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Risk Assessment of Hydrogen Fuel Cell Electric Vehicles in Tunnels

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Abstract. The need to understand the risks and implications of traffic incidents involving hydrogen fuel cell electric vehicles in tunnels is increasing in importance with higher numbers of these vehicles being deployed. A risk analysis was performed to capture potential scenarios that could occur in the event of a crash and provide a quantitative calculation for the probability of each scenario occurring, with a qualitative categorization of possible consequences. The risk analysis was structured using an event sequence diagram with probability distributions on each event in the tree and random sampling was used to estimate resulting probability distributions for each end-state scenario. The most likely consequence of a crash is no additional hazard from the hydrogen fuel (98.1–99.9% probability) beyond the existing hazards in a vehicle crash, although some factors need additional data and study to validate. These scenarios include minor crashes with no release or ignition of hydrogen. When the hydrogen does ignite, it is most likely a jet flame from the pressure relief device release due to a hydrocarbon fire (0.03–1.8% probability). This work represents a detailed assessment of the state-of-knowledge of the likelihood associated with various vehicle crash scenarios. This is used in an event sequence framework with uncertainty propagation to estimate uncertainty around the probability of each scenario occurring.

Keywords: Hydrogen, Risk, Fuel cell electric vehicle, Event sequence diagram

1. Introduction

Hydrogen fuel cell electric vehicles (FCEV) will become more prevalent on public roads and highways as the technology and supporting infrastructure mature. A description of the fuel cell vehicle and general diagram of components is given in [1]. The deployment of FCEVs and their required infrastructure has been initiated in the state of California within the United States. The next region that will see the introduction of FCEVs is the northeast corridor, a region stretching from Washington DC to Boston. As the geographical area of FCEVs increases, the impact of these vehicles on various road structures, such as tunnels, must be considered. This work documents a risk framework, analysis, and quantification for potential traffic incidents in tunnels.

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1.1. Hydrogen Vehicle Requirements

Hydrogen vehicles have robust requirements which evolved from other alternative fuel vehicle requirements, such as compressed natural gas (CNG) as well as from hydrogen release behavior research and experimental studies [2]. Global Technical Regulation No. 13 (GTR #13) [3] provides requirements for the integrity of compressed and liquid hydrogen motor vehicle fuel systems. The intent of GTR #13 is to establish a global regulation for FCEVs that attains levels of safety equivalent to those for conventional gasoline powered vehicles. The test procedures and methods specified in GTR #13 include pressure cycling tests (pneumatic and hydraulic with temperature variations), a burst test, a permeation test, and a bonfire test (localized and engulfing).

1.2. Tunnel Safety Requirements

The National Fire Protection Association (NFPA) 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways, provides fire protection, life safety and design requirements for authorities having jurisdiction (AHJs) to use in ensuring tunnel safety [4]. Annex G of NFPA 502 provides specific recommendations for addressing alternative fuel vehicles and specifically states that in the long term, regulators should be able to rely on the approved listing and labeling to permit these vehicles in road tunnels. NFPA 502 states that the AHJ is ''responsible for evaluating each tunnel on a case-by-case basis… by risk analysis, computer modeling, experimental testing or all of the above.'' Although the safety standards and regulations for FCEVs are more developed than when that guidance was written in NFPA 502, a risk analysis may still be warranted. Unlike other alternative fueled vehicles, FCEVs are built only by original equipment manufacturers (OEMs) and are required to comply with the same rigorous safety standards as all gasoline- and diesel-fueled vehicles: the GTR and Federal Motor Vehicle Safety Standards (FMVSS) [5].

1.3. Previous Alternative Fuel Vehicle Tunnel Studies

In 1994–1995, a hazard analysis was completed by Worcester Polytechnic Institute (WPI) on alternative fuel vehicles in tunnels including CNG, liquefied petroleum gas (LPG), and liquefied natural gas (LNG) (hydrogen was not included) [6]. These studies specifically excluded both the extremely small release scenarios (resulting in a loose fitting in the fuel system and a slow small leak) as well as the pressure vessel rupture scenario. The basis for excluding the pressure vessel rupture scenario was that the CNG pressure vessel industry standards include specific regulations on the fuel system integrity and the required pressure vessel testing ensured resilient pressure vessels. The venting of CNG due to an external fire scenario was also eliminated because the external fire presented an existing hazard and an additional jet fire of CNG was deemed to be not significant enough to drive the evaluation. Additionally, if the venting CNG did not immediately ignite, it was assessed that the fire induced buoyancy would enhance the dispersion of the released gas.

The results of this study determined that the size and duration of flammable vapor regions are highly dependent on the tunnel ventilation rates. For all ventilation rates examined, the expected size and duration of a flammable vapor cloud was less than the equivalent gasoline scenario. Also, the flammable cloud of natural gas would not persist for more than a few minutes before dissipating. The fire consequence analysis concluded that the gasoline spill would result in a larger heat release rate and larger smoke cloud than the CNG fire. As a result of this study, a policy allowing CNG vehicles in Massachusetts tunnels was adopted.

1.4. Hydrogen Vehicle Risk Assessments

There are a number of challenges in performing a risk assessment of hydrogen vehicles and infrastructure; many factors are unknown or uncertain, and even solid quantitative information may not overcome perceived risk [7]. Some quantitative risk assessments have been performed on hydrogen vehicles [8, 9] and fueling stations [10]. One of these studies [8] considered vehicles in tunnels; one possible consequence scenario was a semi-confined environment, such as a city, tunnel, gas station, or parking garage. This study found that the risk of a hydrogen-powered vehicle is dominated by explosions in semi-confined environments; in turn, the risk of these scenarios was driven by the assumption that any crash (even at low speeds) to the rear of the car would result in an explosion. The HyTunnel project (part of HySafe) conducted a risk analysis specifically for hydrogen vehicles in tunnels [11]. This study compared a hydrogen car and bus to an analogous natural gas car and bus and used computational fluid dynamics simulations to evaluate the consequence of various scenarios. This study assigned a relative probability to each scenario, but it was stated that these probabilities were an "educated guess" and not elaborated on further [11].

A recent study focused on hydrogen-powered vehicles on roads in London in the UK [9]. This study used a quantitative risk assessment methodology using both fatalities and costs as harm metrics. The study concluded that thermally-unprotected composite storage pressure vessels onboard the vehicle have an unacceptably high risk to loss of life when exposed to a crash causing a fire that leads to pressure vessel rupture. These results were based on a consideration of both engulfing and localized fires; localized fires led to a rupture frequency that was two orders of magnitude higher than for engulfing fires. This study also focused on varying the fire resistance rating, which is the time from the start of a fire to pressure vessel rupture. The authors found that increasing this fire resistance rating (e.g., through the use of an intumescent paint) would greatly reduce the risk associated with hydrogen vehicles. Previous studies focus on characterizing the consequences of prescribed hydrogen ignition scenarios, with mostly qualitative assessment of the deterministic likelihood of those scenarios.

1.5. Focus of Current Effort

This work addresses the risk of hydrogen vehicles in tunnels by estimating the likelihood of possible scenarios for a crash of a light-duty hydrogen FCEV. The consequence of each of these scenarios is not quantified in the current work

because many of these outcomes are quantified in previous studies, but the added consequence due to the presence of hydrogen is qualitatively estimated. An event sequence diagram is used to determine possible scenarios and the probability of each scenario occurring. Uncertainties are propagated through the event sequence diagram, so the final scenario probabilities are estimated with uncertainty that is characterized using exceedance probability curves.

2. Calculation Methods

A framework for risk analysis consists of identifying what can happen, how likely it is to happen, and what the consequences are if it does happen [12]. The risk analysis was conducted to provide a logical, visual framework to catalog the different potential outcomes of various magnitude incidents in road tunnels. This section provides a detailed construction and explanation of an event tree used to analyze the risks of FCEVs in tunnels. The overall event tree is discussed and the derivation of uncertainty is presented for each event.

2.1. Event Sequence Diagram

An event sequence diagram (ESD) is a tool used in risk assessments to represent an undesired event as a sequence of sub-events [13]. An event tree presents a visual representation of all possible scenarios and is particularly useful for calculating how multiple safeguards can affect the consequence. The event tree begins with an initiating event and illustrates the chronological sequence of events involving the successes and/or failures of the system components. Each bifurcation is assigned a probability of occurrence and thus the probability of various possible outcomes can be calculated. The total for each outcome is the combination of all the probabilities leading to that outcome. The probabilities of occurrence included in the ESD are themselves uncertain due to the current state-of-knowledge. This uncertainty is estimated using distributions and incorporated explicitly in the analysis. The ESD for a hydrogen FCEV crash is illustrated in Fig. 1 and is discussed in subsequent sections.

2.2. Uncertainty Analysis

The ESD framework for risk assessment uses conditional probabilities that, when combined in the ESD structure, result in probabilities for each of the scenarios characterized by the ESD. However, due to the limited use of FCEVs, there is not enough data to estimate these probabilities with high confidence. Instead, uncertainty distributions that describe the range of possible values were derived for each of the branch probabilities based on the current state-of-knowledge. These distributions do not suggest that the probabilities are random variables; they describe where the true value is expected to be with the assumption that the range will narrow as the state-of-knowledge improves. The shapes of these uncertainty distributions are reflective both of the data and assumptions used to derive them and are expected to change over time as the state-of-knowledge improves.

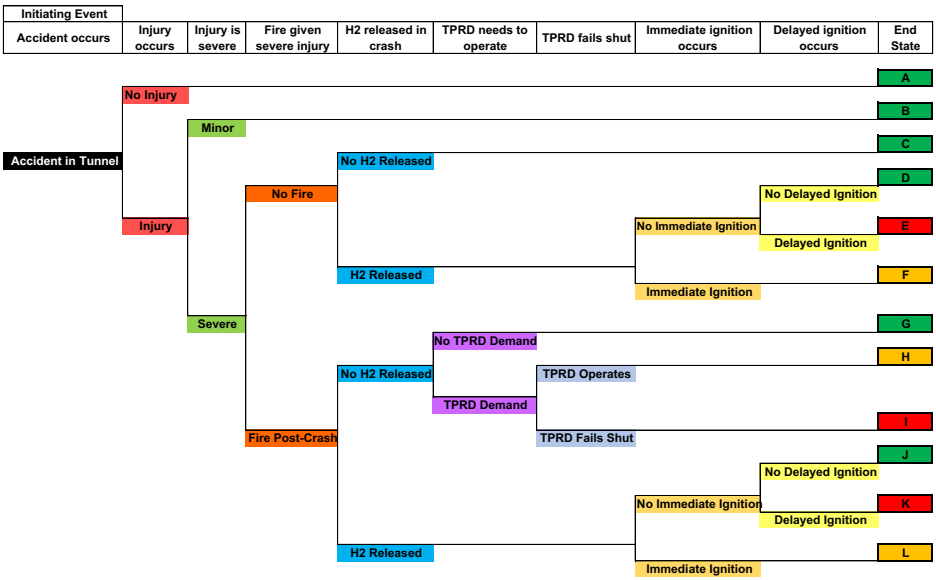


Figure 1. Event sequence diagram for hydrogen FCEV crash.

With distributions rather than probabilities assigned to each branch point in the ESD, the final result is not a probability for each scenario, but rather a range of possible probabilities for each scenario. The true probabilities are believed to be within those ranges, but a more precise understanding of their values cannot be obtained without additional data. Each of the branch point uncertainties were propagated through the ESD using simple random sampling to perform a Monte Carlo analysis. In other words, the probabilities for the scenarios in the ESD were estimated many times ($N = 10^5$), using a different sample for each branch point probability every time. The distributions of these multiple calculations are presented as the final results for the probability of each scenario.

2.3. Hydrogen Vehicle Crash in Tunnel Event

The initiating event for the event tree is a crash involving a FCEV in a tunnel. Since there are currently no published data sources for FCEV crashes in tunnels specifically, this analysis uses the generic crash rate for tunnels as a conservative estimate. This means that every crash in a tunnel involves a FCEV—a conservative assumption as approximately 6000 FCEV are on the road in the U.S. as of early-2019 [14]. Over time, the number of FCEVs on the road will increase so it is expected that this proportion will change with time. A recent review paper for crashes in tunnels reports tunnel crash frequency estimates averaged over a 3-year period for 10 different countries. The average estimates, expressed as crashes per million vehicle kilometers, were: 0.277, 0.337, 0.355, 0.420, 0.315, 0.8, 0.303, 0.253, 0.145, 0.483, and 0.345 [15].

To obtain an uncertainty distribution on the crash frequency, these estimates were used to obtain a gamma distribution parametrized by shape and scale using the maximum likelihood approach. The distribution (6.2, 0.059), has a median value of 0.35 which compares well to the mean estimate provided in [15] for the U.S., 0.337. Two key assumptions for this derivation are the form of the distribution (gamma), and that the variation in frequency between countries is representative of variation that would be expected in the estimate for the U.S. if the data ranged over a longer period of time. The former assumption is common for uncertainty distributions on frequencies and can be refined as the state-of-knowledge improves. The latter assumption may be incorrect if further experience demonstrates significant differences exist in crash frequencies across countries. For example, whether a country has a higher proportion of one-way vs two-way tunnels may have an impact on the crash rate and especially the severity of the crash should one occur. Some of this uncertainty is addressed in the probability distribution used here, but more specific data for a particular situation should be used in a targeted analysis. However, including this assumption in the analysis is conservative with respect to incorporating more uncertainty around the estimate than would be included if only data from the U.S. was used. The final uncertainty distribution on crash frequency derived from data in [15] is shown in Fig. 2. It is used as the initiating event frequency in the ESD. This means that the estimate is used in the calculation of frequency results, but it is not used in the calculation of probability results, since probabilities are presented as the probability of a scenario given a crash.

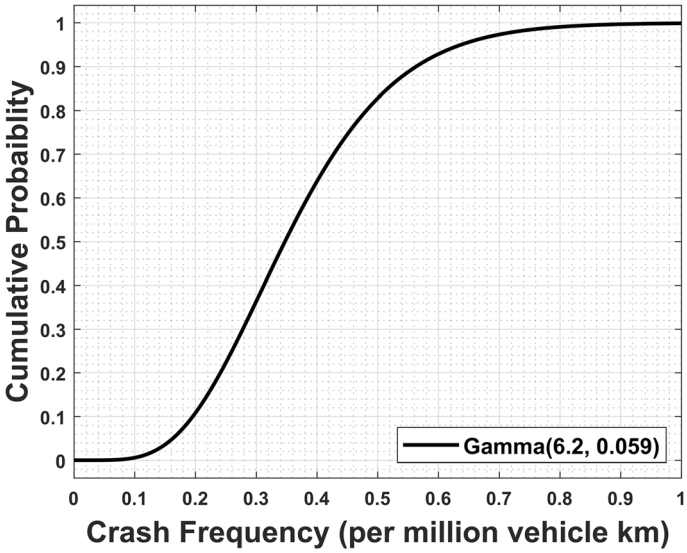


Figure 2. Uncertainty distribution on the car crash frequency in tunnels.

2.4. Severity of Crash

The scale of the crash will determine if the hydrogen plays a role in the consequence of the crash. This allows for a distinction to be made between the majority of crashes that do not cause significant damage to either vehicle and crashes that could significantly damage a hydrogen fuel system. To account for crash severity, data summarized in [15] was used along with data from [16]. The form of this data supports separation of the probability of a severe crash into two components: the probability, given a crash, that an injury occurs and the probability, given an injury, that the injury is severe. The probability, with uncertainty, of each of these components was estimated and they combine within the ESD structure to characterize uncertainty in the probability of a severe crash.

The key assumption underlying this application of the data is that severe injury is an appropriate proxy for crash severity with respect to predicting hydrogen tank damage; if a crash severely damages a human, it could also severely damage a hydrogen tank. This proxy is used because injury data are typically collected and available for crashes, while the extent of a damage to a vehicle in a crash is not as easily quantifiable. The cost to repair a vehicle can vary widely for different vehicle price points, and typically includes significant cosmetic repair that does not suggest the crash would damage a hydrogen tank. A proxy based on injury may therefore be able to separate potentially damaging crashes from minor crashes. The reasonableness of this assumption is difficult to judge in the absence of data specifically relating to injury and tank damage rates in FCEV crashes.

For the probability of an injury given a crash, the data from [15] summarizes 116 crashes with 35 injuries. The data from [16] summarizes 2304 crashes with 765 injuries. This gives a total of 2420 crashes and 800 injuries. Data of this form is appropriate for a beta distribution. A Jeffrey's prior beta distribution, Beta(0.5, 0.5), was assumed and updated with n = 2420 and k = 800, resulting in a Beta(800.5, 1620.5) uncertainty distribution on the probability of an injury given a crash [17]. This distribution is shown in Fig. 3.

For the probability of a severe injury given an injury, the data from [15] summarizes four different studies with 562, 1130, 35, and 503 injuries, 97, 125, 11, and 45 of which were severe, respectively. This gives a total of 2230 injuries, with 278 of them severe. As with the previous distribution, a Jeffrey's prior beta distribution was assumed, and the resulting uncertainty distribution obtained by applying this data to the prior is Beta(278.5, 1952.5). This distribution is shown in Fig. 4.

2.5. Hydrocarbon Fire

The next branch of the event tree describes the likelihood of a crash causing a fire given that the crash was severe. This pertains to fires of traditional hydrocarbons that are present in gasoline or diesel-powered vehicles. Because there are so few FCEVs on the road, it was assumed that a crash involves at least one traditionally-fueled vehicle. A review paper reported average severe crash rates and average fire crash rates from Italy, Norway, and Switzerland over a 4 year period [15]. For each year, the ratio of the fire crash rate to the severe crash rate is an estimate of the probability that a severe crash results in a fire, under the assumption that any

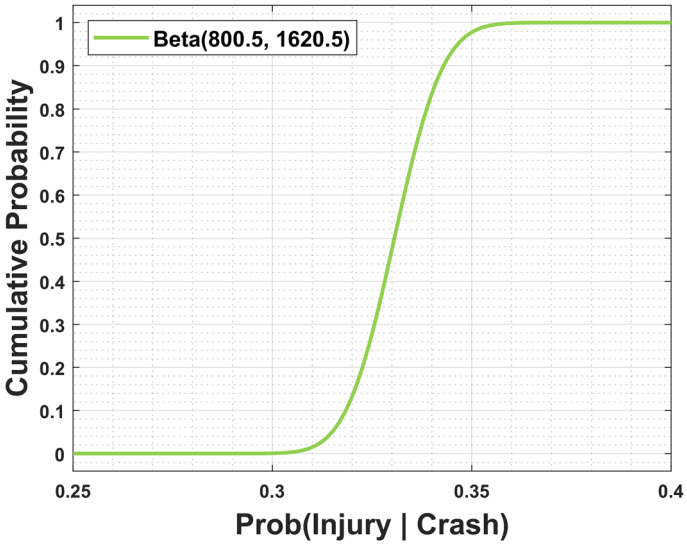


Figure 3. Uncertainty distribution on the probability that a crash is severe enough to cause an injury.

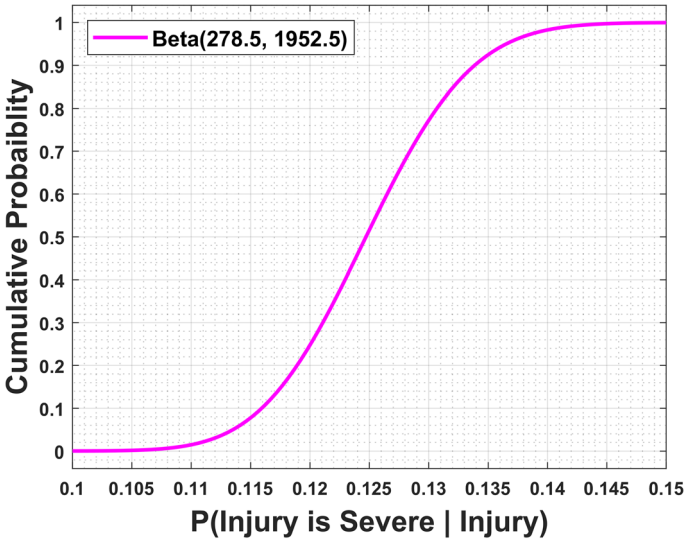


Figure 4. Uncertainty distribution on the probability that a crash results in a severe injury given that it caused an injury.

crash resulting in a fire is considered severe. The data from [15] is duplicated in Table 1.

For this uncertainty distribution, a beta distribution was assumed and the parameters were determined using maximum likelihood estimation with the four

Table 1
Annual Crash Rates for Severe Crashes and Crashes Resulting in Fire Averaged Over Italy, Norway, and Switzerland [15]

Year	2006	2007	2008	2009
Average severe crash rates	0.2045	0.1608	0.0913	0.1284
Average fire crash rates	0.0510	0.0619	0.0507	0.0433
P(fire | severe crash)	0.249	0.385	0.555	0.337

point estimates given in Table 1. An alternative approach would be to use the empirical distribution calculated from these four points, though many more points are required for accuracy. Both distributions are plotted in Fig. 5, showing that the empirical distribution shape is consistent with the beta distributional assumption. As such, the beta distribution was used for this analysis. Both distributions, however, represent a strong assumption due to the limited amount of data.

2.6. Damage-Induced Hydrogen Release

The next event tree branch analyzes whether hydrogen was released from the hydrogen system in a crash. In order to characterize this probability, published crash test data was used from [18] and [19]. In all five tests there was not enough damage to the system for it to leak or release hydrogen. A Jeffrey's beta prior distribution was assumed and updated with the zero failures out of five tests. The

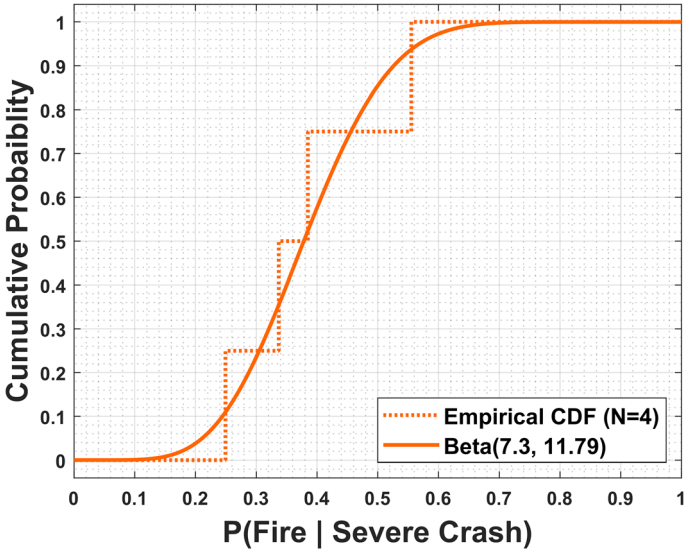


Figure 5. Uncertainty distribution on the probability that a crash results in a fire given that it was severe enough to cause a severe injury.

resulting Beta(0.5, 5.5) uncertainty distribution for the probability of hydrogen release due to damage is plotted in Fig. 6.

2.7. Pressure Relief Device Demand

A hydrocarbon fire from another vehicle involved in a crash can result in a release of hydrogen from the thermally-activated pressure relief device (TPRD) if the fire is located close enough to the hydrogen pressure vessel for the TPRD to reach the activation temperature of 110°C (nominally). If the fire is not located close enough to activate the TPRD, the hydrogen remains in the pressure vessel. The specifics of an actual crash determine the extent of the fire and the proximity of the vehicle and pressure vessel to the fire; neither of these parameters are known. To characterize this lack of knowledge, a uniform distribution between zero and one was assumed for the probability of TPRD demand to operate given a fire. This is a significant assumption as it represents no expert knowledge about this probability, even with respect to whether it may be high or low. If the actual probability is low, this uncertainty distribution over predicts TPRD demand. If the actual probability is high, this uncertainty distribution under predicts TPRD demand. The uniform distribution is shown in Fig. 7.

2.8. Pressure Relief Device Activation

Assuming the severe crash has caused a fire which necessitates the activation of the TPRD, there is still a possibility that the TPRD fails to operate as intended. In this case, the TPRD would fail shut; i.e., it would fail to vent the hydrogen when needed. This could potentially lead to a catastrophic failure of the pressure

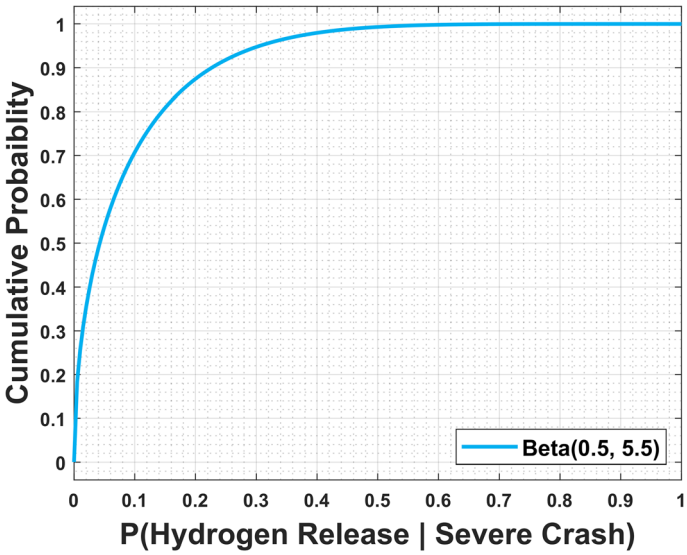


Figure 6. Uncertainty distribution on the probability that a crash results in hydrogen release.

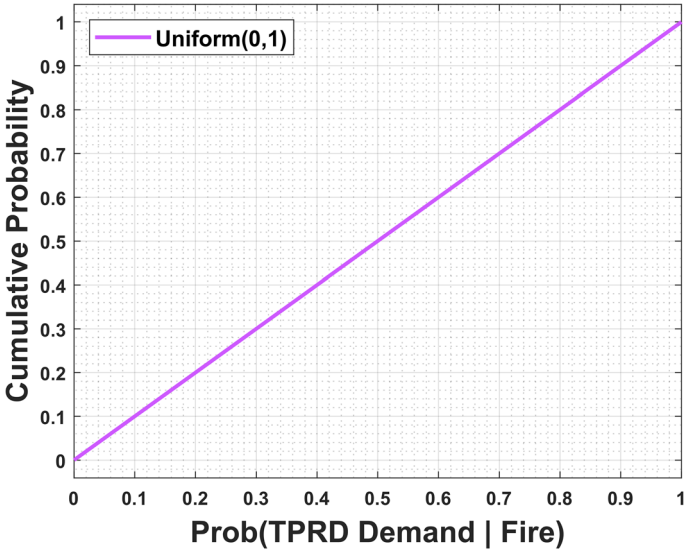


Figure 7. Uncertainty distribution on the probability that a fire will result in a demand for the TPRD to operate.

vessel if the fire causes damage to the pressure vessel itself or simply heats the hydrogen to a high enough pressure to fail the vessel. Dadashzadeh et al. [9] recently calculated the failure probability of a TPRD to be 0.604. This value was calculated for an engulfing fire of the pressure vessel and is based on the mechanical failure probability of pressure relief devices from reliability data. However, this value was not used in the analysis because it may not be applicable to crash conditions. The reliability data used in its derivation does not explicitly define mechanical failure, so the data may represent TPRD leak, rather than failure of the TPRD to release pressure.

Instead, a literature review was performed on pressurized hydrogen tank fire testing. Experiments that included TPRDs, of any design, were included. Experiments that did not include TPRDs were excluded. Generally, the experiments reviewed were designed to test the hydrogen tank structures rather than the TPRDs themselves and the TPRDs were included in the experimental design as a safety measure. However, this means that each experiment represents a condition in which a demand was made on a TPRD and it either functioned as designed or did not. This data, shown in Table 2, was assumed to be representative of the actual TPRD failure-to-operate probability. This assumption may not hold if there are significant differences between the designs of the TPRDs used in experiments and those in operation in FCEVs.

Again, assuming a Jeffrey's beta prior distribution, the data in Table 2 results in a Beta(0.5, 16.5) distribution. Because of the small number of data points, the prior distribution assumption has an effect on the resulting posterior distribution. The actual failure rate of the TPRDs is lower than that encoded in the Jeffrey's

Table 2
Summary of TPRD Operations in Hydrogen Tank Fire Experiments [20–24]

Source	TPRD demands	TPRD operation
Yamazaki	2	2
Suzuki	4	4
Zheng	1	1
Wyandt	6	6
Sekine	3	3

prior, so the effect of this assumption is conservative. The uncertainty distribution on the probability of TPRD failure on demand is shown in Fig. 8.

2.9. Hydrogen Ignition

The next bifurcation in the diagram is whether released hydrogen will ignite. Hydrogen ignition probabilities were derived for the Canadian Hydrogen Safety Program [2] by adapting non-hydrogen ignition values suggested in Cox et al. [18]. These ignition probabilities were used for hydrogen quantitative risk assessment in [25] and to develop separation distances in NFPA 2, the Hydrogen Technologies Code, and NFPA 55, the Compressed Gases and Cryogenic Fluids Code [26]. The ignition probabilities are shown in Table 3.

Two top events were defined in order to apply this data in the ESD to characterize the ignition probability. The first is immediate ignition and the second is

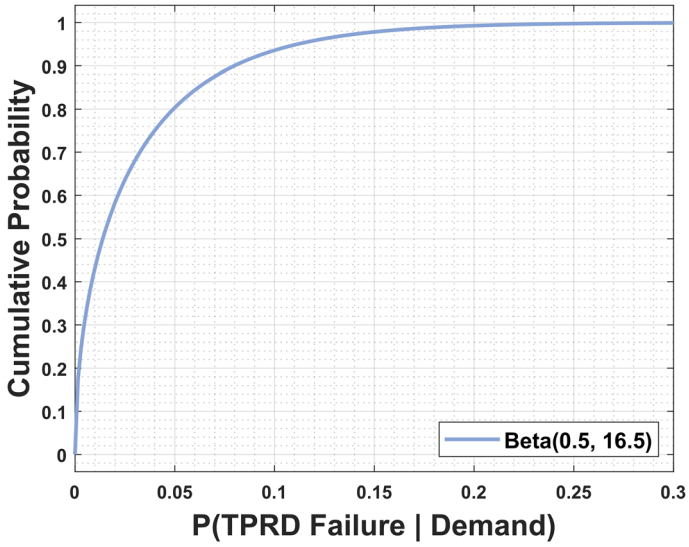


Figure 8. Uncertainty distribution on the probability that a TPRD will fail to operate on demand.

Table 3
Hydrogen Ignition Probabilities [18]

Hydrogen release rate (kg/s)	Immediate ignition	Delayed ignition
< 0.125	0.008	0.004
0.125–6.25	0.053	0.027
> 6.25	0.23	0.12
Average	0.098	0.049

delayed ignition. Immediate ignition occurs if the leak is ignited within the first few fractions of a second after the leak occurs and delayed ignition allows the hydrogen to accumulate and mix with ambient air before being ignited [27]. The ignition probabilities from Table 3 are used to estimate these probabilities. These probabilities are inherently conditional because an immediate ignition cannot be proceeded by a delayed ignition due to the consumption of hydrogen by the first ignition. Because the actual hydrogen release rate would be incident- specific, the full range of values shown in Table 3 was used and the distributions for immediate and delayed ignition were defined as uniform between the bounding values in the table. These uncertainty distributions are shown in Fig. 9.

Based on the pressure vessel testing detailed previously, it is most likely that hydrogen released would be small amounts present in the fuel line. GTR-qualified hydrogen cylinders contain an internal solenoid valve that prevents the tank from releasing all of its contents through the fuel line if a severe crash occurs (triggered by an accelerometer). Using a uniform distribution was conservative and deemed

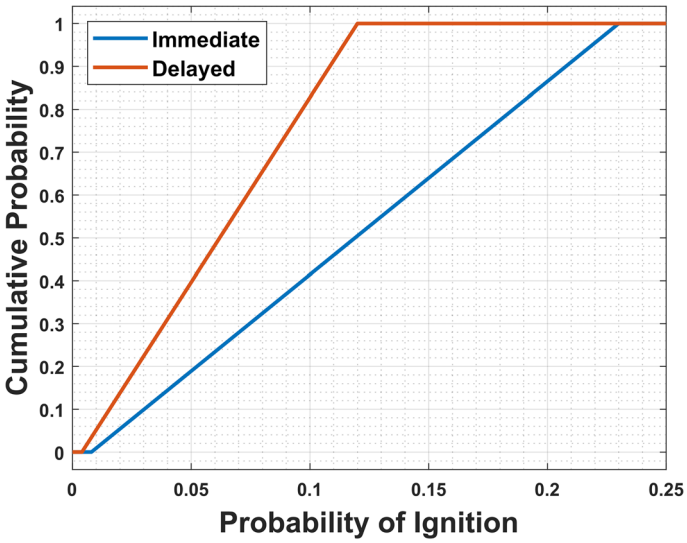


Figure 9. Uncertainty distributions on the probability of immediate ignition and delayed ignition.

appropriate given the uncertainty involved in quantifying this parameter across scenarios.

One exception to these probabilities is the case when a severe crash leads to a post-crash fire, with no release of hydrogen from the pressure vessel due to the physical insult of the crash, but hydrogen released from the TPRD. If the fire was large enough to activate the TPRD which releases hydrogen from the pressure vessel, it is assumed to ignite the released hydrogen immediately, forming a jet flame. As the state-of-knowledge about FCEV fires increases, this assumption may change. Thus, it is assumed that for that particular case there is a 100% chance of ignition and 100% chance of immediate ignition. Note that separate branches are not shown for the cases of 0% probability.

3. Probability Calculation Results

Each of the distributions described for the branches in the ESD was sampled using simple random sampling and the samples were propagated through the ESD to calculate the probability of each scenario. This approach leads to a distribution on the probability of each scenario. The distributions should be interpreted as representing the uncertainty around the true value induced by the uncertainties in each branch point. In other words, there is a true probability for each scenario but it is not known due to the uncertainties in each branch. So, the scenario probability distributions describe the range of possible probabilities supported by the current state-of-knowledge. If the state-of-knowledge was perfect, the distributions on each branch point would converge to a single point and the distributions on scenario probabilities would subsequently also converge to single points.

The uncertainty distributions on each scenario probability are shown in Fig. 10 as exceedance probability curves. This plot shows, for example, that the scenarios with the highest contributions from hydrogen on the consequences are believed to have probabilities less than about 1E−03. Based on the median, these probabilities are believed to be on the order of 1E−05 to 1E−04. Of the scenarios with moderate to severe consequences, scenario H (severe crash resulting in a fire, no hydrogen release due to damage, TPRD demand due to fire and successful TPRD operation followed by ignition) has the highest probability, believed to be on the order of 1E−04 to 1E−02 based on the current state-of-knowledge.

Figure 11 presents a condensed version of the information presented in Fig. 10. Rather than the full exceedance probability curves, Fig. 11 shows the range between the 2.5th and 97.5th percentiles of the distributions in Fig. 10. This characterizes the ranges in which the true scenario probabilities are expected, with 0.95 probability. The plot is purposefully presented on a linear scale to emphasize the differences in the relative probabilities of the scenarios. Overwhelmingly, the most likely scenarios captured in the ESD are those in which hydrogen does not significantly contribute to the consequences.

The 95% uncertainty interval for the probability of each scenario is shown in Table 4 along with a description of the contribution of hydrogen to the severity of

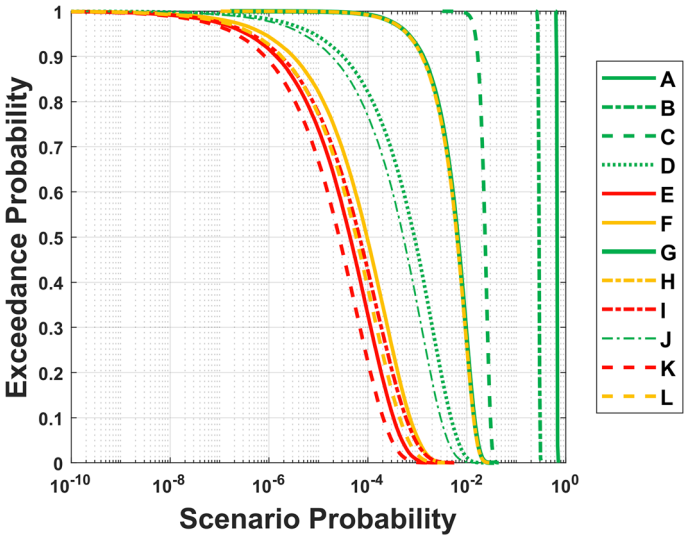


Figure 10. Characterization of uncertainty around the ESD scenario probabilities presented using exceedance probability curves.

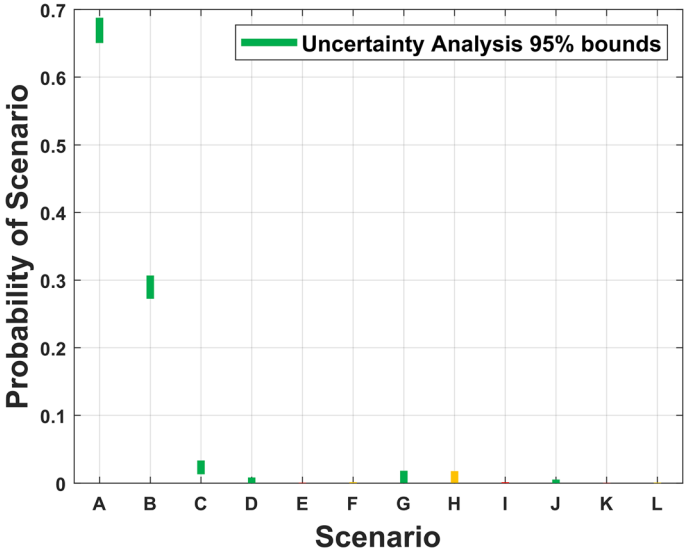


Figure 11. Characterization of uncertainty around the ESD scenario probabilities presented using 95% uncertainty bounds.

the crash consequence. The probabilities are presented as the conditional probability of a scenario given a crash with a single FCEV in a tunnel; the frequencies reported take the uncertain frequency of the initiating event into account as well

Table 4
Event Sequence Diagram Scenario Probability Estimates for a Crash in Tunnels Involving a Single Hydrogen FCEV

Scenario	Probability 95% bounds	Probability median estimate	Median frequency[a]	Severity
A	[6.5E−01, 6.9E−01]	6.7E−01	2.3E−01	No effect
B	[2.7E−01, 3.1E−01]	2.9E−01	1.0E−01	No effect
C	[1.3E−02, 3.3E−02]	2.4E−02	7.9E−03	No effect
D	[1.9E−06, 8.3E−03]	8.7E−04	2.8E−04	No effect
E	[8.8E−08, 6.5E−04]	4.4E−05	1.4E−05	Overpressure
F	[1.9E−07, 1.4E−03]	9.5E−05	3.1E−05	Jet flame
G	[3.3E−04, 1.8E−02]	6.5E−03	2.1E−03	No effect
H	[3.1E−04, 1.8E−02]	6.3E−03	2.0E−03	Jet flame
I	[1.1E−07, 1.3E−03]	6.7E−05	2.3E−05	Overpressure
J	[1.1E−06, 5.2E−03]	5.2E−04	1.7E−04	No effect
K	[5.1E−08, 4.1E−04]	2.6E−05	8.6E−06	Overpressure
L	[1.1E−07, 8.8E−04]	5.7E−05	1.9E−05	Jet flame

[a]Per million vehicle kilometers

as the probability values. Each scenario is described, the probability of the scenario given, and the consequence of the scenario is discussed.

Scenario A A FCEV is involved in a minor crash in a tunnel. This is the most likely scenario. No additional consequence due to no hydrogen release. The pressure vessel is expected to survive intact, holding pressure without leaking.

Scenario B A FCEV is involved in a moderate crash in a tunnel (injurious but not severe). This is the second most likely scenario. No additional consequence due to no hydrogen release. The pressure vessel is expected to survive intact, holding pressure without leaking.

Scenario C A FCEV is involved in a severe crash. No hydrogen is released and there is no external fire. Probability on the order of 1E−2. No additional consequence. The pressure vessel is expected to survive intact, holding pressure and without leaking.

Scenario D A FCEV is involved in a severe crash. There is no external fire, hydrogen is released from the system due to damage but does not ignite. A fuel line break is most likely because of the robustness of the pressure vessel, and the actuation of the solenoid valve that prevents hydrogen in the pressure vessel from being released via the broken fuel line. This is downstream of the pressure regulator, limiting released hydrogen to < 100 psi (< 0.69 MPa). In this scenario, there is no ignition of hydrogen due to dilution below the flammable limit.

Scenario E A FCEV is involved in a severe crash. There is no external fire, hydrogen is released due to damage to the system and has a delayed ignition. The consequence depends on the amount of hydrogen released and ventilation rate of the tunnel which acts to dilute the concentration of hydrogen.

Scenario F A FCEV is involved in a severe crash. There is no external fire, hydrogen is released from the fuel system and ignites immediately. A fuel line

break is most likely because of the robustness of the pressure vessel and the actuation of the solenoid valve. This is downstream of the pressure regulator, limiting released hydrogen to < 100 psi (< 0.69 MPa). The hydrogen ignites immediately.

Scenario G A FCEV is involved in a severe crash. Hydrogen is not released, there is an external fire, but there is no TPRD demand. The TPRD release is only required if the relative location and size of the fire is enough to require it; in this case, they are not. If no hydrogen is released, there is no additional consequence.

Scenario H A FCEV is involved in a severe crash. Hydrogen is not released from the fuel system due to damage, there is an external fire, and hydrogen is released from the TPRD, which operates successfully. External fire could cause TPRD to vent hydrogen, which ignites immediately. The GTR requires the TPRD to be pointed at the ground, but in a worst-case scenario, the vehicle could be flipped over and the TPRD release could be pointed at the ceiling or walls of the tunnel.

Scenario I A FCEV is involved in a severe crash. Hydrogen is not released from the fuel system due to damage, there is an external fire, and the configuration of the fire relative to the pressure vessels requires a TPRD release. However, the TPRD does not operate successfully and fails to open. This scenario could cause a catastrophic failure of the pressure vessel.

Scenario J A FCEV is involved in a severe crash. Hydrogen is released from the fuel system, and there is an external fire. However, the hydrogen does not ignite. Even with an external fire, there is still a significant probability of the hydrogen not igniting, especially if only a small amount is released; the release is due to damage from the crash, not the fire, and the release could occur away from the fire itself. A small release could be below the flammability limit of hydrogen in air, and it would likely dissipate rapidly. If the hydrogen does not ignite, there is no additional consequence.

Scenario K A FCEV is involved in a severe crash. Hydrogen is released from the fuel system and there is an external fire. The hydrogen is not ignited immediately but there is a delayed ignition. The consequence depends on the amount of hydrogen released from the small fuel lines and ventilation rate of the tunnel which acts to dilute the concentration of hydrogen. However, the credibility of this scenario is questionable given the robust pressure vessel and vehicle crashworthiness requirements noted.

Scenario L A FCEV is involved in a severe crash. Hydrogen is released from the fuel system, and there is an external fire. The hydrogen ignites immediately. A fuel line break is most likely because of the robustness of the pressure vessel. This scenario likely results in a jet fire.

4. Discussion

Scenarios E and K describe the scenario where a FCEV is involved in a severe crash, hydrogen is released and ignites, but not immediately. These scenarios have a varied consequence due to the amount of hydrogen released. The pressure vessel is designed to survive a severe crash scenario, so the inclusion of a pressure vessel

rupture scenario is likely conservative. In addition to surviving the abuse testing prescribed by GTR 13, which is performed on unprotected tanks, the tanks installed in the FCEV are protected by the structure of the vehicle chassis and body. This limits the tank's exposure to the direct forces of a severe crash. In a crash, sensors on the vehicle detect the forces associated with the crash and a fail-safe interlock operates a shut-off valve located inside the pressure vessel. This limits the hydrogen released to the amount that is contained in the fuel line, if that tubing is damaged in the crash. The most likely consequence for these scenarios is that a fuel line leak releases hydrogen, however since the amount of hydrogen in the fuel line is minimal the consequence would be a brief combustion of the fuel that generates no overpressure.

Scenario I describes where a FCEV is involved in a severe crash, a fire results and necessitates a TPRD release, but the TPRD fails to operate. This could therefore lead to a catastrophic failure of the hydrogen pressure vessel, leading to an overpressure from the sudden release of pressure as well as ignition of the hydrogen. This is the worst-case scenario. The hazard will most directly depend on the amount of hydrogen in the pressure vessel upon catastrophic failure. However, it will also depend on a number of factors that are more difficult to predict: configuration of the vehicle(s) involved in the crash, obstructions that may exacerbate the overpressure, and the number of people nearby. That said, this scenario has by far the lowest probability due to the combination of events that need to occur for this scenario to happen. Some recent works (e.g., [9]) correctly point out that localized fires can lead to a much higher likelihood of TPRD failure to operate. However, for the case of an external fire on a pressure vessel which itself is surrounded by the metallic structure of the FCEV, a localized fire on the pressure vessel is not deemed credible. A typical vehicle crash fire may be a pool fire of gasoline or diesel, which spreads without containment towards the downward slope of the road surface, or a vehicle fire that quickly engulfs the vehicle due to the combustible contents such as foam seating, carpeting, and plastic trim panels. These fire scenarios were judged to engulf a vehicle and, therefore, the potential for one end of a tank that is less than 1 m long to be preferentially heated would be negligible.

Given a crash in a tunnel, statistics for the probability of each of the branch line scenarios occurring are provided in Table 4, along with a description of the effect of the hydrogen on the severity of the event consequence are illustrated in Figs. 10 and 11. The colors used in the figures correspond to the event tree where green is used to indicate that the hydrogen does not contribute to the severity of the consequences. The bar is green for all scenarios where the hydrogen remains sealed in the FCEV system or, if released, is vented without igniting. Yellow is used to indicate that the hydrogen ignites and contributes to the severity of the incident. Red is used to indicate a catastrophic event. Scenarios where there is no additional consequence due to the hydrogen FCEV clearly dominate the probability of scenarios. Only Scenario H (yellow—moderate additional consequence) had a probability on the order of 1E−02. Thus, the consequence of this scenario (a jet fire) is the most appropriate scenario for further study. The consequences on nearby vehicles, nearby people, and the tunnel itself should be assessed.

5. Conclusions

The results of this risk analysis will help quantify what potential scenarios and outcomes are feasible and credible as FCEVs become available in more and more jurisdictions and help answer questions about regulatory decisions regarding access limitations or prohibitions to enclosed spaces such as tunnels. A thorough analysis of the potential risks and hazards related to FCEV incidents in tunnels was performed to estimate which scenarios are most likely to occur. These scenarios were qualitatively categorized based on the possible consequences of each, though more work is needed to assess these consequences in detail. Some factors lack specific and directly-applicable data, but the estimated most likely consequence of a crash is that the hydrogen poses no additional hazard. This is not to say that vehicle crashes are not dangerous, but rather that the hydrogen fuel does not contribute additional hazard beyond that which already exists in a vehicle crash. This is because the most likely outcome of a crash is a minor crash in which the hydrogen is not released or does not ignite. Of the scenarios in which hydrogen does ignite, the most likely is a jet flame resulting from the release of hydrogen through the TPRD due to the heat from a typical crash-related hydrocarbon fire. Catastrophic releases are considered but are found to be much less likely than the jet fire release.

It is difficult for any risk assessment to place the absolute values of the results in a specific context, as this context will vary by location, locale attitudes, and other specific factors. Furthermore, this work focused on a quantitative estimation of the probability and likelihood of each specific end-state scenario given that a crash had occurred, not on assessing the specific consequences of each scenario. Depending on the uncertainty, there is a roughly 0.7% chance of a jet fire resulting from a FCEV crash, but this result is likely a conservative estimate based on the uncertainty in whether a TPRD demand occurs. The majority of the probability ($> 99\%$) results in no additional consequence from the hydrogen. In a more thorough risk assessment, the specific consequences would need to be assessed for each of the end-state scenarios, and the overall risk should be compared to the analogous risk for traditionally-fueled vehicles.

As the hydrogen fuel cell industry continues to grow, better data will help to reduce uncertainty. Although distributions were used to account for the uncertainty, obtaining data in these areas would strengthen this analysis by reducing the uncertainty, potentially with respect to both the shape and the domains of the distributions. The distribution with the most uncertainty was whether or not TPRD operation would be required if a fire was present; a completely uniform probability distribution was used in this analysis to reflect the high level of uncertainty. Additionally, future work could be done on analyzing the risk of differently-sized vehicles (i.e. buses) within a tunnel, as these vehicles may have specific differences in hazardous scenarios and consequences. Different types of vehicles will likely have very different consequences for similar types of crashes.

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References

1. California Fuel Cell Partnership (2019) How It Works. https://cafcp.org/sites/default/files/HowItWorks-Fuel-Cell-Booklet.pdf. Accessed 10 Apr 2019
2. Tchouvelev A, Hay D, Bénard P (2006) Quantitative risk comparison of hydrogen and CNG refuelling options. Final technical report to Natural Resources Canada
3. United Nations (2013) Global technical regulation on hydrogen and fuel cell vehicles. ECE/TRANS/180/Add.13 http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a13e.pdf
4. National Fire Protection Association (2010) NFPA 502, standard for road tunnels, bridges, and other limited access highways
5. Code of Federal Regulations. Standard No. 304; Compressed natural gas fuel container integrity. 49 CFR 571.304
6. Zalosh R, Pilette Y, Wang W (1994) Hazard analysis of alternative fueled vehicles in CA/T tunnels, part 1: CNG fueled vehicles. Center for Firesafety Studies, Worcester Polytechnic Institute report prepared for Bechtel/Parsons Brinckerhoff Massachusetts Highway Department
7. Pasman H (2011) Challenges to improve confidence level of risk assessment of hydrogen technologies. Int J Hydrog Energy 36:2407–2413. https://doi.org/10.1016/j.ijhydene.2010.05.019
8. Rodionov A, Wilkening H, Moretto P (2011) Risk assessment of hydrogen explosion for private car with hydrogen-driven engine. Int J Hydrog Energy 36(3):2398–2406. https://doi.org/10.1016/j.ijhydene.2010.04.089
9. Dadashzadeh M, Kashkarov S, Makarov D, Molkov V (2018) Risk assessment methodology for onboard hydrogen storage. Int J Hydrog Energy 43(12):6462–6475. https://doi.org/10.1016/j.ijhydene.2018.01.195

10. Zhiyong LI, Xiangmin PAN, Jianxin MA (2011) Quantitative risk assessment on 2010 expo hydrogen station. Int J Hydrogen Energy 36(6):4079–4086. https://doi.org/10.1016/j.ijhydene.2010.12.068
11. Middha P, Hansen OR (2009) CFD simulation study to investigate the risk from hydrogen vehicles in tunnels. Int J Hydrog Energy 34(14):5875–5886. https://doi.org/10.1016/j.ijhydene.2009.02.004
12. Kaplan S, Garrick BJ, Apostolakis G (1981) Advances in quantitative risk assessment—the maturing of a discipline. IEEE Trans Nucl Sci 28(1):944–946. https://doi.org/10.1109/TNS.1981.4331310
13. Hall JR, Watts JM (2008) Fire risk analysis. In: Fire protection handbook, 20th edn. National Fire Protection Administration (NFPA): 3-135 to 3-143
14. California Fuel Cell Partnership (2019) FCEV Sales, FCEB, & Hydrogen Station Data. https://cafcp.org/by_the_number. Accessed 10 Apr 2019
15. Bassan S (2016) Overview of traffic safety aspects and design in road tunnels. IATSS Res 40(1):35–46. https://doi.org/10.1016/j.iatssr.2016.02.002
16. Caliendo C, De Guglielmo ML, Guida M (2013) A crash-prediction model for road tunnels. Accid Anal Prev 55:107–115. https://doi.org/10.1016/j.aap.2013.02.024
17. Nathan O, Siu DLK (1998) Bayesian parameter estimation in probabilistic risk assessment. Reliab Eng Syst Saf 62(1–2):89–116. https://doi.org/10.1016/S0951-8320(97)00159-2
18. Pape D, Cox A (2015) Compressed hydrogen container fueling options for crash testing. DOT HS 812 133. National Highway Traffic Safety Administration, Washington, DC
19. Batelle Memorial Institute (2015) Crashworthiness research of prototype hydrogen fuel cell vehicles: task order 7 project report. DOT HS 812 112. National Highway Traffic Safety Administration report, Washington, DC
20. Yamazaki K, Tamura Y (2017) Study of a post-fire verification method for the activation status of hydrogen cylinder pressure relief devices. Int J Hydrog Energy 42(11):7716–7720. https://doi.org/10.1016/j.ijhydene.2016.07.197
21. Suzuki J, Tamura Y, Watanabe S, Takabayashi M, Sato K (2006) Fire safety evaluation of a vehicle equipped with hydrogen fuel cylinders: comparison with gasoline and CNG vehicles. Paper presented at the 2006 SAE World Congress, Detroit, Michigan, 4/3/2006–4/6/2006
22. Zheng J, Bie H, Ping X, Chen H, Liu P, Li X, Liu Y (2010) Experimental and numerical studies on the bonfire test of high-pressure hydrogen storage vessels. Int J Hydrog Energy 35(15):8191–8198. https://doi.org/10.1016/j.ijhydene.2009.12.092
23. Weyandt N (2009) Compressed hydrogen cylinder research and testing in accordance with FMVSS 304. DOT HS 811 150. National Highway Traffic Safety Administration, Washington, DC
24. Seike M, Ejiri Y, Kawabata N, Hasegawa M, Tanaka H (2014) Fire experiments of carrier loaded FCV in full-scale model tunnel: estimation of heat release rate and smoke generation rate. Paper presented at the third international conference on fire in vehicles, Berlin, Germany, 10/1/2014–10/2/2014
25. LaChance J, Houf W, Middleton B, Fluer L (2009) Analyses to support development of risk-informed separation distances for hydrogen codes and standards. SAND2009-0874. Sandia National Laboratories, Albuquerque, NM
26. National Fire Protection Association (2016) NFPA 55, Compressed gases and cryogenic fluids code

27. Groth KM, LaChance JL, Harris AP (2012) Early-stage quantitative risk assessment to support development of codes and standard requirements for indoor fueling of hydrogen vehicles. SAND2012-10150. Sandia National Laboratories, Albuquerque, NM

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