38-45 Liters per minute). Propane systems differ from gasoline in that they are sealed systems. This leaves the system vulnerable to leaks from sealed connections between refueling components. To reduce the vulnerability, redundant safety devices, such as check valves, are employed to prevent back flow from the tank in the case of a leak. A boiling liquid expanding vapor explosion, or BLEVE, is also a hazard. This occurs when there is a complete failure of the tank, and it can produce high velocity projectiles and high heat release rates. To reduce this hazard, propane fuel tanks used in highway vehicles are designed to be 20 times as puncture resistant as gasoline tanks at four times the normal operating pressure (National Propane Gas Association, 2004).

2.1.5 Ethanol and Methanol

Ethanol vehicle fuel is usually mixed with gasoline. E85 is 85% ethanol and 15% gasoline. This changes many properties compared to normal gasoline. Consumers need to be no more cautious with ethanol than with gasoline (Pharmco-AAPER, 2005). Blends of fuel with concentrations of alcohol higher than 10% require the use of alcohol-resistant foams during fire suppression (Kidde Fire Fighting, 2006). Additionally, alcohol fires generally produce dimmer flames than those of gasoline or diesel fires.

Fire hazards involved with methanol are similar to those associated with ethanol (Machiele, 1990).

2.1.6 Biodiesel

Biodiesel poses no severe fire hazards other than the normal hazards associated with diesel fuel. Biodiesel refueling uses the same equipment as standard diesel refueling equipment (Sundan, 2004).

2.1.7 P-Series Fuel

P-series fueled vehicles are composed of many types of fuels, including ethanol and natural gas (Structure Supplies, 2006). P-series fuels can also be mixed with gasoline. Therefore, the fire hazards involved with P-series vehicles encompass the same hazards as ethanol and gasoline. P-series fuels are liquid, so additional concerns of spilling or leakage, which can lead to fire or explosion, are also present. P-series fuels are not currently widely used.

2.2 *Fuel System Hazards*

Each of the emerging fuel systems presents unique hazards and challenges for emergency responders. Based on hazards identified in the previous section, past research, previously documented events, and personal communication with experts, this section discusses the hazards of emerging fuel systems and their effects on the traveling public and emergency responders.

In this section several adverse effects of traditional emergency response tactics are observed. The descriptions of traditional emergency response methods presented here may vary from actual performance methods since procedures are known to vary by location or may have become outdated.

The complete list of experts interviewed, diagrams of several vehicle component layouts, and a table of emergency response guides referenced can be found are provided in Appendix A through C. It should be noted that all possible component layouts found during this research were considered to determine the vehicle system hazards, but there were too many to include all of them here. The component layouts presented in Appendix B are given to aid the reader in understanding the systems and their operation. The layouts represent some of the most commonly found component layouts but are not meant to encompass all possible designs.

With the exception of a purely electric vehicle, the fire safety concerns for a traditionally fueled vehicle still apply to all other EFVs. While compressed gas fueled systems do not contain a liquid fuel that can cause a pooling hazard, there are other components that contain other flammable or combustible liquids that cause the same type of pooling hazard. The following hazards are those that are specifically not present in traditionally fueled vehicles.

2.2.1 Gasoline-Electric Hybrid

In hybrid vehicles there are two primary fire concerns that are different from traditional fuel vehicles: fires involving the high voltage battery pack and electrification of components with high voltage. If the battery pack casing is breached in a fire, toxic runoff from liquid fire suppression methods may need to be diverted from watershed areas. Toxic gas emissions are also a concern if the battery pack should become involved in a fire. These gases vary depending on the battery type. It may be important for firefighters to use self-contained breathing apparatus devices to avoid the inhalation of such toxic gases. Furthermore a fire involving the battery pack should not be extinguished and the battery pack should not be flooded. Firefighters should cool surrounding components with water while allowing the fire to burn itself out (Toyota, 2006).

2.2.2 Compressed Natural Gas

The most significant concern associated with CNG is the potential for high pressure, flammable gas leakage. In the case that the tank or fuel line is breached, a high pressure, flammable gas will be released that is easily ignitable. CNG can also be released via the operation of a pressure relief device (PRD) (Toyota, 2006).

Dimmick has suggested that many vehicles, depending on their use, benefit from venting their PRDs downward and that this configuration is the most likely to be encountered (Dimmick, 2006). A long pipeline to the release point can create other failures should the release pipeline be damaged in an accident. For this reason a short distance from the tank to the release point is preferable. The position of the release point is often placed near probable sources of ignition. An ignited gas jet fed by the PRD burns at a subsonic speed. While when a collection of natural gas burns, it is possible for it to result in a detonation instead. Thus, the gas release is generally less likely to cause extreme damage if it is ignited in subsonic conditions. A PRD venting upward is not as close to probable sources of ignition. It is therefore less likely to be ignited and may lead to an explosion that is far more damaging than an ordinary burning flame jet from a downward venting PRD (Seiff, 2006b). This warrants that in any situation where a venting or leakage of gas is suspected, possible ignition of the gas in one of these two modes will be possible.

Examples of locations where these flame scenarios could become a threat include any enclosed areas where escaping gas could accumulate into an ignitable mixture. Sufficiently cooled natural gas by the Joule-Thompson effect while escaping high pressure tanks is heavier than air and will travel along the ground. Natural gas at ambient temperature will rise in air. The venting from the PRD can be identified by the loud noise it makes while venting. In addition, to prevent accumulation of gas, natural gas leakage that is already ignited should not be extinguished as this can create an explosive re-ignition scenario. Instead it is suggested that surrounding components be cooled to prevent further damage.

Also it is suggested that fires that involve a pressurized fuel tank "should be fought from behind…cover and be at least 50 meters from the incident. If substantial cover does not exist then possible evacuation of members of the public and/or rescue personnel to a distance of 200 meters should be considered" due to the shrapnel that can be generated from the failure of the storage tank (Hassan et al., 2006). This recommendation comes from research performed on propane fueled vehicles that have tanks very similar to both CNG and Hydrogen vehicles.

In Seiff's documentation of natural gas vehicle incidents, one case is suspected of having caused a chain of PRD failures. It is suspected that due to the venting and ignition of one bus's PRD the fire spread to three other buses (Seiff, 2006b). It is reasonable to assume that a chain of PRD activations could be caused if they all happened in close proximity to one another such as in a truck yard. It is important to be aware how the operation of the PRD by one vehicle can possibly involve another vehicle that also employs a PRD.

2.2.3 Hydrogen Fuel Cell

Many hydrogen vehicles contain similar electrical components as hybrid vehicles and thus require similar safety procedures in regard to electrical hazards during fires. Most hydrogen systems do not include a liquid fuel system and so there are new and different hazards present than in traditional fuel systems. Similar to the CNG system, the most significant concern associated with the use of compressed hydrogen as fuel is the potential for high pressure, flammable gas leakage through a breach or the operation of the PRD (George et al., 2006). All of the same hazards from explosion that apply to CNG also apply to hydrogen. Hydrogen has a wider flammable range and so is even more likely to ignite than CNG.

Due to the unique properties of hydrogen, it is common for flames involving only hydrogen to be virtually invisible to the human eye. Thus, in any situation where hydrogen is suspected to be involved, it is prudent to use more extensive fire detection measures. These include using a thermal sensing camera to look for flames before approaching a possible fuel leakage scenario. This can also be performed by approaching the vehicle with a long handled broom preferably with straw bristles that will ignite when the bristles encounter the flames.

For compressed fuels it is important to note that unlike gasoline, fighting the fire from an uphill position is not recommended. Since the hydrogen gas rises, it is important to fight fires and approach the vehicle from upwind, where gas accumulation is less likely. Hydrogen can be lighter or heavier than air depending on its temperature. If it is heavier than air it will travel along the ground accumulating in low areas until it is heated by contact with the ground and dispersion in air. Fighting these fires upwind is the most appropriate approach to avoid areas where gas has accumulated in explosive mixture quantities. For these reasons identifying not only that a compressed gas is the source of a fire is important, but also what type (Slaughter, 2003).

2.2.4 Propane

The same hazards apply to propane fuel systems as applied to CNG except in the cases where there is a gas leakage and explosion. Propane is heavier than air and will sink to the ground. For propane, liquid leakage and BLEVE are principal fire considerations. It is important to note that for both CNG and propane fuel systems on the road, after-market conversions may be provided by vehicle owners, and as such may not have installed PRDs in the system. Thus, any situation where a PRD has not already proven its presence should be treated as a possible BLEVE hazard, or explosion hazard for CNG and Hydrogen systems, further necessitating the large exclusion zone for fighting these fires as mentioned in the quote of the suggested CNG exclusion zone earlier in this paper.

2.2.5 Ethanol and Methanol

For systems that may contain ethanol or methanol, extra precaution should be taken to apply only alcohol resistant foams during fire suppression if foams are used. It is also not recommended to apply water from straight-stream nozzles because this can cause the fire to spread.

2.3 *Hazard Identification Future Research*

Several issues have arisen during the previously discussed hazard identification research that warrants further research. These issues are summarized as follows:

- Many of the current EFV symbols are similar and it is hard for emergency responders to differentiate vehicle fuel types, especially from a distance. Further research should be conducted to develop easily differentiable symbols or electronic markers. There is a large difference in the safe firefighting distance and priorities of suppression for situations where there is an explosion hazard versus when there is not. Thus immediate vehicle identification is critical to maintaining safe suppression measure.
- Rupture and possible explosion of vehicle fuel tanks is a significant fire hazard. Further research is needed to determine safe exclusion zone distances for each type of emerging fuel. This would then also define the distance at which their previously mentioned symbols or electronic markers would need to be identifiable.
- In trying to acquire statistics on EFV fires, it was found that they are not directly identifiable by their Vehicle Identification Number (VIN) or in emergency responder accident reports. VINs do identify model number; however the VINs of EFV models must be identified for each manufacturer separately since they are not consistent between manufacturers. Additionally there is no “fuel system” data entry on emergency responder accident report forms or in either the NFIRS or FARS databases. Therefore the accident data based on accident reports cannot be used to identify statistics for EFVs alone. Further research could improve these systems so that EFVs can be identified easily for statistical purposes.
- The buoyancy and dispersion of released natural gas from the system remains an uncertainty that still needs to be addressed. Further research into modeling the behavior of natural gas release would provide more definite characteristics of how fire scenarios may form.

Chapter 3: Failure Modes and Effects Analysis

3.1 *FMEA Methods*

FMEAs were created for three generic EFV fuel systems to identify possible modes of failure and the consequences of those failures. These are generalizations and different designs could lead to different FMEA results. A hazard is defined here as a possible source of injury or damage. Failure is defined here as a function that causes injury or damage by either creating a fire hazard at any time or creating a hazard during fire suppression activities. Using statistics acquired in the future, these initial ratings can be replaced with quantitative ratings for greater accuracy.

The FMEA method in this research adopts characteristics of a number of different sources from related industries such as mechanical design, (Otto et al., 2001; Crow, 2006; Dyadem Press, 2003) fire protection, (Mowrer et al., 1989; US Nuclear Regulatory Commission, 1975; Vesely et al., 1981) and SAE (FMEA, 1995). Both failure modes and consequences are identified by consulting the literature on the emerging fuels, EFV components, laboratory experiments, and accidents. The FMEA uses the likelihood of the failure modes and the severity of consequences to understand the relative risk associated with each failure mode (Dyadem Press, 2003). The highest risk modes of failure are assessed by the risk priority number (RPN).

Diagrams of the common fuel system component layouts used in the FMEA and the full FMEA are provided in Appendices B and D. The diagrams show the general component layouts that were considered to represent the systems in the FMEA. The FMEA summary table of the six highest risk modes of failure for particular components of each system is shown in Table 3.1.

Table 3.1. Summary of design FMEA fire related hazards

	Component Name	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Probability	RPN
Gasoline-Electric Hybrid	Fuel Tank (And fuel lines)	Cracking	Flammable leakage	6	Protective casing breach.	6	36
	Hybrid Vehicle (HV) Battery Pack	Electrical Short	Arcing, electrifies other components with high voltage and possible ignition source.	9	Short Circuit	4	36
	Power Cables (with GFI)	Electrical Short	Arcing, electrifies other components with high voltage and possible ignition source.	9	Excessive loading	4	36
	Rear/Front Inertia Switch	Electrical Open	No high voltage shutoff in hazardous situation.	9	Improper maintenance	4	36
	Hybrid Vehicle (HV) Battery Pack	Cracking	Corrosive liquid leakage, toxic fire hazard, loss of power to electric motor, loss of power to vehicle.	6	Protective casing breach.	6	36
	Electronic Monitoring System	Miscalibration	Failure to prevent exposure to High Voltage.	9	Improper algorithm	4	36
Compressed Natural Gas	Storage Tank	Over-Pressure	Rupture, Explosion, Sonic Conditions	9	Improper operating conditions, Inoperative PRD	6	54
	Check Valve	Freezing	Prevents isolation, high pressure flammable back flow at the fill receptacle.	7	Fuel deposit buildup, Thermal Expansion	7	49
	Fill Receptacle	Deformation	Flammable leakage of high pressure gas during refueling.	8	Excessive loading	6	48
	Fill Receptacle	Seal Embrittlement	Flammable leakage of high pressure gas during refueling.	8	Improper maintanance	6	48
	Pressure Relief Device	Deformation	Premature operation, Flammable leakage.	5	Excessive loading	9	45
	Storage Tank	Localized Flame	Rupture, Flammable Leakage	9	Fuel line failure	5	45
Hydrogen Fuel-Cell	Direct Current High Voltage Cables (without GFI)	Electrical Short	Arcing.	9	Protective Casing Breach	7	63
	Alternating Current High Voltage Cables (without GFI)	Electrical Short	Arcing.	9	Protective Casing Breach	7	63
	Hydrogen Tanks	Over-Pressure	Leaks high pressure flammable gas. Possible explosion.	10	Improper operating conditions	6	60
	Pressure Relief Device (PRD)	Flame	Leaks large volume of high pressure flammable gas in presence of ignition source.	6	Flame	9	54
	High Pressure Tank Inlet Lines	Cracking	Leaks high pressure flammable gas.	7	Excessive loading	7	49
	Low Pressure Tank Outlet Lines	Localized flame	Leaks low pressure flammable gas in presence of ignition source.	7	Small flame	7	49

The modes of failure describe all the ways a component is capable of failing. Each identified failure mode can have a number of effects. Each of these effects is given a risk rating and is briefly described. The effect is then rated on a qualitative scale of severity numbering from 1, where no injuries or damage is expected, to 10, where death or complete destruction is expected in the event of failure. The most significant predicted causes of failure are described and ranked on another qualitative scale, also from 1 – 10. A hazard with a probability of 1 is not expected to cause a fire even in the lifetime of one out of one million vehicle systems. A rating of 10 represents that the probability of the failure scenario is assured to occur during the lifetime of at least one out of one million vehicle systems. Lastly, the product of the severity and probability ratings gives the RPN from which a determination of the priority of the hazard extends. The explicit rating descriptions are specified to describe EFV failures on the scales based on common industry practice (Otto and Wood, 2001, Dyadem, 2003).

3.2 *FMEA Results*

From the FMEA several issues with each vehicle became evident. The issues identified for each individual vehicle type are addressed in the following sections. Details of related failure scenarios from literature review and expert interviews are given to describe possible scenarios and justification for the qualitative result.

3.2.1 Gasoline-Electric Hybrid

The vehicle evaluated by the FMEA used an inertia switch to detect crashes, however not all vehicles use this method of detection. Other crash sensing systems can be defeated by different means resulting in the same hazard.

Failures involving the numerous electrical systems in this EFV type may result from a collision. Failures of the electrical system may also not be the initial cause of a fire, but during a fire scenario the prior failure of the system may cause further injury or damage by failing to activate safety devices.

Failure of the electronic monitoring system can allow fire hazards to become worse. For example, sensors may fail to activate shut-off valves when fuel leakage occurs. The unfamiliarity of these systems increases the probability that the system may be incorrectly calibrated or otherwise improperly modified during construction, maintenance, or repair of this EFV type (Scott, 2006).

In some hybrid designs, the battery pack is not protected by a ground fault interruption (GFI) system. If contacting the terminals directly due to an event such as a collision may result in a fire. However, many hybrids include the GFI within the battery pack. GFIs are actually one of many similar electrical safety systems employed by vehicle manufacturers. GFIs are the most commonly found method in the current hybrid vehicle fleet and so they were the method chosen for consideration in this analysis. GFIs may also be known by other names. Toyota names its GFI system a "Ground Fault Monitoring System" though the operation is the same as a standard GFI (Toyota, 2006).

Federal Motor Vehicle Safety Standard 305 specifies the requirement that electrical systems should remain isolated from the passenger compartment at all times (U.S. Department of Transportation, 2005). It is possible that future vehicle designs will have different components that may lower the probability and therefore the risk of failures as well. This could be true of any vehicle system that has different components from the one evaluated here. Electrical hazards are hazards which involve arcing or shorting of an electrical circuit. While electrical hazards may not often be the cause of fire itself it can be caused by a fire or events that cause a fire. The electrical hazard may then affect people involved in a fire scenario or the emergency response to it and thus it is considered among the fire hazards. Scott, an expert in EFV safety training, says that he would “feel confident that fire will not result in electrocution” (Scott, 2006). Given this expert’s opinion the probably of such a scenario is assumed to be low, but the consequence of even a rare occurrence is still significant. This value of consequence results in a notable risk result in the FMEA. As such, all possible measures to deactivate the high voltage system should be taken to avoid the risk of electrocution, such as turning off the car and disabling the battery with the manual breaker switch. The Toyota Camry Hybrid Emergency Response Manual carries the following warning that supports this recommendation. “Failure to shut off the vehicle before emergency response procedures are performed may result in serious injury or death from…the high voltage electrical system” (Toyota, 2006).

It should also be noted that in many vehicles their components will retain some voltage for some time after the vehicle is shut off or disabled. In the case of the Toyota Camry Hybrid Emergency Response Manual, “the SRS (Safety Restraint System) may remain powered up for up to 90 seconds after the vehicle is shut off or disabled.” (Toyota, 2006) It is never assumed to be safe to cut through any high voltage marked components, often identified by an orange coating (Dimmick, 2006).

In addition to the aforementioned electrification issue the lack of detection of a collision from a malfunctioning inertia switch could leave components improperly electrified and active. Following this a breach in the fuel tank caused by a collision could be ignited by arcing electrical components.

Cracking of the battery pack can result in the exposure of the internals of the battery. The electrolyte inside the battery being exposed in a fire can emit different toxic gases depending of the battery type. The explicit hazards vary with battery type, since some containing large quantities of corrosive liquid and others do not. According to Scott, "some large bus batteries can have as little as two soda cans of liquid in them…only to keep the paper moist." (Scott, 2006)

The leakage of fuel from the tank or the fuel line causing pooling is a significantly severe fire hazard resulting in a flammable or explosive scenario. Depending on the configuration of the tank in the vehicle the probability of the tank being ruptured in a collision varies.

3.2.2 Compressed Natural Gas

Over-pressurization of the fuel tank can result from the malfunction of a fueling station's pressure detection and relief devices. This is most likely to happen during refueling if dirt enters the system. Or, it could result from weakening of the tank due to mechanical or chemical damage. Weakening of the tank can result from a collision or acid or Ultra Violet (UV) light exposure. Seiff (Seiff, 2006a) has documented a number of natural gas vehicle fire incidents. One of these incidents exemplifies a situation where UV exposure was suspected as the cause of a CNG tank's rupture (Seiff, 2006b).

"A 12-year old aluminum-lined Type 2 cylinder produced by NGV Systems ruptured on a pick-up truck at Alabama Gas Co. No injuries were reported. The cylinder was suspected of having external physical and ultraviolet (UV) damage as well as being over-pressurized" (Seiff, 2006b).

The overpressure can result in a rupture and rapid leakage of the contained flammable gas. Two significant fire scenarios can result from this situation. If rapidly expelled gas is ignited, a large flame will result. Alternatively, leaked gas could accumulate and ignite resulting in detonation. Seiff has documented a case where the PRD of a CNG vehicle was vented upward without being ignited while venting, which led to an explosion (Seiff, 2006b).

The following account identified the circumstances associated with one incident: “An eleven foot, six inch tall Command bus shuttling race goers around Belmont Park attempted to go under a 9’ 6” underpass. The entire supporting frame of the roof mounted fuel storage system was pushed back approximately 10 feet. A high pressure fuel line detached causing a violent decompression of the entire fuel storage system. As the released gas rose, it was trapped by the overpass and ignited by a damaged underpass light fixture. Three confirmed minor injuries.” (Seiff, 2006b)

SAE 2006-1-0129 includes information about venting directions. This type of failure is not only severe, where detonation can result in the complete destruction of the vehicle and death of personnel, but it is also the most commonly cited mode of failure in Seiff’s documentation (Seiff, 2006b).

A check valve can freeze due to cold weather or during refueling with wet gas due to the Joule-Thompson effect as is documented in a few incidents by Seiff (Seiff, 2006b). For the system to operate normally, at least one check valve is located in the fill receptacle component leading to the high pressure solenoid valve bypass line to allow refueling to take place while the system is shut off and the solenoid valves are closed. If there are several tanks, there may be additional check valves (Orion, 2006; WMATA, 2006; Toyota, 2006). If there is only one check valve in the system and it freezes while refueling takes place there is a good chance that gas will be expelled when the operator removes the refueling nozzle from the fill receptacle while the operator is present. The pressure could expel the nozzle with a high force when it is disengaged from the fill receptacle injuring the operator. The possible ignition of this gas could burn the operator and thus has very severe consequences. If the system employs multiple check valves two possible scenarios could occur. If the check valve at the fill receptacle is independently frozen, the system will vent gas through the receptacle as soon as it is started, which is when the high pressure solenoids are opened. In the other case if one of the check valves on the bypass line is frozen but the receptacle check valve is not, then the high pressure lines will remain pressurized even when the system is shut off, creating a high pressure flammable gas hazard if the pipes are opened for maintenance.

Two similar modes of failure affect the fill receptacle. Deformation from physical damage and seal embrittlement from wear over time can both result in a high pressure flammable gas leakage at the fill receptacle during refueling in the presence of the operator. Because refueling requires the presence of the operator, they will most likely be in the presence of the fuel leak. However, the operator must visually guide the part of the nozzle to the receptacle and is therefore reasonably expected to spot the damage. For this reason it is less likely the failure will occur than with the previously mentioned check valve since the freezing may not be visually apparent and procedures to avoid check valve failure are not intuitive.

In most CNG vehicles, PRDs soften at a certain temperature to vent fuel and prevent pressure build up. PRDs can fail to activate if they are damaged, e.g., by impact. PRDs can fail to activate before the tank ruptures. Deformation is even more likely to cause PRDs to deploy prematurely in the presence of an otherwise small fire or frictional heat in a collision. Additionally ice damage is noted as a common reason PRDs vent when they should not (Dimmick, 2006).

A PRD may not activate because there is no redundant safety system provided to support the PRD. It is possible that deformation could cause the relief line leading to the PRD to be too constricted to relieve the pressure adequately, which would raise the severity of this scenario to the same level as for the overpressure state of the storage tank.

In a compressed gas vehicle PRDs are designed only to sense temperature at a single location for each PRD. For this reason a localized flame, for example, caused by the ignition of a leak in the high pressure fuel line on a part of the tank not occupied by a PRD can weaken the tank so that the rupture occurs. In addition, the flame could also raise the temperature and therefore the pressure inside the tank beyond the maximum limits of the tank. This mode of failure can result in explosion or flammable leakage from the tank in the presence of an ignition source. This specific mode of failure requires the PRD safety devices to not activate due to the location of the flames, and for any other redundant safety device to also fail to detect and deal with the flame.

3.2.3 Hydrogen Fuel Cell

Hydrogen is easier to ignite than CNG. For this reason, the rating of the severity and probability are higher. The description of the cause and effects of such a failure remain the same as described earlier for CNG. Because hydrogen flames can be invisible, detection is more difficult than for ignited flames from a CNG tank, further contributing to the higher RPN.

Many hydrogen vehicles, such as the Toyota Highlander, (Toyota, 2006) are designed to protect both their AC and DC high voltage cables with a GFI monitoring system, which automatically shuts off the current. However, other hydrogen vehicles do not have such systems and it is not required by vehicle regulations. In the case of a breach of the cable's protective coating without GFI protection, arcing due to high voltage may occur. It is known that arcing can occur through the air as well as through water. The additional possible methods of arcing increase the probability of failure beyond the probability of arcing through air alone. As stated before from emergency response manuals and expert interviews, the probability of such occurrences is still expected to be low.

The PRD for the hydrogen vehicle works in the same way as the PRD in the CNG vehicle, activating in the presence of flame. The presence of a flame is part of the device's normal operating procedure, since a hazardous scenario being present is how the device activates. The PRDs venting under normal conditions is assured to vent away from critical zones where it could cause damage or injury since it is operating within its design parameters. Still, the damage incurred by this component's operation may be moderate and if left unattended could result in damage spreading to other components if they are not cooled. It is highly probable that the component's operation will cause damage. However this damage is relatively small compared to the rupture that could occur if the tank were allowed to remain pressurized while exposed to weakening conditions.

Cracking in the high pressure gas line can leak high pressure flammable gas. This scenario is most likely to occur in a collision. Since the size of the line is smaller than the tank, the maximum possible rupture will be smaller than the maximum possible from the tank and thus the fire severity is lower. The lines are relatively unprotected in the event of a collision and if other safety components such as the solenoid valves do not isolate the breached line from the tank, the entire contents of the tank could vent. There is also the chance that the gas will not ignite when initially released and will accumulate and form an explosive mixture. Because this mode of failure requires the failure of additional safety devices in the system, it has a lower probability than a system without such safety precautions.

When exposed to a localized flame, breaching of the low pressure tank outlet lines could occur without activating temperature sensors, which would isolate the lines from the tank and other components. A localized flame of hydrogen leaking from another component would have an adiabatic flame temperature of 2384 K in air; (The Engineering Tool Box, 2005) stainless steel’s melting temperature is 1693 K (H. Cross Company, 2005). Pressure in these systems is monitored, (Toyota, 2006) so after a short time other leak preventative measures may respond to the hazard. In addition, the close proximity of this component to other components, which are easily affected by the failure and able to cause a localized flame in the engine compartment, raises its RPN.

3.3 *FMEA Future Research*

Several issues have arisen during the development of the FMEA that warrant further research. These issues are summarized as follows:

- Improving the safety of each component to improve the design would lower the present risk ratings. Future improvements will need to be reevaluated to be accurately assessed.
- Additional work on FMEA analyses of emerging fuel vehicles is warranted. This work could include developing FMEAs for fuel systems other than the three presented here and could consider specific designs and components of the systems included here. The analyses included here need to be validated with known statistics of vehicle fires and component failures for further accuracy.

Chapter 4: Quantitative Risk Assessment

While the FMEA presented in Chapter 3 helps identify and rank specific fire hazards for each vehicle type, it is not well suited to comparing the overall fire hazards or risks of these vehicle types. Thus a quantitative risk assessment is presented here for the vehicle types of Chapter 3: traditional, Gasoline-Electric Hybrid, CNG, and Hydrogen Fuel-Cell.

This assessment begins with detailed fire statistics for traditional vehicles in the U.S.. For each of the other vehicle types, the assessment then estimates multipliers on each fire cause frequency, each area of origin probability, and each probability of death. These multipliers are estimated using engineering judgment of the hazard identification and the results of knowledge gained from the FMEA analysis.

Applying these multipliers to existing statistics for traditional vehicles yields estimates of the numbers of fire deaths per vehicle per year for each vehicle type. The results are also generalized to obtain a plot of the variation in fire deaths associated with variations in the individual multipliers.

The quantitative risk assessment method applied in this analysis of EFVs follows a structure similar to a risk assessment of CNG Buses by Chamberlain and Modarres (2005). Their analysis differs in several ways from the ones performed for this research, primarily in how statistics are acquired and used. The overall structure remains the same where quantitative values are calculated for the probability and consequence of a scenario occurring to find the overall risk for a particular vehicle type. The analysis provides valuable information and a method for comparing the risk of one type of vehicle fleet to another with quantitative values as well as several other conclusions. This section first describes the overall risk calculation process and then presents the statistical source used to find each value, which was put into the aforementioned calculation.

4.1 *Traditional Fuel Vehicles*

Table 4.1. Traditional (Not EFV) fuel vehicle fire death risk calculation

Fire Cause			Area of Origin			Scenario Freq., fires/veh/yr	Consequence		Risk, deaths/ veh/yr
	Cause Mult.	Cause Freq., fires/veh/yr		Origin Mult.	Origin Prob.		Conseq. Mult.	Conseq., deaths/fire	
Failure of Equipment or Heat Source	1	8.43E-4	Fuel	1	0.01	9.95E-6	1	5.26E-3	5.24E-8
			Other	-	0.99	8.33E-4	1	1.89E-4	1.57E-7
Unintentional	1	2.72E-4	Fuel	1	0.03	7.85E-6	1	2.67E-2	2.09E-7
			Other	-	0.97	2.64E-4	1	3.97E-3	1.05E-6
Intentional	1	2.17E-4	Fuel	1	0.01	3.14E-6	1	0	0
			Other	-	0.99	2.14E-4	1	7.35E-4	1.57E-7
Other Known or Unclassified	1	6.07E-5	Fuel	1	0.02	1.05E-6	1	5.00E-2	5.24E-8
			Other	-	0.98	5.97E-5	1	2.63E-3	1.57E-7
Total		1.39E-3				1.39E-3			1.83E-6

Totals for the fleet result in 2.66E+5 fires/year and 350 deaths/year for a fleet of 1.91E+8 vehicles (EIA, 2005) and therefore an average of 1.32E-3 deaths per fire.

Note: All statistics are from or calculated from, Ahrens, 2005b except the fleet size.

Table 4.1 is a quantitative risk assessment for traditional fuel vehicle fire deaths. All entries in this table are statistics from Ahrens (2005b) and pertain to fire deaths in 2001. A sample equation and calculation for the first line of Table 4.1 is shown below:

A sample equation for the failure of equipment or heat source with the fire originating in the fuel tank or fuel line area for a traditional fuel vehicle is shown below:

(Cause Mult.)(Cause Freq.)(Origin Mult.)(Origin Prob.)(Conseq. Mult.)(Conseq.) = Risk

(1)(8.43e-4 [fires/vehicle/year])(1)(0.01)(1)(5.25e-3 [deaths/fire])=5.24e-8 [deaths/vehicle/year]

OR

(Scenario Freq.)(Consequence) = Risk

(9.95e-6 [fires/vehicle/year])(5.25e-3 [deaths/fire]) = 5.24e-8 [deaths/vehicle/year]

The statistics used to calculate the Cause Frequency, Origin Probability, and Consequence column values of Table 4.1 are reproduced in Table 4.2 for reference. Nearly all highway vehicle incidents in 2001 involved gasoline and diesel fueled non-hybrid engine systems.

Table 4.2. Statistics used for risk calculations

Origin	Cause	Fires	Deaths	Consequence, Deaths/Fire
All Areas	Failure of Equipment	161000	40	2.48E-4
	Unintentional	51900	240	4.62E-3
	Intentional	41400	30	7.25E-4
	Unclassified	11600	40	3.45E-3
Fuel Tank or Fuel Line	Failure of Equipment	1900	10	5.26E-3
	Unintentional	1500	40	2.67E-2
	Intentional	600	0	0
	Unclassified	200	10	5.00E-2
All Areas Except Fuel	Failure of Equipment	159100	30	1.89E-4
	Unintentional	50400	200	3.97E-3
	Intentional	40800	30	7.35E-4
	Unclassified	11400	30	2.63E-3

Note: All statistics are from or calculated from Ahrens, 2005b

The first three columns in Table 4.1 pertain to fire cause. These causes are divided into the four main categories of Ahrens (2005b): failure of equipment or heat source; unintentional; intentional; or other known or unclassified. Failure of equipment or heat source generally refers to the breakage of components through wear. Unintentional failures are failures resulting from a collision event. Intentional failures refer to cases of arson. Lastly unclassified or other known causes of failure are determined to be the remainder of events where the cause does not fall into one of the previously classified categories.

The cause multipliers (and all other multipliers) for traditional fuel vehicles are unity by definition. These multipliers will be adjusted below for other fuel system types to assess fire death risks.

The fire cause frequencies in Table 4.1 are from Ahrens (2005b). In total these show that there were 1.39E-3 fires per vehicle in 2001.

Two areas of origin are considered in Table 4.1: fuel and other. The fuel area is defined as being in the area of the fuel tank or fuel line components.

The probability of fire originating in the fuel area is low, with a range of 0.01 – 0.03 depending on fire cause. For each cause the origin probabilities have a sum of unity. These origin probabilities were assigned by dividing the number of fires originating in the fuel area due to a particular cause by the total number of fires (All Areas) due to that same cause.

The difference of the probability of fire origin in the fuel area from unity determines the fraction of fires that originate in other areas of the vehicle. Other areas refer specifically to the engine, running gear, wheel, operator, passenger, and trunk areas of the vehicle.

The scenario frequencies were determined by multiplying the cause frequency by the origin probability.

The fire consequence values were obtained from Ahrens (2005b) by dividing the number of deaths per year by the number of fires for each cause-origin scenario possibility.

Finally, the risk of fire death was obtained by multiplying the scenario frequency by the consequence. The sum of this risk for all causes and areas of origin was 1.83E-6 fire deaths per vehicle in 2001.

The 2001 U.S. highway vehicle fleet consisted of 191 million vehicles. When this number is multiplied by the total cause frequency and the risk, respectively, the results are 266,000 vehicle fires and 350 vehicle fire deaths in 2001.

4.2 *Gasoline-Electric Hybrid Vehicles*

A demonstration of how the multiplier is inserted into the fire death risk calculation for hybrid vehicles is shown in Table 4.3.

Table 4.3. Gasoline-electric hybrid fire death risk assessment calculation

Fire Cause			Area of Origin			Scenario Freq., fires/veh/yr	Consequence		Risk, deaths/veh/yr
	Cause Mult.	Cause Freq., fires/veh/yr		Origin Mult.	Origin Prob.		Conseq. Mult.	Conseq., deaths/fire	
Failure of Equipment or Heat Source	1.25	1.05E-3	Fuel	1	0.01	1.24E-5	1	5.26E-3	6.54E-8
			Other	-	0.99	1.04E-3	1	1.89E-4	1.96E-7
Unintentional	1.25	3.40E-4	Fuel	1	0.03	9.82E-6	1	2.67E-2	2.62E-7
			Other	-	0.97	3.30E-4	1	3.97E-3	1.31E-6
Intentional	1	2.17E-4	Fuel	1	0.01	3.14E-6	1	0	0
			Other	-	0.99	2.14E-4	1	7.35E-4	1.57E-7
Other Known or Unclassified	1	6.07E-5	Fuel	1	0.02	1.05E-6	1	5.00E-2	5.24E-8
			Other	-	0.98	5.97E-5	1	2.63E-3	1.57E-7
Total		1.67E-3				1.67E-3			2.20E-6

Totals for the fleet result in 3.19E+5 fires/year and 420 deaths/year for a fleet of 1.91E+8 vehicles (EIA, 2005) and therefore an average of 1.32E-3 deaths per fire.

Note: All statistics are from or calculated from, Ahrens, 2005b except the fleet size.

For gasoline-electric hybrid vehicles the electrical system is the main difference compared to a traditional fuel vehicle. The system involves many more complex components and high-voltage power. These fire hazards lead to an increased probability that a fire will occur; therefore the Cause Multiplier was increased from 1 to 1.25. For hybrid vehicles, the hazards are not likely to involve the fuel system more often, develop significantly faster, or with greater intensity than for traditional fuel vehicles. Therefore it is determined that for hybrid vehicle fire scenarios that are not related to the different electrical system, such as intentional scenarios, all other multipliers should remain the same.

The prediction is that 420 deaths per year are predicted based on a fleet size of 191 million vehicles. This is an increase by a factor of 1.2 from traditional fuel vehicles.

4.3 *Compressed Natural Gas Vehicles*

A demonstration of how the multipliers are applied in the fire risk calculation for CNG vehicles is shown in Table 4.4 below.

Table 4.4. CNG fire death risk assessment calculation

Fire Cause			Area of Origin			Scenario Freq., fires/veh/yr	Consequence		Risk, deaths/veh/yr
	Cause Mult.	Cause Freq., fires/veh/yr		Origin Mult.	Origin Prob.		Conseq. Mult.	Conseq., deaths/fire	
Failure of Equipment or Heat Source	1.5	1.26E-3	Fuel	1.5	0.02	2.24E-5	4	2.11E-2	4.71E-7
			Other	-	0.98	1.24E-3	1	1.89E-4	2.34E-7
Unintentional	1.5	4.08E-4	Fuel	1.5	0.04	1.77E-5	4	1.07E-1	1.88E-6
			Other	-	0.96	3.90E-4	1	3.97E-3	1.55E-6
Intentional	1	2.17E-4	Fuel	1.5	0.02	4.71E-6	4	0	0
			Other	-	0.98	2.12E-4	1	7.35E-4	1.56E-7
Other Known or Unclassified	1	6.07E-5	Fuel	1.5	0.03	1.57E-6	4	2.00E-1	3.14E-7
			Other	-	0.97	5.92E-5	1	2.63E-3	1.56E-7
Total		1.95E-3				1.95E-3			4.76E-6

Totals for the fleet result in 3.72E+5 fires/year and 910 deaths/year for a fleet of 1.91E+8 vehicles (EIA, 2005) and therefore an average of 2.44E-3 deaths per fire.

Note: All statistics are from or calculated from, Ahrens, 2005b except the fleet size.

For CNG vehicles the fuel system involves a high pressure gas storage and delivery system and this is the most significant factor in changing the risk for this vehicle. Given the higher vulnerability of a compressed fuel system due to wider flammability limits, having a greater number of components, and the PRD activation features of CNG vehicles it is more likely that fire scenarios will occur due to failure of equipment or heat sources and unintentional causes. For these aforementioned reasons the Cause Multiplier for CNG is increased by 0.5 giving it a total of 1.5.

Fires will originate in the fuel line or storage tank area of the vehicle more often for the same reason as the Cause Multiplier's increase. The value of the Origin Multiplier's increase is therefore the same as the Cause Multiplier's. The Origin Multiplier therefore is increased by 0.5 for a total of 1.5.

The consequence of fuel originating fire scenarios is increased due to natural gas's ability to produce a jet flame fire scenario or explosive fire scenario when the fuel is involved. An explosion scenario has the ability to affect a greater number of people than simply those carried by the vehicle itself including emergency responders inside the exclusion zone. A previous quantitative risk assessment of CNG buses took these hazards into account and gave an estimated value of consequence (Chamberlain and Modarres, 2005) that was considered when choosing the Consequence Multiplier in this analysis. Buses have a greater number of passengers, larger fuel storage, and different egress measures than passenger vehicles and thus have a higher consequence value. For this reason the Consequence Multiplier determined using the previous analysis was decreased to better represent the consequence of an entire CNG vehicle fleet. Thus the Consequence Multiplier was set to 4 in the current CNG vehicle analysis.

The result is that 910 deaths per year are predicted based on a fleet size of 191 million vehicles. This is an increase by a factor of 2.6 from traditional fuel vehicles.

4.4 *Hydrogen Fuel Cell Vehicles*

A demonstration of how the multiplier is applied in the fire risk calculation for Hydrogen vehicles is shown in Table 4.5 below.

Table 4.5. Hydrogen Fuel-Cell fire death risk assessment calculation

Fire Cause			Area of Origin			Scenario Freq., fires/veh/yr	Consequence		Risk, deaths/ veh/yr
	Cause Mult.	Cause Freq., fires/veh/yr		Origin Mult.	Origin Prob.		Conseq. Mult.	Conseq., deaths/fire	
Failure of Equipment or Heat Source	1.85	1.56E-3	Fuel	1.6	0.02	2.94E-5	5	2.63E-2	7.75E-7
			Other	-	0.98	1.53E-3	1	1.89E-4	2.88E-7
Unintentional	1.85	5.03E-4	Fuel	1.6	0.05	2.32E-5	5	1.33E-1	3.10E-6
			Other	-	0.95	4.79E-4	1	3.97E-3	1.90E-6
Intentional	1	2.17E-4	Fuel	1.6	0.02	5.03E-6	5	0	0
			Other	-	0.98	2.12E-4	1	7.35E-4	1.56E-7
Other Known or Unclassified	1	6.07E-5	Fuel	1.6	0.03	1.68E-6	5	2.50E-1	4.19E-7
			Other	-	0.97	5.91E-5	1	2.63E-3	1.55E-7
Total		2.34E-3				2.34E-3			6.80E-6

Totals for the fleet result in 4.47E+5 fires/year and 1298 deaths/year for a fleet of 1.91E+8 vehicles (EIA, 2005) and therefore an average of 2.9E-3 deaths per fire.

Note: All statistics are from or calculated from, Ahrens, 2005b except the fleet size.

Hydrogen fuel-cell vehicles, as mentioned earlier, have the hazards of a gasoline-electric hybrid vehicle and a CNG vehicle as well as several other unique hazards. As a result the Cause Multiplier of hydrogen vehicles is increased 0.25 above traditional fuel scenarios due to having a similar electric system of the hybrid vehicles. The Cause Multiplier is increased an additional 0.5 due to having a compressed fuel system that is similar to the CNG vehicles as well. Furthermore, since hydrogen has wider flammability limits and a higher leakage propensity the Cause

Multiplier is increased a further 0.10. The total Cause Multiplier for hydrogen is thus estimated at 1.85.

The Origin Multiplier for hydrogen is estimated at 1.6, a 0.6 increase from traditional fuel. Since hydrogen fuel cell vehicles have similar fuel transfer and storage components as CNG they have the same 0.5 increase in this multiplier. The further 0.1 increase to this multiplier is due to hydrogen having wider flammability limits and a higher leakage propensity than CNG.

The Consequence Multiplier for hydrogen vehicles is 5. This value was chosen relative to the chosen multiplier of CNG vehicles. The reason hydrogen has a higher multiplier value comes from hydrogen's low visibility flame and wider flammability limits. Since hydrogen flames are more difficult to detect it is likely that a greater number of people will enter a flame they would have avoided if it had been visually and radiantly more apparent.

The prediction is that 1298 deaths per year are predicted based on a fleet size of 191 million vehicles. This is an increase by a factor of 3.7 from traditional fuel vehicles.

The summary of the results of all four analyses are graphically represented in Figure 4.1.

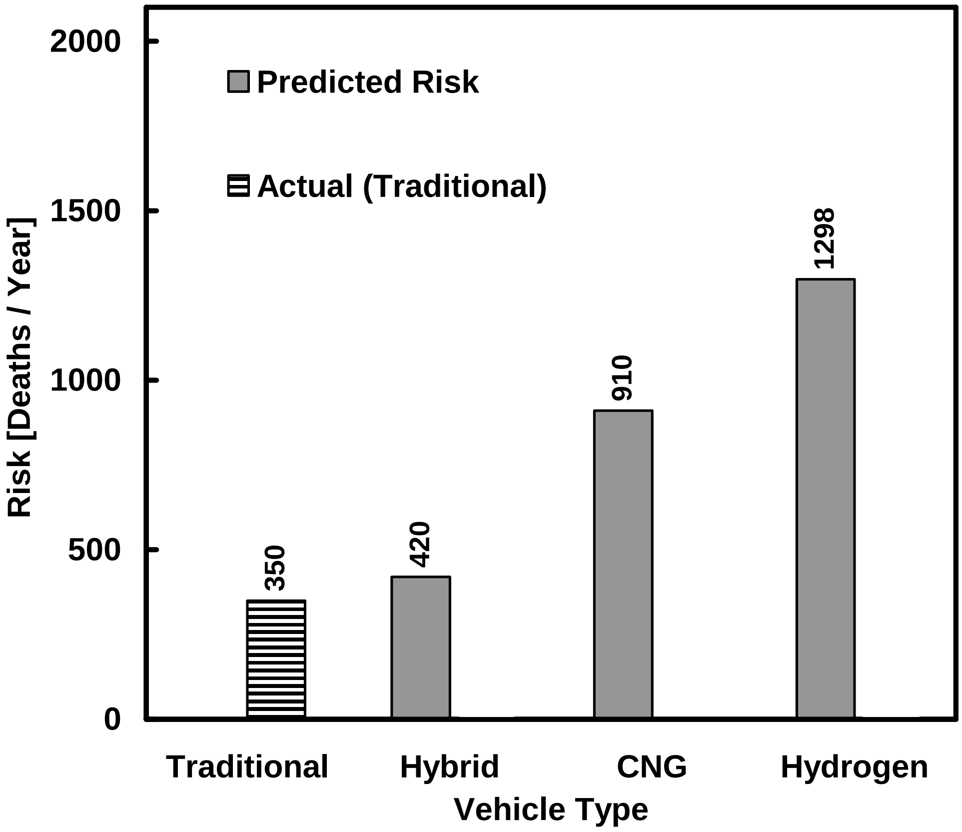


Figure 4.1. Predicted risk values by fuel type.

4.5 *Sources of Error*

There a number of sources of possible error that could affect the risk analysis. These errors may explain differences between the predicted risk and future statistics. The errors are enumerated as follows:

- Statistical Error
- Unprecedented or Unpredicted Vulnerability (Chain events…)
- Design Changes (Component protection, component configuration…)

4.5.1 Statistical Error

The Ahrens's statistics being used may be too dated to effectively represent changes that have been made in safety design and regulation in the last eight years or by the time a particular EFV dominates the vehicle fleet population. Currently there is a full variety in the age of vehicles on the road, and not all comply with current safety regulations. Assuming most of the EFV fleet being analyzed will be built in the future under the effect of these changes in design and regulation the overall risk could be different. Furthermore not all fire related deaths are reported or reported correctly (Wenske, 2006; Ahrens 2005a; Parsons, 1990).

Ahrens's statistics were taken between 1999 and 2001 (Ahrens, 2005b) and will likely not match the current vehicle situation. The number of vehicles on the road has increased each year up to the present time. This will change the risk calculated in units of deaths per year, but will not affect the risk calculated as the number of deaths per year per vehicle. Also the percentage of emerging fuel vehicles has also increased since the statistics were acquired. This change can affect the risk in both terms of both unit calculations. At this time there is no valid way to separate emerging fuel vehicles from the current vehicle data. However, because the percentage at this time is small, less than one percent (U.S. Census Bureau, 2008), this is not believed to have a significant effect on the result for traditional fuel risk.

A fire scenario that involves more than one vehicle can be statistically complicated. If two or more vehicles are involved in a fire scenario, they will be considered to be two separate scenarios in statistical reporting. Such an occurrence was not relevantly possible for traditional fuel scenarios and so the complicated effects it creates were not considered until the EFV analysis was performed. The effect of the new possibility of "chain scenarios" raises the probability of "Unintentional" fire scenarios for that type of vehicle fleet. The prediction of this requires accurate knowledge of fire scenario exclusion zones, average vehicle density, and is highly variable depending on vehicle configuration. The complexity of predicting such occurrences is beyond the scope of the statistics used in this thesis and cannot be predicted with reliable accuracy.

4.5.2 Unprecedented or Unpredicted Vulnerability

Much of safety design and regulation depends on prior experience. Without such experience it is difficult to predict the risk of scenarios that have never occurred before. Due to the large scale of some interesting high risk scenarios it is costly to do full scale testing to provide a better prediction. Two such large scale scenarios are a scenario where a jet flame from a PRD impinges on a fuel tanker in rush-hour type traffic and a scenario where a compressed gas fuel tank explosion occurs in an urban environment with surrounding high-rise structures.

4.5.3 Design Changes

Risk depends heavily on the explicit design choices made to construct a certain vehicle type, such as component choice and layout. In the current EFVs some compressed fuel systems do not have PRDs and some high voltage hybrid systems do not employ GFIs, however others do. Placement of the fuel tank or PRD on the roof or underside of a vehicle can also have an effect on how or whether a fire scenario occurs in a given circumstance. Which design configurations dominate future EFV production will change whether, how, and why certain fire scenarios may occur.

4.6 *Uncertainty Analysis*

Risk multipliers were chosen based on the knowledge gained from the prior research discussed in this thesis. For illustrative purposes are estimated to have an error of 20% or less.

For two of the EFV risk analyses several attributes are multiplied simultaneously and so the uncertainty of the multipliers are calculated using the following equations: (Kline et al., 1953)

$$R = R(v_1, v_2, \ldots v_n)$$

$$\Delta R \equiv Risk\_Change$$

$$\delta R \equiv Risk\_Uncert.$$

$$\Delta v \equiv Multiplier\_Change$$

$$\delta v = \Delta v \cdot 20\% \equiv Multiplier\_Uncert.$$

$$\delta R = \frac{\Delta R}{\Delta v_1}\delta v_1 + \frac{\Delta R}{\Delta v_2}\delta v_2 + \ldots + \frac{\Delta R}{\Delta v_n}\delta v_n$$

The resulting uncertainty value is added and subtracted from the predicted risk values to determine the maximum and minimum values of fire death risk, otherwise referred to as the risk error margin.

The variables used to calculate the value of each fuel type's uncertainty are shown in Table 4.6 below. In the table no multiplier was applied to the traditional fuel and so its uncertainty is assumed to be zero. This assumption is supported by the fact that this value is based on reported vehicle statistics of that year (Ahrens, 2005b) even though the statistics in Table 4.2 are estimated. For ease of comparison between vehicles the maximum and minimum risk values are graphed in Figure 4.2 based on the calculated uncertainty values.

Table 4.6. Predicted range of risk values by fuel type

Fuel	Δv_1	Δv_2	Δv_3	δv_1	δv_2	δv_3	Predicted Risk	ΔR	δR	Max Risk	Min Risk	Actual
Traditional	1	1	1	0	0	0	**0**	-350	0	**0**	**0**	**350**
Hybrid	0.25	0	0	0.05	0	0	**420**	70	14	**434**	**406**	**0**
CNG	0.5	0.5	3	0.1	0.1	0.6	**910**	560	336	**1246**	**574**	**0**
Hydrogen	0.85	0.6	4	0.17	0.12	0.8	**1298**	948	569	**1867**	**729**	**0**

Note: if $\Delta v_i = \Delta v_{i,gasoline}$, $\delta v_i = 0$

if $\delta v_i = 20\% * \Delta vi$, $\delta v_i = 0$

else $\Delta v_i \neq \Delta v_{i,gasoline}$, $\delta v_i = 0.2\ v_i$

Where for each vehicle type:

Δv_1= Cause Multiplier – 1.0

Δv_2= Origin Multiplier – 1.0

Δv_3= Consequence Multiplier – 1.0

ΔR= Total Risk – 350 [deaths/year]

Min. Risk = Risk – δR

Max. Risk = Risk + δR

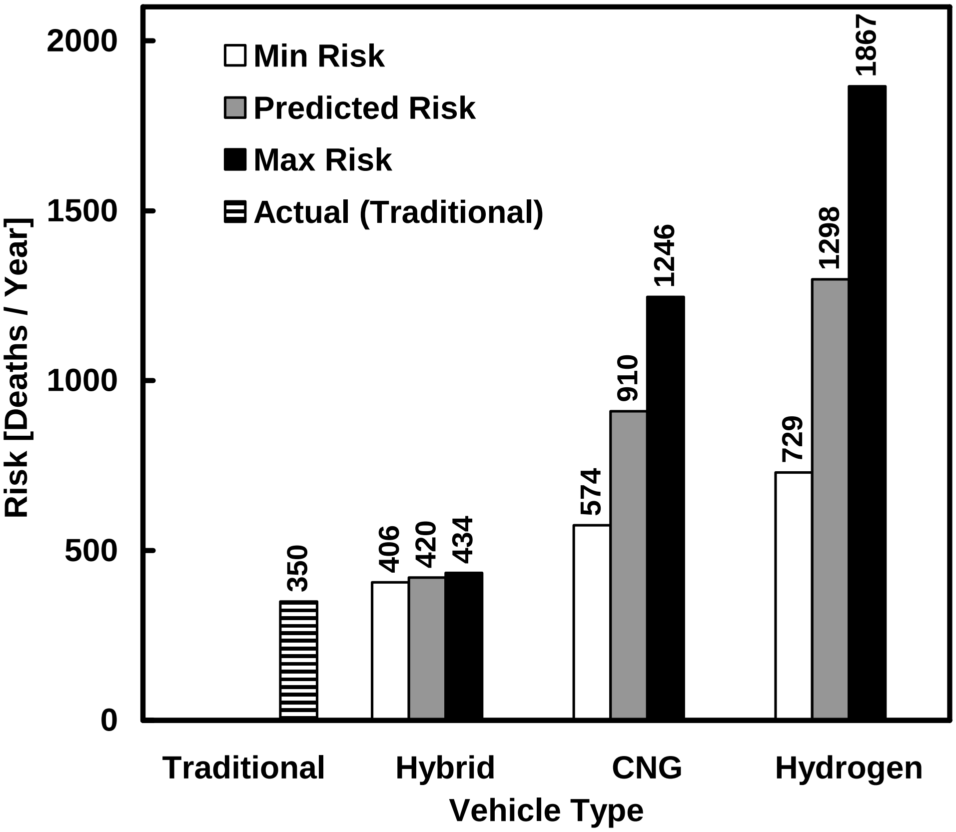


Figure 4.2. Risk with uncertainty values by fuel type.

The "Traditional" value is taken from Ahrens, 2001 statistics. Other values are calculated from Table 4.6 using the stated risk calculation with the number of vehicles on the road in 2001.

In Figure 4.2 above it can be seen that the uncertainty margin from least to greatest is Hybrid, CNG, and Hydrogen. The uncertainty calculation takes the size of the multiplier into account. Hydrogen fuel-cell vehicles are given the largest multiplier values for all three multipliers while gasoline-electric hybrids have the least greatest multiplier for only one multiplier. A greater value and number of changes in the multipliers results in a greater amount of uncertainty in the final amount of risk.

From the graph it is apparent that a gasoline-electric hybrid vehicle's predicted risk, as well as its maximum and minimum values, is above that of traditional fuel vehicles but significantly less than that of the other EFVs. Both compressed gas fuels have predicted, maximum, and minimum risk significantly above that of either traditional or hybrid vehicles. CNG ranged from roughly two times greater to up to four times greater risk than traditional fuel vehicles. There is some overlap between the values of CNG and Hydrogen Fuel-Cell risk and thus it is predicted that the risk of either vehicle may actually be the same due to error. But generally hydrogen fuel-cell vehicles have a higher predicted value and maximum value compared to the maximum values of the other vehicle types.

With future research using additional supporting statistics or experimentation the uncertainty of the risk calculation for these fuels can be reduced. If additional safety features or a major design change in the future are implemented some multipliers will be reduced or eliminated thus reducing the associated error.

4.7 *Multiplier Analysis*

This analysis process provides more than just a calculation method to predict comparable quantitative risk values. By independently varying the multipliers of cause frequency, area of origin probability, and consequence one can observe the relative impact that each scenario dependant multiplier has on the risk. Since there are three multipliers three lines were made on Figure 4.3.

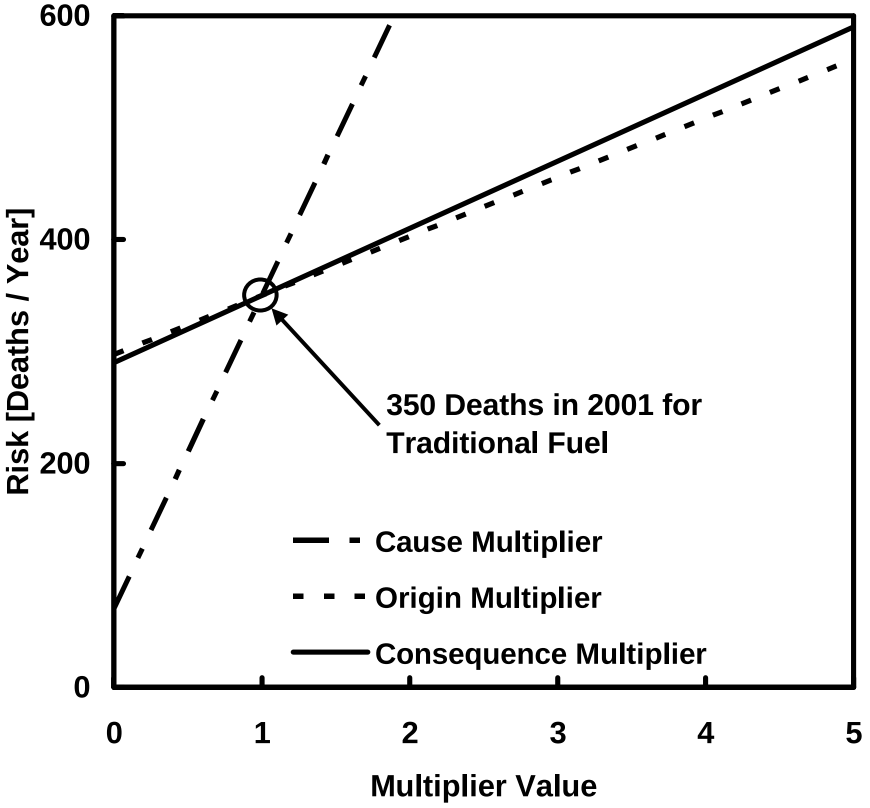


Figure 4.3. Risk trends due to fire risk multipliers.

The lines are made by changing one multiplier independently while keeping the other two multipliers at 1. If the multipliers are all set to 1, the multiplier values of a traditional fuel vehicle, then the number of deaths per year in 2001 is 350. Increasing a multiplier linearly increases the number of deaths per year. The slope of each line indicates the effect of changes in the multiplier on the estimated deaths per year.

The slope of the Origin Multiplier and the Consequence Multiplier are relatively the same. The Cause Multiplier has a much more significant effect than the other two multipliers, roughly 4.67 times greater. This indicates that if vehicle designs and regulations are changed to reduce the probability of fires caused by equipment and unintentional failures they will have a greater effect of reducing the risk than by changing the other multipliers by the same percentage.

Chapter 5: Conclusions

From the quantitative EFV risk assessment research the following conclusions can be made:

1. Hybrid vehicles provide only a moderately greater fire death risk than traditional fuel vehicles, an increase by an estimated factor of 1.2.
2. Compressed fuel vehicles have a much greater relative risk. CNG vehicles are predicted to have a fire death risk that is 2.6 times greater than traditional fuel vehicles. Hydrogen fuel-cell vehicles are predicted to have fire death risk that is 3.7 times that of traditional fuel vehicles. The larger estimated risk stems largely from failures of high pressure fuel tank and fuel line components. Such failures may result in jet and explosion fires. Another significant risk contributor is the activation of PRDs creating a jet flame. Though PRDs lower the probability of a high risk explosion scenario, their operation still presents a greater hazard than those hazards commonly found in traditional fuel vehicles. These EFV risk comparison values only apply to current vehicle designs.
3. The predicted risk uncertainty for the compressed fuel vehicles is much greater than for gasoline-electric hybrids. Further consideration through experimentation and simulation needs to be given to the fire scenarios associated with these fuels before a truly definitive answer can be given with regards to their comparative risk.
4. Reducing the Cause Multiplier results in the greatest reduction in risk, 4.67 times greater than the other two multipliers. To reduce the Cause Multiplier the frequency of fires occurring due to failure of equipment and heat sources as well as unintentional failures must be reduced. The effectiveness of a solution can be measured by considering whether

the solution will simultaneously reduce multiple multipliers, the risk reduction effect of the multiplier, and lastly the cost of implementing the solution.

From this research, opportunities have appeared where future research can aid the qualitative EFV risk assessment that were not addressed already during the hazard assessment suggestions for future research. These opportunities are as follows:

1. In future research experimentation and simulation can be done to provide greater accuracy. It is recommended that this be done with one vehicle type per set of report. This would allow for greater detail, a feasible cost for experimentation, a feasible timetable for simulation, multiple reporting on variations of each fuel type's design, and safety features. The broad range of three different fuel types did not allow as much focus on scenario development as if only one fuel type is considered per research period.
2. Use of a panel of experts to decide the values for estimates such as the multiplier values would increase the knowledge base used to make such estimates.
3. Research that applies simulations of egress success according to different fire scenarios would provide a much more accurate consequence value in the risk calculation. This research would identify what scenarios are most important to prevent due to higher predicted consequence.
4. Research can be done to determine the risk effects of complicated chain reaction event scenarios. Hopefully by focusing on one vehicle type at a time it may be feasible to address the effects of such complicated scenarios. However, these effects alone may each require their own separate research attempt.
5. Though it is too great of an extrapolation for this research to make, it may be relevant in future research to consider that a vehicle fleet entirely composed of compressed fuel type

vehicles will require a number of large sized fuel transport vehicles. The hazard of employing a large number of these vehicles may not be insignificant. While these vehicles currently exist, they are designed with safety margins based on operating in a traditional fuel vehicle fleet where explosions and other possible EFV hazards are a completely unexpected occurrence. The damage of an ignited flame jet of a PRD applied in a collision to a gasoline, natural gas, hydrogen, or other fuel tanker has yet to be quantified. Such large transport vehicles may require revised design, procedures, or regulations to ensure that during an EFV fire scenario they do not contribute to the scenario or otherwise remain outside the exclusion zone.

6. It would be an important contribution to develop the means to identify EFVs in statistics from standard reporting procedures. Using multipliers would then be unnecessary since the risk could be calculated directly from the identified statistics. Using future developed statistics will provide a more up to date comparison of risk. However, it will be increasingly important to separate EFVs from actual traditional fuel vehicles in generic statistics in the future since the percentage of these vehicles on the road is increasing and may eventually dominate the statistics over traditional fuel vehicles.

These recommendations and discoveries do not seek to warn against producing or developing any of the types of EFVs. By providing insight on the relative risks associated with EFVs these recommendations and discoveries will hopefully instead help to give all EFV types a chance at a viable future in the automotive industry.

Appendices

Appendix A – Expert Interviews Contact Information

Table A.1 – Table of Expert Interviews

Name		contact methods			
Last	First	email	phone	Occupation	Expertise
Akers	Bret	Bret_M_Akers@rl.gov	509-376-3712	Hydrogen safety - HAMMER Training and Education Center	H2 Safety
Astredo	Pat		213-922-5830	LA MTA - Largest US CNG fleet	CNG buses
Blake	Meghan	Info@cafcp.org	916-375-8034	Communications Specialist - Media - California Fuel Cell Partnership	Hydrogen Safety
Bush	Kevin	keberofpe@hotmail.com		FPE - MD State FM Office	Electrical fires and Non-Crashes
Chernicoff	William/Bill	william.chernicoff@dot.gov	202-360-6623	DOT	Government funded safety studies
Clemens	Richard		410-859-7481	BWI airport FD	BWI airport CNG bus fire incident, supply hose and vent hose for PRD
DeFlavis	Richard				BWI airport CNG incident contact info
Dickens	Jack	Jdickens@ci.chula-vista.ca.us			Hydrogen Refueling, Trailer
Dimmick	John	john.dimmick@sbcglobal.net	262-549-1894	NGV2 member	NG design standard changes
Flanagan	Timothy	timothy.flanagan@exeloncorp.com	610-832-6450	Peco Energy - Exelon Crop	CNG Delivery systems
Fluer	Larry	larryfluer@earthlink.net	805-238-7896		H2 Refueling
Fusco	Chuck	Chuckfusco@aol.com		Fire Chief - Berywn Heights	Emergency Response
Gambone	Livio	livio.gambone@powertechlabs.com		Presentation on CleanVehicle.org	CNG bus Fire incident video
Golden	Bob	rgolden@wmata.com	301-618-1181	Bus Vehicle Engineer - WMATA	CNG Buse Fire Hazards
Gromis	Adam			California Fuel Cell Partnership	H2 first responder's guide
Guilmette	Aaron		248-728-7000	R. L. Polk and Co.	Registered Vehicle Statistics
Halpert	Jeff	Jhalpert@ci.glendale.ca.us		Alum	CNG Bus Fires in Sacramento and Palms Springs from the LA Area Fire Marshals
Hamilton	Jennifer		916-375-4914	Safety Officer - California Fuel Cell Partnership	Hydrogen Safety
Haq	Kathy	khaq@apep.uci.edu		National Fuel Cell Research Center	Fuel Cell Safety
Hoagland	Bill		303-530-1140	Hydrogen 2000	DOE funded H2 Miami research
Holland	Geoff	h2000@earthlink.net		Hydrogen 2000	Hydrogen Safety Video
Jakubowski	Greg	gregory_jakubowski@merck.com		Alum with a PA FD	Emergency Response
Joseph	Tom	josepht@airproducts.com	610-481-8416	Air Products	H2 Refueling
Kerber	Steve	kerb24lgb@aol.com		Assistant Chief - College Park FD	Emergency Response
Knight	Cindy	Cindy_Knight@Toyota.com	310-468-2170	Marketing Communications PR Manager, Toyota Motor Sales, USA, Inc.	
Kolly	Joseph	KollyJ@ntsb.gov		NTSB	BWI CNG Bus fire report
Korn	James	jkorn@co.ba.md.us	410-887-4860	Baltimore County FD	Emergency Response
Leach	Susan	sdleach@comcast.net		Executive Director - Hydrogen 2000	Hydrogen Safety Video
McCoy	Danny	dmccoy@bhvfd14.org	301-741-8089	Wagon Driver of 10 Engine in WDC and Deputy Chief of Berywn Heights	Emergency Response

Milliken	Andrew	amilli@umd.edu, Andrew6512@aol.com		Sergeant	Emergency Response
Mount	Andy	Amount@plymouthtownship.org	610-277-4311	Fire Marshal in Plymouth Twp, Montgomery County, PA	traffic accidents in their area
O'Neill	Joe	Joneill@uppermoreland.org		Fire Marshal in Upper Moreland Twp., Montgomery County, PA	traffic accidents in their area
Panagiotou	Joe	panagij@ntsb.gov		NTSB	BWI CNG Bus fire report
Pehrson	Nancy	nancy.pehrson@centerpointenergy.com		Center Point Energy	NFPA 52 VAF Technical Committee
Platt	Tom			Assistant Fire Marshal	Emergency Response
Sawyer	Steve	ssawyer@nfpa.org	617-984-7423	Senior Fire Service Specialist/Executive Secretary IFMA - NFPA	traffic accidents
Scott	Marc	mwscott@lacofd.org	909-620-2202	Vehicle Extrication Instructor - Los Angeles County FD	CNG, Hybrid, H2 experience
Seiff	Hank	hseiff@cleanvehicle.org	703-534-6151	Director of Technology - Clean Vehicle Education Foundation	NG incidents and 1st responder training
Snyder	Bill	3094@bavfc.org		Bel Air, MD FD	Emergency Response
Stiteler	Don	don@uprov-montco.org		Fire Marshal in Upper Providence Twp., Montgomery County, PA	traffic accidents in their area
Stuart	Lurae	lstuart@apta.com	202-496-4844	Senior Program Manager-Bus Programs - American Public Transportation Association	CNG Buse Fire Hazards
Swain	Michael	mswain@miami.edu		Professor, University of Miami, Florida	H2 tests of Gasoline vs. Hydrogen fire
Tefft	Brian	brtefft@aaafoundation.org	202-638-5944 ex	Research Analyst - AAA Foundation for Traffic Safety	FARS and NASS data
Tucker	Elizibeth		202-737-1226	State Fire Marshal's Association	Electrical fires and Non-Crashes
Wallace	Phil	pwallace@wmata.com	301-618-1097	Head of Bus Maintenance - WMATA	CNG Buse Fire Hazards
Welsh	Fred	fhwelsh@att.net	240-777-2477	CFPS, EFO, Fire Chief - College Park	Emergency Response
Winston	Emily	ebwinston@ucdavis.edu			Hydrogen Refueling
Wolff	Ossana	owolff@umd.edu			CNG Buse Fire Hazards

Appendix B - Vehicle Layout

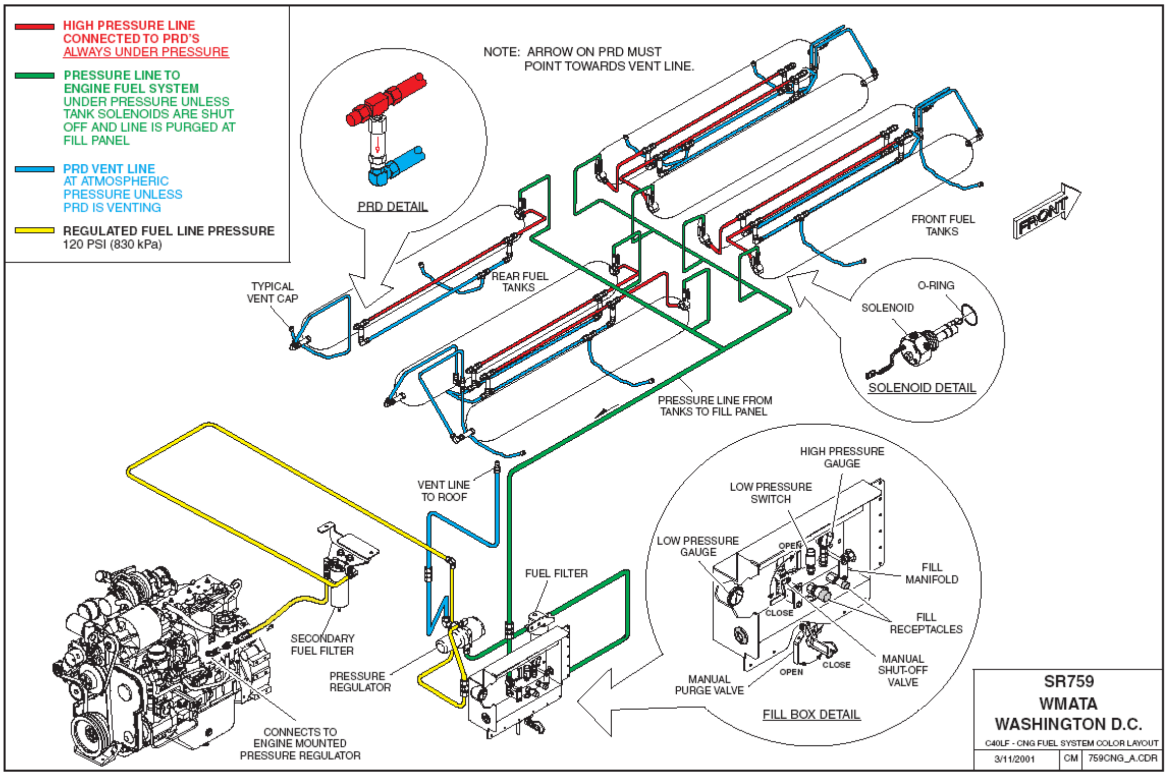


Figure B.1 - CNG Vehicle, in Color (WMATA, 2006)

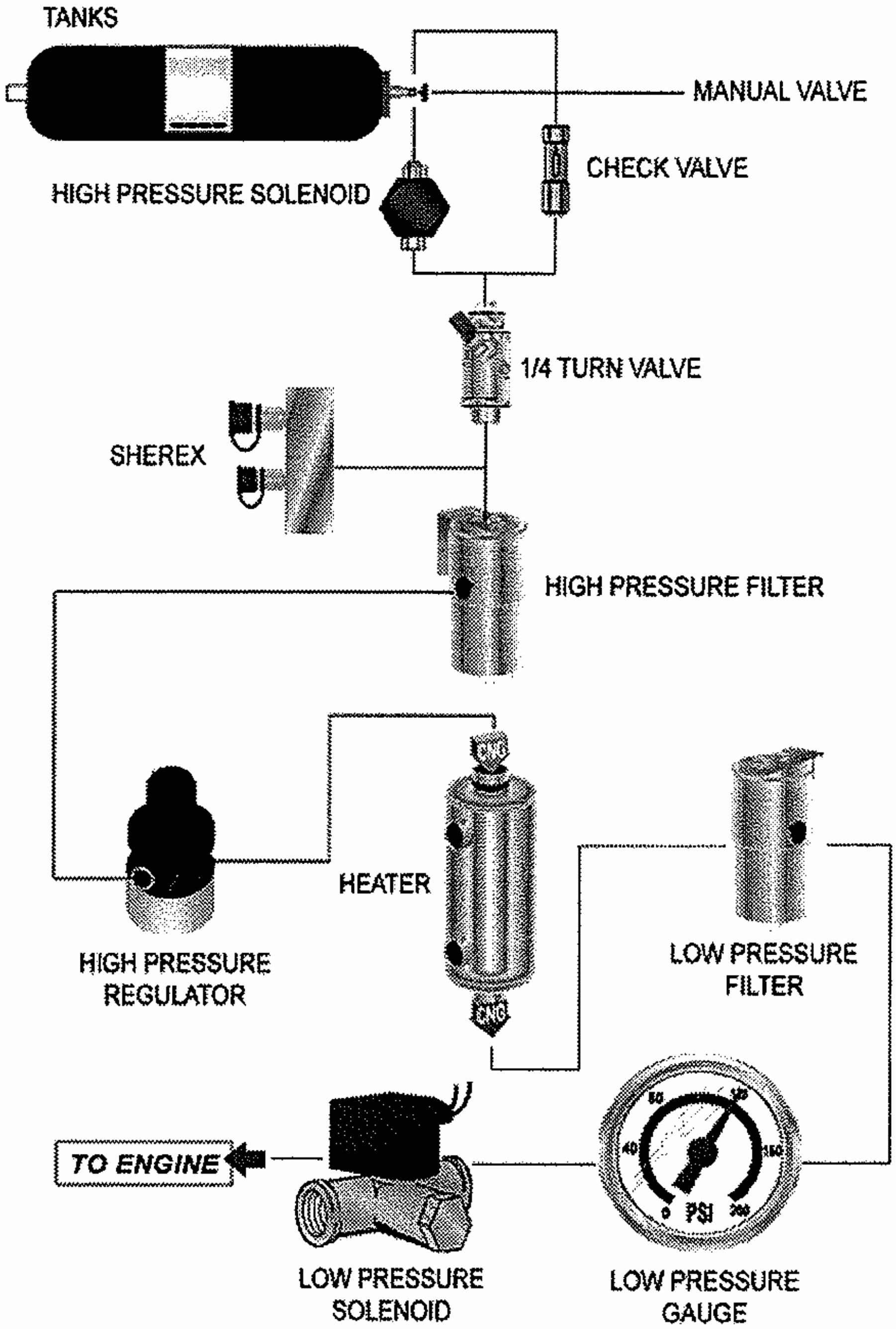
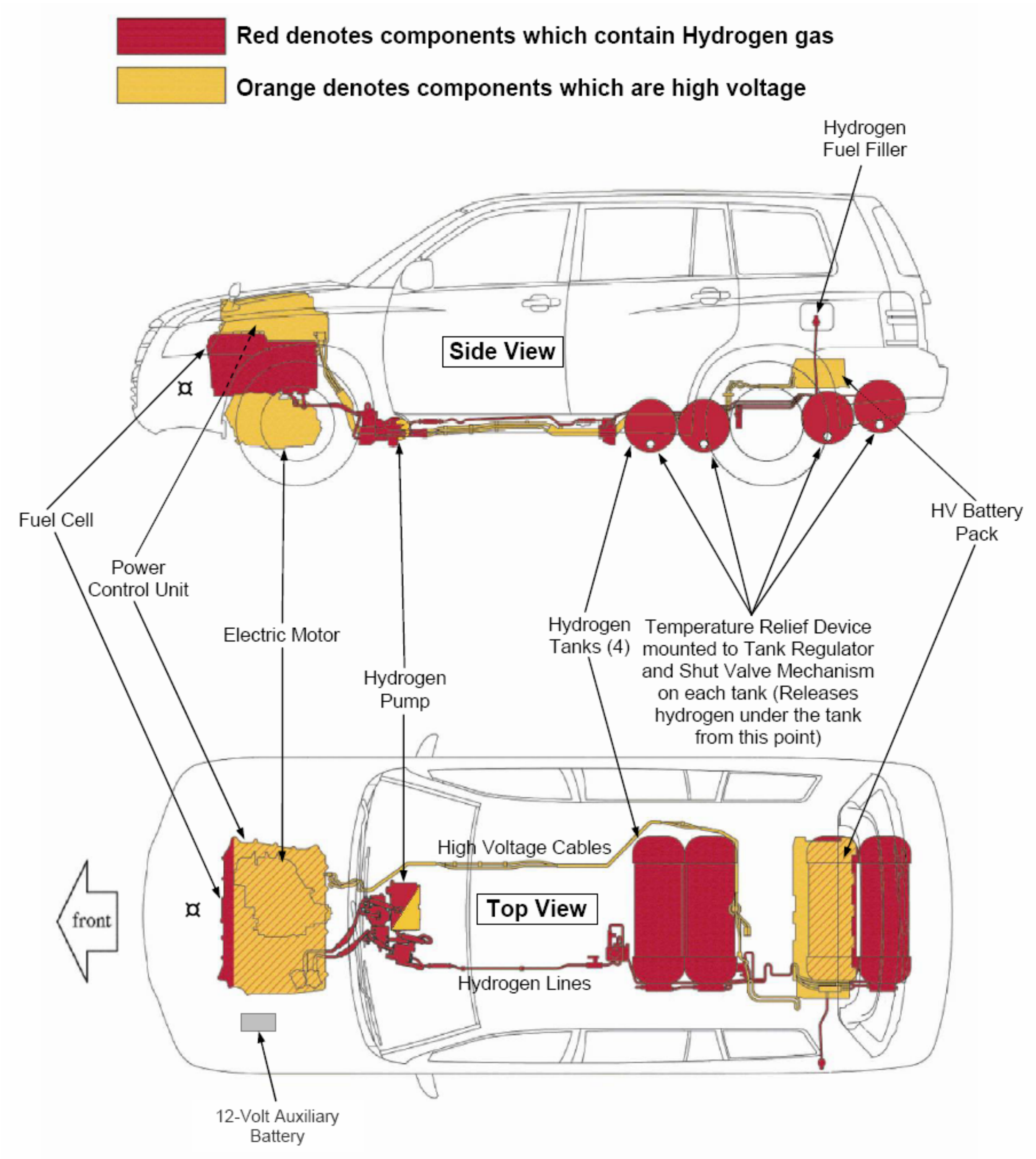


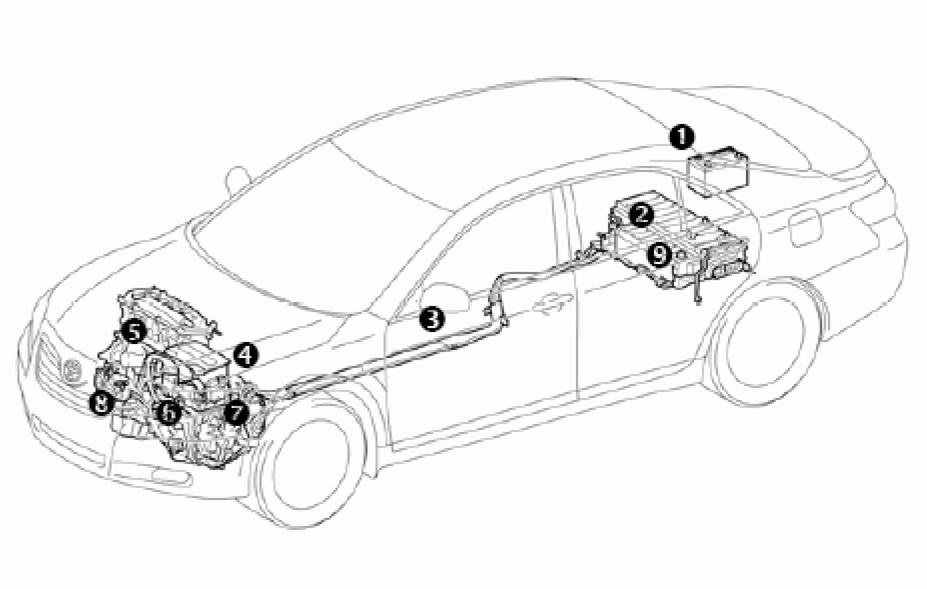
Figure B.2 - CNG Vehicle (Orion, 2006)



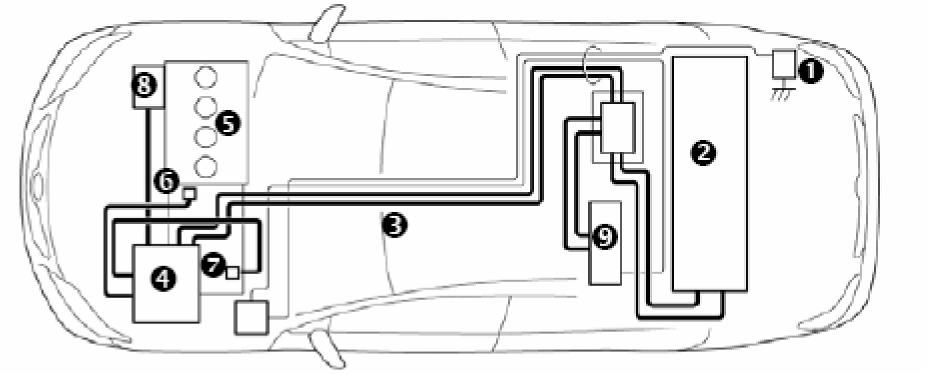
¤Although not shown in the illustration, the Fuel Cell Water Pump, Fuel Cell Air Pump, and the A/C Compressor are components located in the motor compartment. These components operate with high voltage electricity.

Figure B.3 - Hydrogen Fuel Cell Vehicle, in Color (Toyota, 2006)

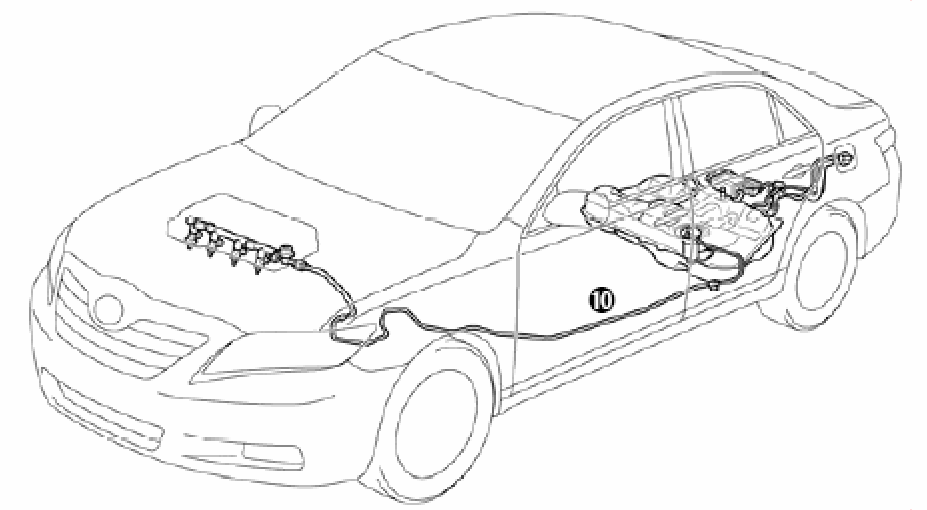
Reproduced with permission from Toyota Motor Corporation, April 21, 2008.



Hybrid Synergy Drive Components



Components (Top View) and High Voltage Power Cables



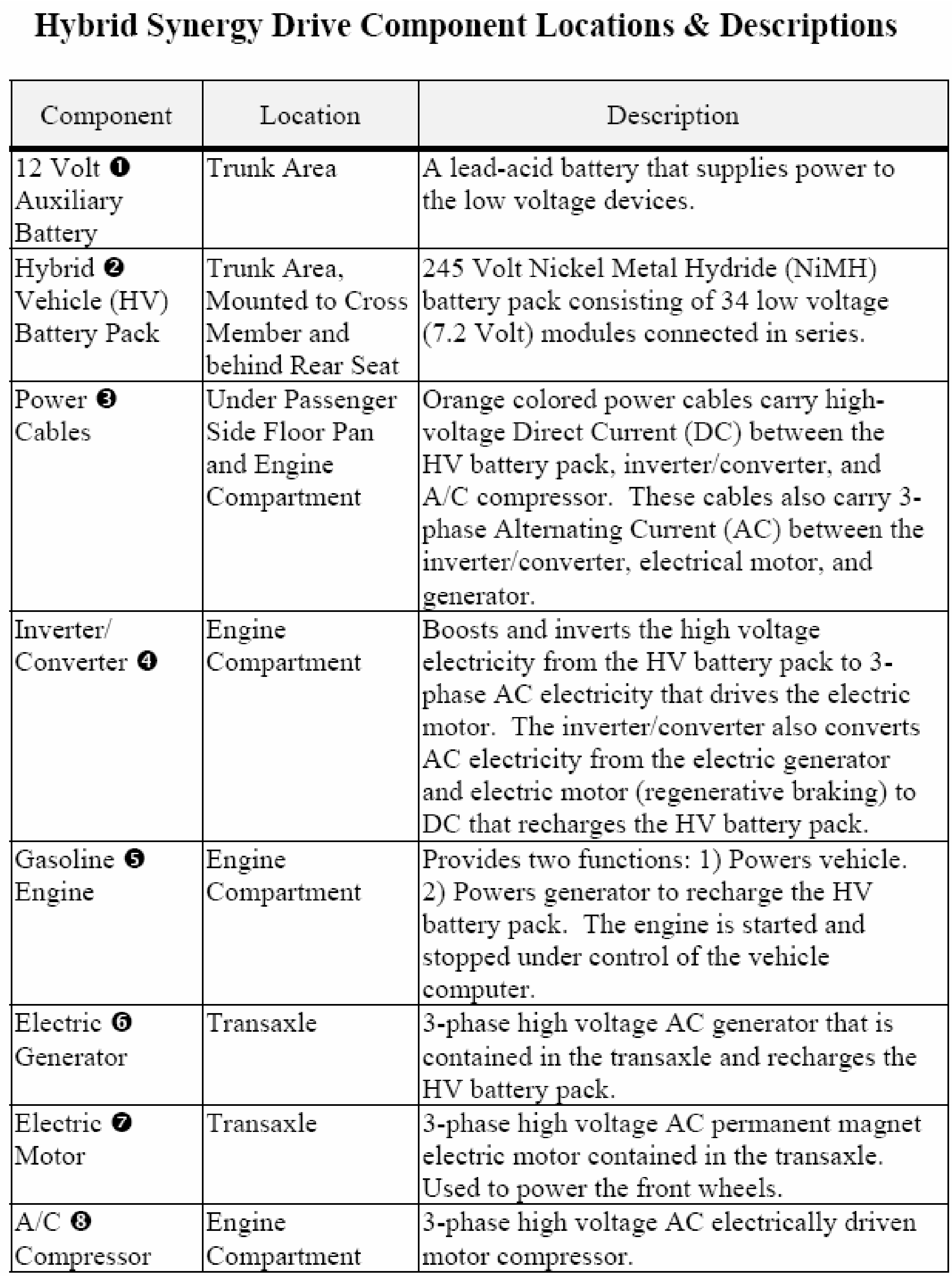
Fuel Tank and Fuel Line

Figure B.4 - Hybrid Vehicle (Toyota, 2006)

Used with permission from Toyota Motor Corporation, April 21, 2008.

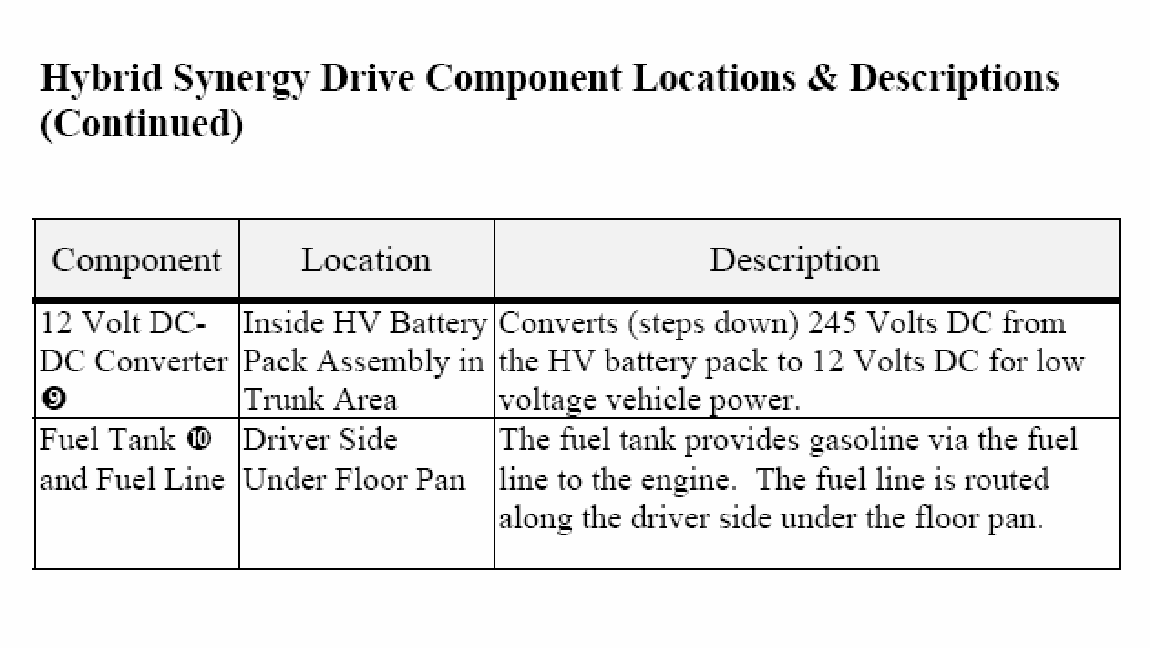
Table B.1 – Hybrid Vehicle Component Summary (Toyota, 2006)

Used with permission from Toyota Motor Corporation, April 21, 2008.



Hybrid Synergy Drive Component Locations & Descriptions

Component	Location	Description
12 Volt ❶ Auxiliary Battery	Trunk Area	A lead-acid battery that supplies power to the low voltage devices.
Hybrid ❷ Vehicle (HV) Battery Pack	Trunk Area, Mounted to Cross Member and behind Rear Seat	245 Volt Nickel Metal Hydride (NiMH) battery pack consisting of 34 low voltage (7.2 Volt) modules connected in series.
Power ❸ Cables	Under Passenger Side Floor Pan and Engine Compartment	Orange colored power cables carry high-voltage Direct Current (DC) between the HV battery pack, inverter/converter, and A/C compressor. These cables also carry 3-phase Alternating Current (AC) between the inverter/converter, electrical motor, and generator.
Inverter/ Converter ❹	Engine Compartment	Boosts and inverts the high voltage electricity from the HV battery pack to 3-phase AC electricity that drives the electric motor. The inverter/converter also converts AC electricity from the electric generator and electric motor (regenerative braking) to DC that recharges the HV battery pack.
Gasoline ❺ Engine	Engine Compartment	Provides two functions: 1) Powers vehicle. 2) Powers generator to recharge the HV battery pack. The engine is started and stopped under control of the vehicle computer.
Electric ❻ Generator	Transaxle	3-phase high voltage AC generator that is contained in the transaxle and recharges the HV battery pack.
Electric ❼ Motor	Transaxle	3-phase high voltage AC permanent magnet electric motor contained in the transaxle. Used to power the front wheels.
A/C ❽ Compressor	Engine Compartment	3-phase high voltage AC electrically driven motor compressor.



Hybrid Synergy Drive Component Locations & Descriptions (Continued)

Component	Location	Description
12 Volt DC-DC Converter ❾	Inside HV Battery Pack Assembly in Trunk Area	Converts (steps down) 245 Volts DC from the HV battery pack to 12 Volts DC for low voltage vehicle power.
Fuel Tank ❿ and Fuel Line	Driver Side Under Floor Pan	The fuel tank provides gasoline via the fuel line to the engine. The fuel line is routed along the driver side under the floor pan.

Appendix C – Table of Supporting Emergency Response Guides

Table C.1 - Supporting Emergency Response Guides

	Messages for:	**Emergency Responders**									**Traveling Public**								
Source		H2	CNG	Hybrid	Methanol	E-85	Propane	Biodiesel	P-Series	Electric	H2	CNG	Hybrid	Methanol	E-85	Propane	Biodiesel	P-Series	Electric
Toyota EFV Emergency Response Guide (ERG)	http://techinfo.toyota.com/	✓	✓	✓						✓									
RFA E85 Guides, Specs, and Procedures	http://www.ethanolrfa.org/objects/pdf/MemberDocuments/RFA_IndustryGuidelines.pdf					✓													
CaFCP - ERG - Fuel Cell Vehicles	http://www.hydrogensafety.info/resources/CaFCP_EmergencyGuide.pdf#search=%22Emergency%20Response%20Guide%20for%20Hydrogen%20Fuel%20Cell%20Vehicles%22	✓																	
CaFCP - H2 ERG Video	http://www.cafcp.org/resource-ctr_ermaterials.htm#er_video	✓																	
NHTSA - DOT - Approaching AFV Crashes (1996)	http://www.nhtsa.dot.gov/people/injury/enforce/pub/altfuel.pdf		✓		✓	✓	✓			✓									
NAFTC Training Courses (No free available material)	http://www.naftc.wvu.edu/curriculum/courses/coursedesc.html	✓	✓	✓			✓	✓		✓									
Risk…LPG Tanks	Hassan - SAE 2006-01-1274						✓												
GM Service Technical College	Hybrid Truck Emergency Personnel Training (2004)			✓															
B. Gustin, New fire tactics for new-car fires	Fire Engineering 149:43 (1996)			✓	✓	✓													
PECO Energy	ERG for Emergencies Involving Electricity and Gas	✓		✓						✓	✓		✓						✓
Consumer Reports Hybrid Safety Concerns	http://autos.msn.com/advice/CRArt.aspx?contentid=4023717												✓						
Texas State Safety manual Section 16 Vehicle Safety	http://www.vpfss.txstate.edu/riskmgt/Assets/16-VehicleSafety.pdf											✓				✓			
AFV Transit in Florida	http://www.clean-cities.org/pdf/afvguide.pdf											✓		✓	✓	✓	✓		✓
US DOE - AF Driver Training Manuals	http://www.eere.energy.gov/afdc/resources/altfueltraining/driver_training.html											✓			✓	✓	✓		
NYSERDA	Garage Guidelines for Alternative Fuels (1996)											✓	✓	✓	✓	✓			✓
DOE - Hydrogen Safety	http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_safety.pdf										✓								

Appendix D - FMEA

Table D.1 - FMEA Hybrid, arranged by components.

Potential Failure Mode and Effects Analysis (Design FMEA)

Component ID: Hybrid

Component Name	Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Probability	RPN
Hybrid Vehicle (HV) Battery Pack	Stores High Voltage Electricity	Electrical Short	Arcing, electrifies other components with high voltage and possible ignition source.	9	Short Circuit	4	36
		Cracking	Corrosive liquid leakage, toxic fire hazard, loss of power to electric motor, loss of power to vehicle.	6	Protective casing breach.	6	36
		Corrosion	Loss of power to electric motor, loss of power to vehicle.	5	Improper maintenance	4	20
High Voltage Cables (with GFI)	Carries Power Between System Components	Electrical Short	Arcing, electrifies other components with high voltage and possible ignition source.	9	Excessive loading	4	36
		Corrosion	Arcing, electrifies other components with high voltage and possible ignition source.	8	Improper Maintenance	4	32
		Cracking	Arcing, electrifies other components with high voltage and possible ignition source.	8	Protective casing breach.	4	32
Electronic Monitoring System	Monitors and Measures Electric Components.	Miscalibration	Failure to prevent exposure to High Voltage.	9	Improper algorithm	4	36
		Electrical Short	Loss of power to vehicle and system components.	1	Short Circuit	4	4

Fuel Tank (And fuel lines)	Holds Gasoline Fuel (and Carries Fuel to Engine)	Cracking	Flammable leakage	6	Protective casing breach.	6	36
		Deformation	Prevents fuel flow	2	Excessive loading	5	10
		Corrosion	Flammable leakage	6	Improper maintenance	1	6
		Clogging	Prevents fuel flow	2	Dirty Fuel	1	2
Rear/Front Inertia Switch	Disconnects High Voltage and Fuel in Collision	Electrical Open	No high voltage shutoff in hazardous situation.	9	Improper maintenance	4	36
		Electrical Short	Loss of power	1	Short Circuit	3	3
		Deformation	Loss of power to vehicle	1	Improper maintenance	7	7
Gasoline Engine	Powers Vehicle and Generator to Recharge HV Battery.	Corrosion	Rupture, flammable leakage.	6	Improper maintenance	5	30
		Deformation	Damage to engine, loss of power to the vehicle.	5	Improper maintenance	5	25
		Contamination	Prevents fuel flow	5	Dirty Fuel	5	25
		Torque Fatigue	Mechanical Failure	5	Excessive loading	5	25
Electric Motor	Powers Vehicle.	Torque Fatigue	High force mechanical failure	6	Excessive loading	5	30
		Electrical Short	Arcing, electrifies other components with high voltage and possible ignition source.	8	Short Circuit	3	24
		Cracking	Arcing, electrifies other components with high voltage and possible ignition source.	6	Protective casing breach.	3	18
		Deformation	Loss of power to vehicle	5	Improper maintenance	3	15
Inverter/Converter	Boosts and Inverts Power to and from AC and DC.	Electrical Short	Loss of power.	3	Short Circuit	7	21

Ground Fault Interrupt Cable Coating	Monitors and Prevents Exposure to High Voltage Wiring.	Miscalibration	Failure to prevent exposure to high voltage.	10	Improper maintenance	2	20
		Electrical Short	Loss of power to vehicle and system components.	2	Short Circuit	8	16
		Cracking	Loss of power to vehicle and system components.	2	Protective casing breach.	8	16
Electric Generator	Charges HV Battery Pack	Torque Fatigue	Failure to charge HV battery pack, loss of vehicle power, High force mechanical failure	4	Excessive loading	5	20
		Deformation	Failure to charge HV battery pack, loss of vehicle power, possible ignition source	5	Improper maintenance	3	15
		Cracking	Exposed high voltage component	8	Protective casing breach.	3	24
12 volt DC-DC Converter	Steps Down High Voltage to Low Voltage for System Components	Deformation	Failure to step down voltage	6	Excessive loading	3	18
		Cracking	Failure to step down voltage, exposed high voltage components	8	Protective casing breach.	2	16
		Electrical Short	Failure to step down voltage	6	Short Circuit	2	12
12 Volt Auxiliary Battery	Powers Low Voltage Devices	Cracking	Corrosive liquid leakage, loss of power to low voltage components.	2	Protective casing breach.	6	12
		Electrical Short	Loss of power to low voltage electrical equipment	1	Short Circuit	5	5
		Corrosion	Loss of power to low voltage electrical equipment	1	Improper maintenance	6	6

Table D.2 - FMEA CNG, arranged by components.

Potential Failure Mode and Effects Analysis (Design FMEA)

Component ID: CNG

Component Name	Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Probability	RPN
Storage Tank	Stores gas.	Over-Pressure	Rupture, Explosion	9	Improper operating conditions, inoperative PRD	6	54
		Localized Flame	Rupture, Flammable Leakage	9	Fuel line failure	5	45
		Corrosion	Rupture, Flammable Leakage	7	Exposure to acid	5	35
		Deformation	Rupture, Flammable Leakage	7	Excessive loading	5	35
Check Valve	Allows fuel to flow to the cylinders during fuelling (bypassing the high pressure solenoids) and close when fuelling is complete.	Freezing	Prevents isolation, high pressure flammable back flow at the fill receptacle	7	Fuel deposit buildup, Thermal Expansion	7	49
		Deformation	Prevents isolation, high pressure flammable back flow at the fill receptacle	7	Excessive loading	5	35
Fill Receptacle	Receives fuel from pump.	Deformation	Flammable leakage of high pressure gas during refueling.	8	Excessive loading	6	48
		Seal Embrittlement	Flammable leakage of high pressure gas during refueling.	8	Improper maintenance	6	48
		Cracking	Flammable leakage of high pressure gas.	7	Excessive loading	5	35

Pressure Relief Device	Vents pressure in the tank when exposed to temperatures between 212°F. and 250°F	Deformation	Premature operation, Flammable leakage	5	Excessive loading	9	45
		Localized Flame away from component	Failure to operate, Tank over-pressure	8	Fuel line failure	3	24
		Blockage	Explosion in tank	10	Dirty fuel	2	20
		Localized Flame near component	Premature operation, Flammable leakage	3	Fuel line failure	3	9
Manual Shutoff Valve on Fueling Manifold	Isolates the fill receptacle from the storage cylinders in case the check valves fail.	Fatigue	Prevents isolation of flammable leakage	7	Improper torque applied	5	35
		Freezing	Prevents isolation of flammable leakage	7	Fuel deposit buildup, Thermal Expansion	4	28
Magnetic Fuel Door Interlock Switch	Shuts off engine during refueling.	Localized Impact	Damaged components leak flammable gas.	6	Puncture of hood or door	6	36
		Electrical Short	Prevents isolation, high pressure flammable back flow at the fill receptacle	8	Improper maintenance	3	24
High Pressure Fuel Lines	Transmits fuel through system	Corrosion	Rupture, Flammable Leakage	7	Exposure to acid	5	35
		Cracking	Rupture, Flammable Leakage	7	Excessive loading	5	35
		Over-Pressure	Rupture, Flammable Leakage	8	Improper operating conditions	3	24
		Deformation	Prevents fuel flow	1	Excessive loading	6	6

Tube Fittings	Seals connection of fuel lines to components.	Torque Fatigue	Rupture, Flammable Leakage	6	Improper torque applied	5	30
		Corrosion	Rupture, Flammable Leakage	6	Exposure to acid	5	30
		Cracking	Rupture, Flammable Leakage	6	Excessive loading	4	24
Low Pressure Fuel Lines	Transmits fuel through system	Corrosion	Rupture, Flammable Leakage	6	Exposure to acid	5	30
		Cracking	Rupture, Flammable Leakage	6	Excessive loading, Thermal Expansion	5	30
		Over-Pressure	Rupture, Flammable Leakage	6	Regulator deformation	2	12
		Deformation	Prevents fuel flow	1	Excessive loading	5	5
High Pressure Solenoid Valve	Provides fuel isolation for the tank when the vehicle is shut off, or upon activation of the safety system.	Deformation	Prevents isolation, high pressure flammable back flow at the fill receptacle	6	Excessive loading	5	30
		Internal Corrosion	Prevents isolation during system shutdown	7	Dirty fuel	4	28
		External Corrosion	Rupture, Flammable Leakage	6	Exposure to acid or salt	2	12
		Electrical Short	Premature isolation, Prevents fuel flow	1	Wire failure	5	5
Pressure Regulator	Drops pressure in the fuel line from the storage pressure to the pressure required for the engine (~120PSI)	Deformation	Over-pressure of low pressure components	6	Excessive loading	5	30
		Clogging	Prevents fuel flow	1	Dirty fuel, Fuel line contamination	5	5

Manual Shutoff Valve on Tank	Isolates each individual cylinder manually.	Corrosion	Flammable leakage, Prevents isolation	5	Exposure to acid	5	25
		Deformation	Prevents isolation	4	Excessive loading	5	20
		Fatigue	Prevents isolation	4	Improper torque applied	4	16
Low Pressure Solenoid Valve	Isolates the fuel injectors from the low pressure fuel lines	Deformation	Prevents isolation	5	Excessive loading	5	25
		Internal Corrosion	Prevents isolation during system shutdown	5	Dirty fuel	3	15
		External Corrosion	Rupture, Flammable Leakage	6	Exposure to acid	2	12
		Electrical Short	Premature isolation, Prevents fuel flow	1	Wire failure	5	5
Fuel Heater	Heats the fuel.	Cracking	Rupture, Cold fuel clogs and damages components in further processes	4	Excessive loading	5	20
		Corrosion	Rupture, Cold fuel clogs and damages components in further processes	4	Exposure to acid	2	8
High Pressure Fuel Filter	Filters fuel.	Internal Corrosion	Unfiltered fuel, further component damage in further processes	2	Dirty fuel	9	18
		Excess Moisture	Unfiltered fuel, further component damage in further processes	2	Dirty fuel, Fuel line contamination	9	18
		External Corrosion	Rupture, Flammable Leakage	4	Exposure to acid	3	12
		Clogging	Prevents fuel flow	1	Dirty fuel	8	8
Low Pressure Fuel Filter	Filters fuel.	Internal Corrosion	Unfiltered fuel, further component damage in further processes	2	Dirty fuel	8	16
		Excess Moisture	Unfiltered fuel, further component damage in further processes	2	Dirty fuel, Fuel line contamination	8	16

		External Corrosion	Rupture, Flammable Leakage	4	Exposure to acid	3	12
		Clogging	Prevents fuel flow	1	Dirty fuel	6	6
Fuel Injector	Injects fuel into the engine.	Cracking	Rupture, Flammable Leakage	3	Excessive loading	5	15
		Deformation	Prevents fuel flow	1	Excessive loading	6	6
		Clogging	Prevents fuel flow	1	Dirty fuel	3	3
High Pressure Gauge	Measures the pressure in the high pressure fuel lines.	Deformation	Faulty measurement	2	Excessive loading	4	8
		Over-Pressure	Faulty measurement	2	Improper operating conditions	3	6
		Miscalibration	Faulty measurement	2	Improper operating conditions	1	2
Low Pressure Gauge	Measures the pressure in the low pressure fuel lines available to the fuel injectors.	Over-Pressure	Faulty measurement	4	Regulator deformation	2	8
		Deformation	Faulty measurement	2	Excessive loading	3	6
		Miscalibration	Faulty measurement	2	Improper operating conditions	1	2

Table D.3 - FMEA Hydrogen Fuel Cell, arranged by components.

Potential Failure Mode and Effects Analysis (Design FMEA)

Component ID: H2

Component Name	Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Severity	Potential Cause(s) / Mechanism(s) of Failure	Probability	RPN
Direct Current High Voltage Cables (without GFI)	Carries high voltage DC between the PCU and the fuel cell or HV battery pack.	Electrical Short	Arcing.	9	Protective Casing Breach	7	63
Alternating Current High Voltage Cables (without GFI)	Carries 3 phase AC between PCU and components in the motor compartment along with the hydrogen pump.	Electrical Short	Arcing.	9	Protective Casing Breach	7	63
Hydrogen Tanks	Stores compressed hydrogen	Over-Pressure	Leaks high pressure flammable gas. Possible explosion.	10	Improper operating conditions	6	60
		Localized flame	Leaks large volume of high pressure flammable gas.	8	Small flame	6	48
		Deformation	Compresses tank to over-pressure situation and lowers burst pressure limit.	8	Excessive loading	5	40
		Cracking	Leaks large volume of high pressure flammable gas.	8	Excessive loading	5	40
		Corrosion	Leaks large volume of high pressure flammable gas.	7	exposure to acid	4	28
Pressure Relief Device (PRD)	Fusible temperature plug that quickly vents the tank if the plug exceeds 230°F (110°C).	Flame	Leaks large volume of high pressure flammable gas in presence of ignition source.	6	Flame	9	54

		Deformation	Clogs and allows tank to overheat and exceed burst pressure.	10	Excessive loading	4	40
		Clogging	Allows tank to overheat and exceed burst pressure.	10	Dirty fuel	3	30
		Cracking	Premature fuel release.	5	Excessive loading	5	25
		Corrosion	Premature fuel release.	5	exposure to acid	4	20
High Pressure Tank Inlet Lines	Transports high pressure H2 from the filler to the fuel tank.	Cracking	Leaks high pressure flammable gas.	7	Excessive loading	7	49
		Localized flame	Leaks high pressure flammable gas in presence of ignition source.	8	Small flame	6	48
		Over-Pressure	Leaks high pressure flammable gas.	8	Improper operating conditions	5	40
		Corrosion	Leaks high pressure flammable gas.	7	exposure to acid	4	28
		Deformation	Stops fuel flow.	1	Excessive loading	9	9
Low Pressure Tank Outlet Lines	Transports lower pressure H2 from the filler to the fuel tank.	Localized flame	Leaks low pressure flammable gas in presence of ignition source.	7	Small flame	7	49
		Cracking	Leaks low pressure flammable gas.	6	Excessive loading	7	42
		Corrosion	Leaks low pressure flammable gas.	6	exposure to acid	5	30
		Over-Pressure	Leaks high pressure flammable gas.	6	Improper operating conditions	3	18
		Deformation	Stops fuel flow.	1	Excessive loading	9	9

Temperature Sensors	Measures temperature at the H2 tank and distribution lines and components.	Localized flame	Does not signal ECU system shutdown in presence of overheating and weakening of components lowering their burst pressure in presence of ignition source.	8	Small flame away from sensor	6	48
		Miscalibration	Does not signal ECU system shutdown in presence of hazardous situation, allows over temperature of components.	8	Improper construction	2	16
		Electrical Short	Premature ECU engine shutdown.	1	Excessive voltage	2	2
Check Valve	Ensures one way flow of fuel at the H2 filler, each tank and at locations in the distribution lines.	Freezing	Does not shut down fuel flow, allowing high pressure flammable gas leak.	7	Thermal Expansion	6	42
		Deformation	Does not shut down fuel flow, allowing high pressure flammable gas leak.	7	Excessive loading	5	35
		Cracking	Leaks high pressure flammable gas.	6	Excessive loading	5	30
Hydrogen Fuel Receptacle	Inlet coupling receptacle for fueling.	Seal Degradation	Leaks high pressure flammable gas.	7	Wear	6	42
		Deformation	Leaks high pressure flammable gas.	7	Excessive loading	4	28
		Cracking	Leaks high pressure flammable gas.	6	Excessive loading	3	18
Pressure Sensors	Detects abnormal pressure loss (leak) or increase (regulator/valve malfunction).	Localized flame	Does not signal ECU system shutdown in presence of overheating and weakening of components lowering their burst pressure in presence of ignition source.	8	Small flame	5	40

		Miscalibration	Does not signal ECU system shutdown in presence of overheating and weakening of components lowering their burst pressure.	10	Improper construction, Overpressure	2	20
		Electrical Short	Premature ECU engine shutdown.	1	Excessive voltage	2	2
Impact Sensors	Sense a predetermined level of frontal, side, or rear impact.	Localized Impact	Does not signal ECU system shutdown in presence of hazardous situation.	8	Projectile collision	5	40
		Electrical Short	Does not signal ECU system shutdown in presence of hazardous situation.	6	Wire breakage.	3	18
Fuel door/Hood Sensor	Detects open/closed state of the fuel door or hood.	Localized Impact	Damaged components leak flammable gas.	6	Puncture of hood or door	6	36
		Electrical Short	Does not signal ECU system shutdown while fueling or performing maintenance.	8	Improper operating conditions	2	16
Tank Outlet Pressure Regulator	Regulates fuel pressure at the outlet of each tank to a lower pressure.	Deformation	Allows over-pressure of lower pressure fuel lines.	7	Excessive loading	5	35
		Cracking	Leaks large volume of high pressure flammable gas.	7	Excessive loading	4	28
HV Battery Pack (BP)	274-Volt NiMH battery pack consisting of modules connected in series.	Electrical Short	Electrifies other components with high voltage and possible ignition source.	8	Improper operating conditions	4	32
		Cracking	Leaks toxic and burnable battery acid.	4	Excessive loading	6	24
Engine Control Unit (ECU)	Monitors system pressures and temperatures and actuates tank shut valves.	Miscalibration	Does not activate safety devices in presence of hazardous heat or pressure situations.	9	Erroneous algorithms	3	27
		Electrical Short	Does not activate safety devices in presence of hazardous heat or pressure situations.	9	Improper construction	2	18

		Electrical Short	Does not activate safety devices in presence of hazardous heat or pressure situations.	9	Excessive loading	2	18
Water Pump	Circulates coolant between the fuel cell, hydrogen pump and radiators.	Deformation	Possible ignition source and increases temperature in fuel cell.	4	Excessive loading	6	24
		Cracking	Possible ignition source and increases temperature in fuel cell.	4	Excessive loading	6	24
		Electrical Short	Possible ignition source and increases temperature in fuel cell.	4	Excessive voltage	5	20
Tank Shut Valve Mechanism	Shuts off fuel flow from each tank with normally closed solenoid.	Cracking	Leaks high pressure flammable gas.	6	Excessive loading	4	24
		Corrosion	Does not shut down fuel flow, allowing high pressure flammable gas leak.	7	Dirty fuel, Exposure to acid	3	21
		Deformation	Does not shut down fuel flow, allowing high pressure flammable gas leak.	7	Excessive loading	3	21
		Electrical Short	Premature valve closing.	1	ECU malfunction	2	2
Electric Motor	3 Phase AC permanent magnet electric motor contained in the transaxle. Driven by the PCU and used to power the vehicle during "coasting" or braking.	Electrical Short	Arcing.	8	Protective Casing Breach	3	24
		Torque Fatigue	Mechanical failure.	5	Excessive loading	4	20
		Corrosion	Mechanical failure.	5	exposure to acid	3	15
		Deformation	Engine shut down.	1	Excessive loading	6	6

Hydrogen Pump	Circulates H2 through the fuel cell.	Deformation	Possible ignition source and leaks flammable gas.	4	Excessive loading	5	20
		Cracking	Possible ignition source and leaks flammable gas.	4	Excessive loading	5	20
		Electrical Short	Possible ignition source and leaks flammable gas.	4	Excessive voltage	4	16
Fuel Cell (FC)	Utilizes H2 and O2 from the air to generate high voltage DC.	Electrical Short	Possible ignition source in presence of flammable gas.	4	Excessive voltage	5	20
		Cracking	Leaks flammable gas and possible ignition source.	4	Excessive loading	4	16
		Contamination	Engine loses energy.	1	Dirty fuel	9	9
Hydrogen Sensors	Detect hydrogen gas accumulation.	Electrical Short	Does not signal ECU system shutdown when hydrogen accumulation causes explosive conditions to develop.	8	Improper operating conditions	2	16
		Miscalibration	Does not signal ECU system shutdown when hydrogen accumulation causes explosive conditions to develop.	8	Improper construction	1	8
BP High Voltage Fuse	Provides short circuit protection in the HV battery pack.	Electrical Short	Allows short circuit of high voltage lines.	8	Improper operating conditions	2	16
FC and BP Electric Relays	Stops electric flow from both the fuel cell and the HV battery pack.	Electrical Short	Does not prevent component electrification with high voltage current.	8	Improper operating conditions, Melting relay contacts	2	16
Direct Current High Voltage Cables (with GFI)	Carries high voltage DC between the PCU and the fuel cell or HV battery pack.	Electrical Short	Arcing.	8	Protective Casing Breach	2	16
Power Control Unit (PCU)	Converts DC current to 3 phase AC current and vice versa.	Electrical Short	Arcing.	8	Excessive voltage	2	16

Alternating Current High Voltage Cables (with GFI)	Carries 3 phase AC between PCU and components in the motor compartment along with the hydrogen pump.	Electrical Short	Arcing.	8	Protective Casing Breach	2	16
Air Pump	Pumps air to the fuel cell.	Deformation	Possible ignition source.	2	Excessive loading	5	10
		Cracking	Possible ignition source.	2	Excessive loading	5	10
		Electrical Short	Possible ignition source.	2	Excessive voltage	4	8
Ground Fault Monitor	Monitors for high voltage leakage to the metal chassis while the vehicle is running. Actuates electric relays.	Electrical Short	Does not prevent component electrification with high voltage current.	8	Monitor Malfunction	1	8

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