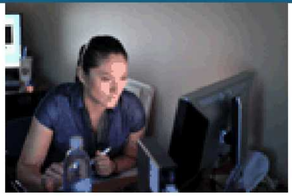
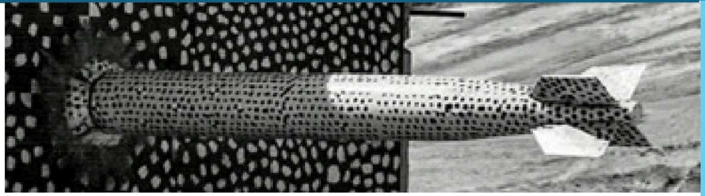
SAND2019-7907PE

Tunnel Scenario Estimation & Discussion





Chris LaFleur, Sandia National Laboratories

Codes & Standards Technical Team – July 11, 2019

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Outline

Event Sequence Diagram

Uncertainty

Step Through Event Tree

Results

Discussion

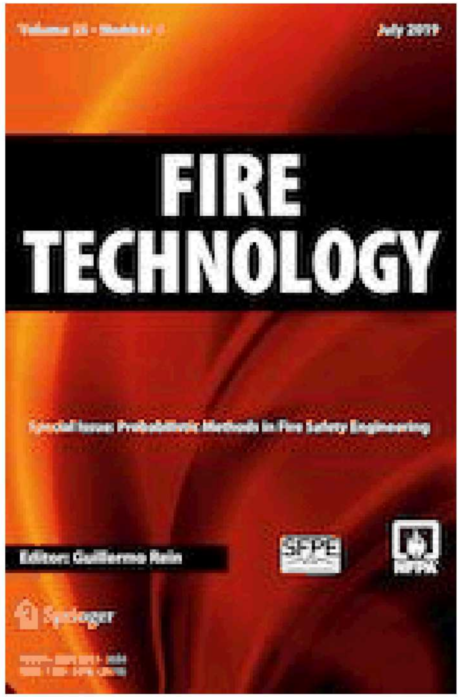
Method to Estimate the Risk of FCEV Incidents in Tunnels

Event Sequence Diagram - represents an undesired event as a sequence of sub-events

- 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
- Total for each outcome is the combination of all the probabilities leading to that outcome

Branch line results are calculated via Monte Carlo sampling of all conditional probabilities

Journal paper with all the analysis and results Accepted with Revision and currently revisions are Under Review for publication in Fire Technology



Uncertainty

Not enough data to estimate probabilities with high confidence

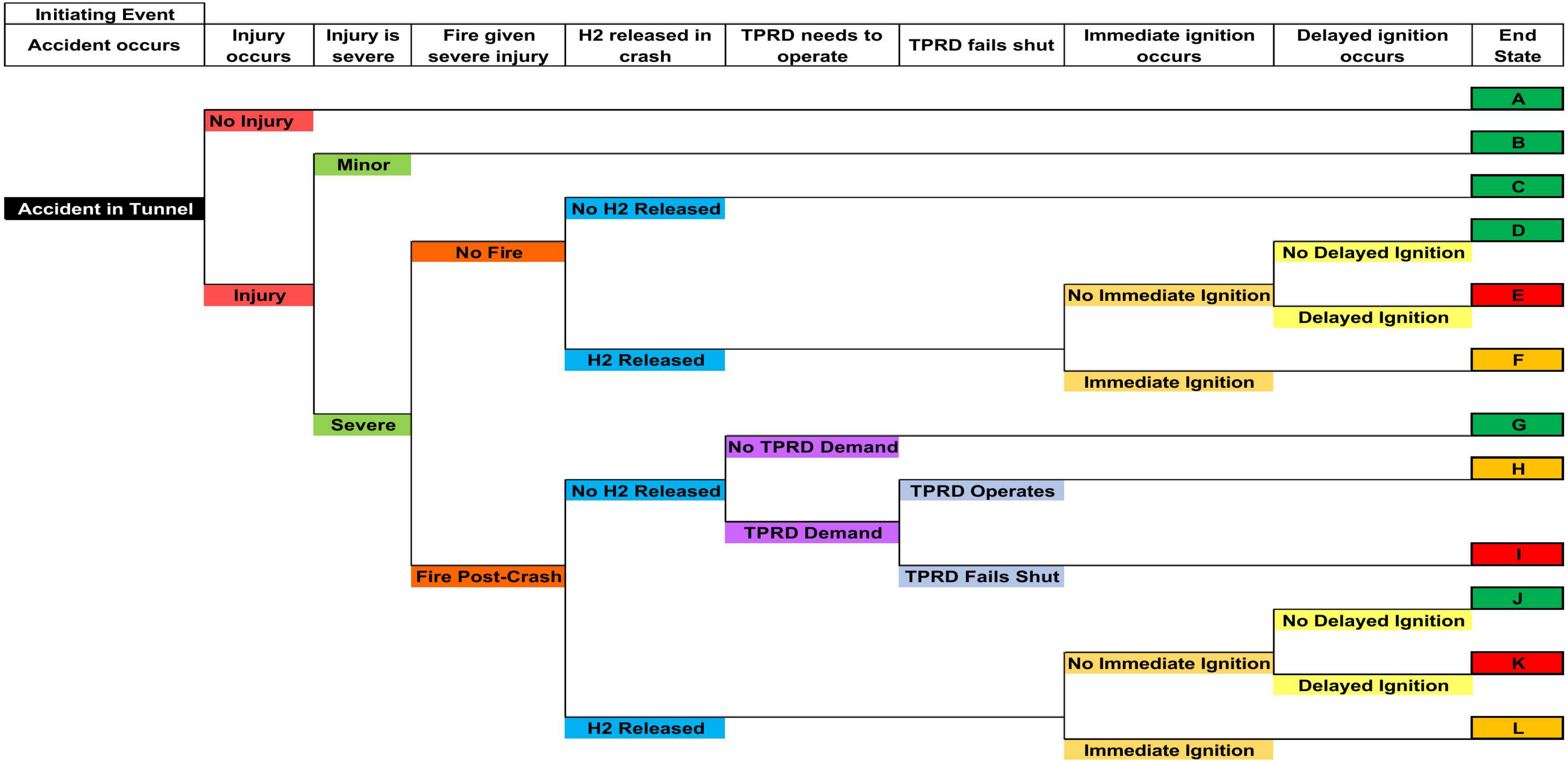
Uncertainty distributions were derived based on the current state-of-knowledge

Each branch line result is a range of possible probabilities for each scenario

Each branch point uncertainty was propagated through the event tree to perform a Monte Carlo analysis

Probability of each scenario is presented as a distributions of these multiple calculations

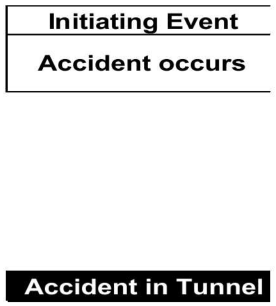
Event Tree

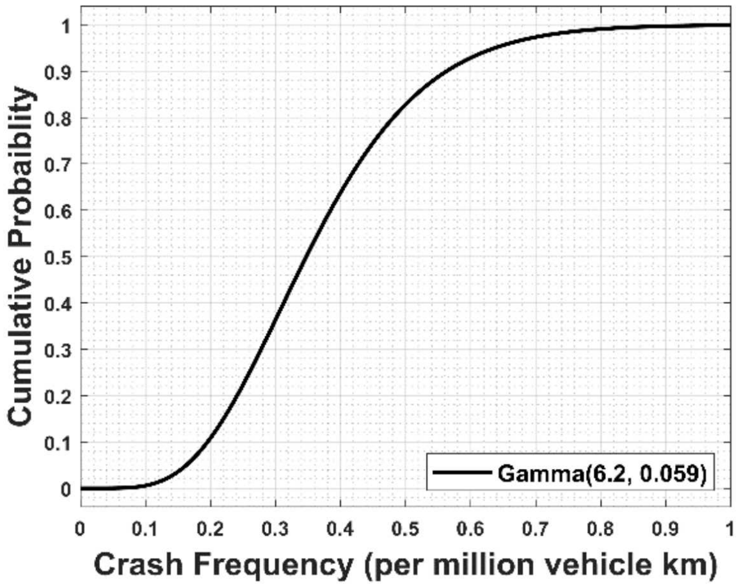

Initiating Event
Accident occurs
Injury occurs
Injury is severe
Fire given severe injury
H2 released in crash
TPRD needs to operate
TPRD fails shut
Immediate ignition occurs
Delayed ignition occurs
End State
Accident in Tunnel
No Injury
Injury
Minor
Severe
No Fire
Fire Post-Crash
No H2 Released
H2 Released
No TPRD Demand
TPRD Demand
TPRD Operates
TPRD Fails Shut
No Immediate Ignition
Immediate Ignition
No Delayed Ignition
Delayed Ignition
A
B
C
D
E
F
G
H
I
J
K
L

Event Tree

Initiating Event – Hydrogen Vehicle Crash in a Tunnel

- Generic crash rate for tunnels used as a conservative estimate
- Tunnel crash frequency estimates averaged over a three-year period for 10 different countries published
- Expressed as crashes per million vehicle kilometers:
  0.277, 0.337, 0.355, 0.420, 0.315, 0.8, 0.303, 0.253, 0.145, 0.483, and 0.345



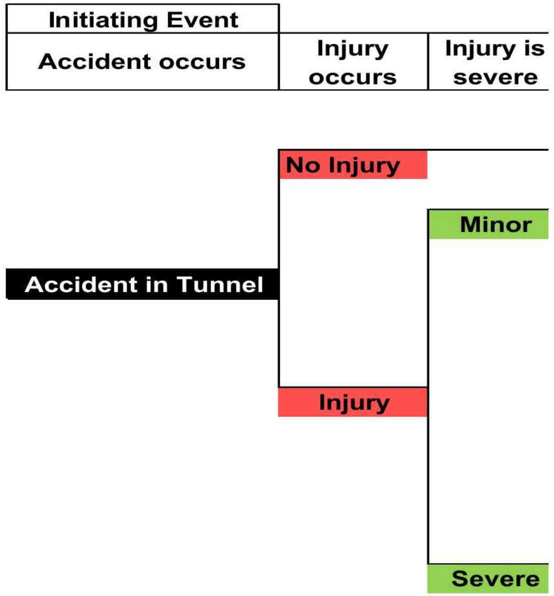


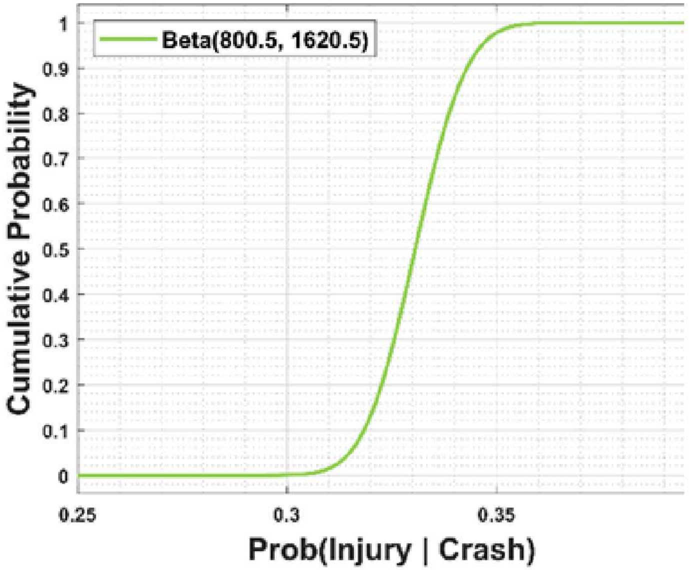
Reference: Bassan S (2016) Overview of traffic safety aspects and design in road tunnels. IATSS Research 40 (1):35-46.

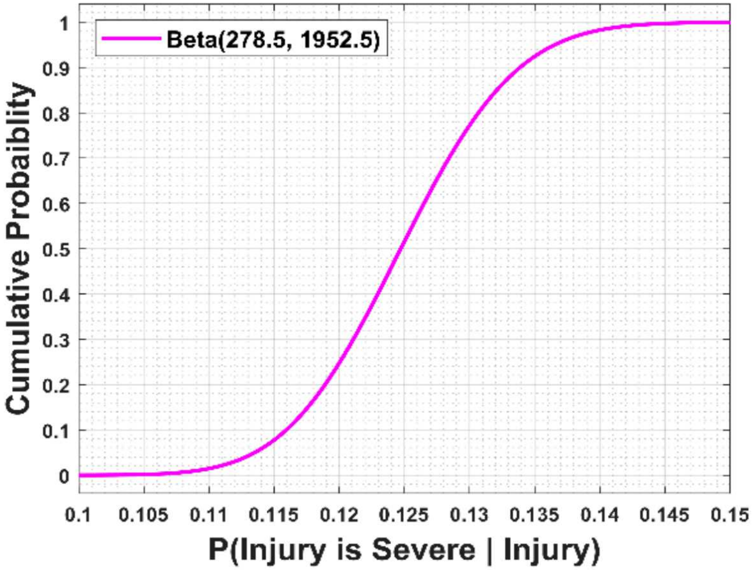
Event Tree

Severity of a Crash - Severe injury is a proxy for crash severity (people are very vulnerable)

- Breaks 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
- Total of 2420 crashes and 800 injuries for Probability of Injury occurring
- Total of 2230 injuries with 278 of them severe from 4 different studies







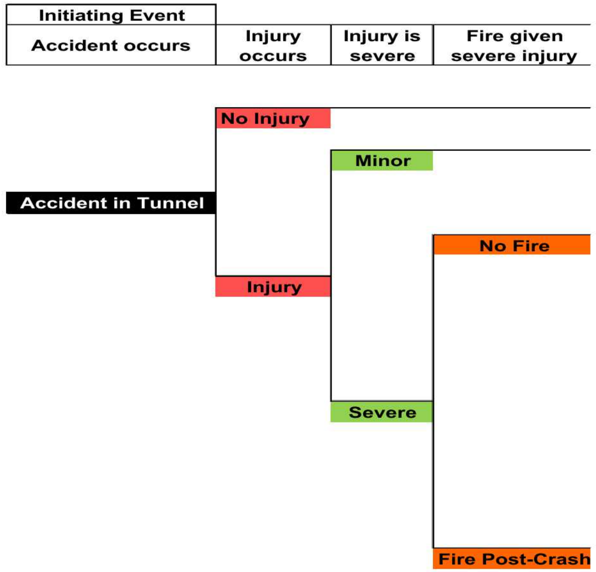
References: Bassan S (2016) Overview of traffic safety aspects and design in road tunnels. IATSS Research 40 (1):35-46.
Ciro Caliendo MLDG, Maurizio Guida, (2013) A crash-prediction model for road tunnels, . Accident Analysis & Prevention, 55:107-115.

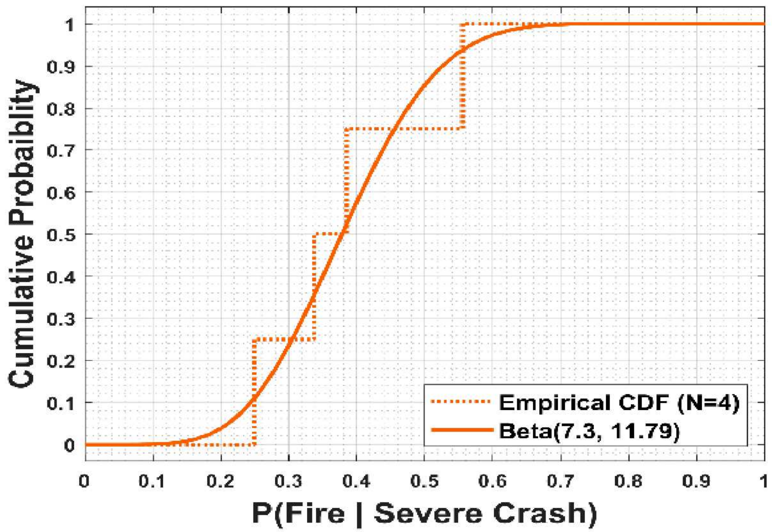
Event Tree

Hydrocarbon Fire - likelihood of a crash causing a fire given that the crash was severe

- Assumes than a crash involves at least one traditionally-fueled vehicle and that any crash resulting in a fire is considered severe
- Used average severe crash rates and average fire crash rates from Italy, Norway, and Switzerland over a four year period

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





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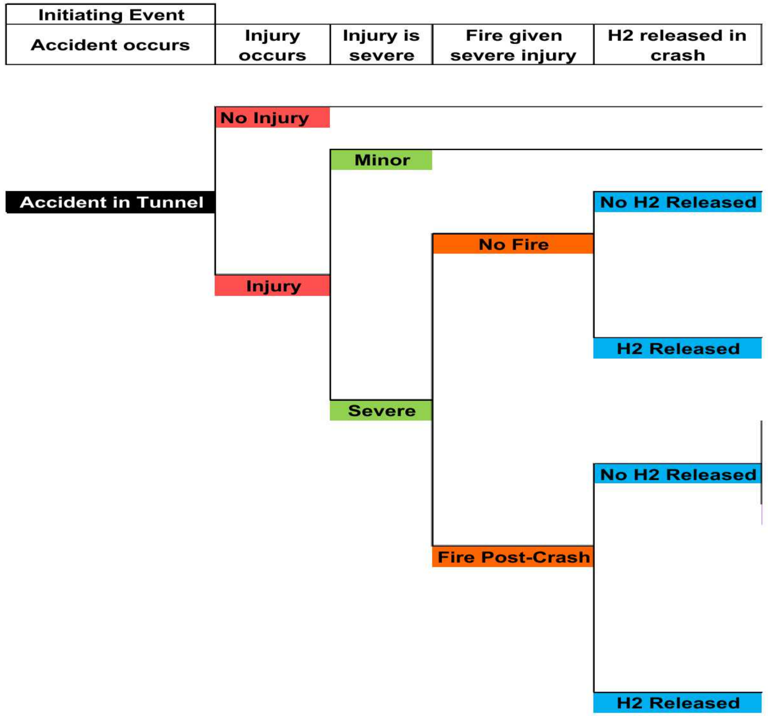
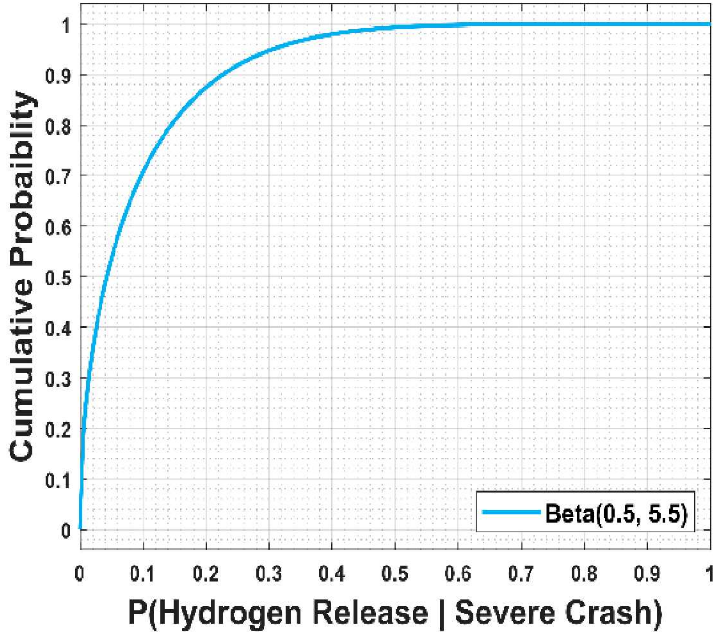
Event Tree

Damage-Induced Hydrogen Release – Probability that hydrogen is released due to crash

- Used published crash test data
- Five tests were available, no releases
- Used Jeffrey's prior (0.5 event)



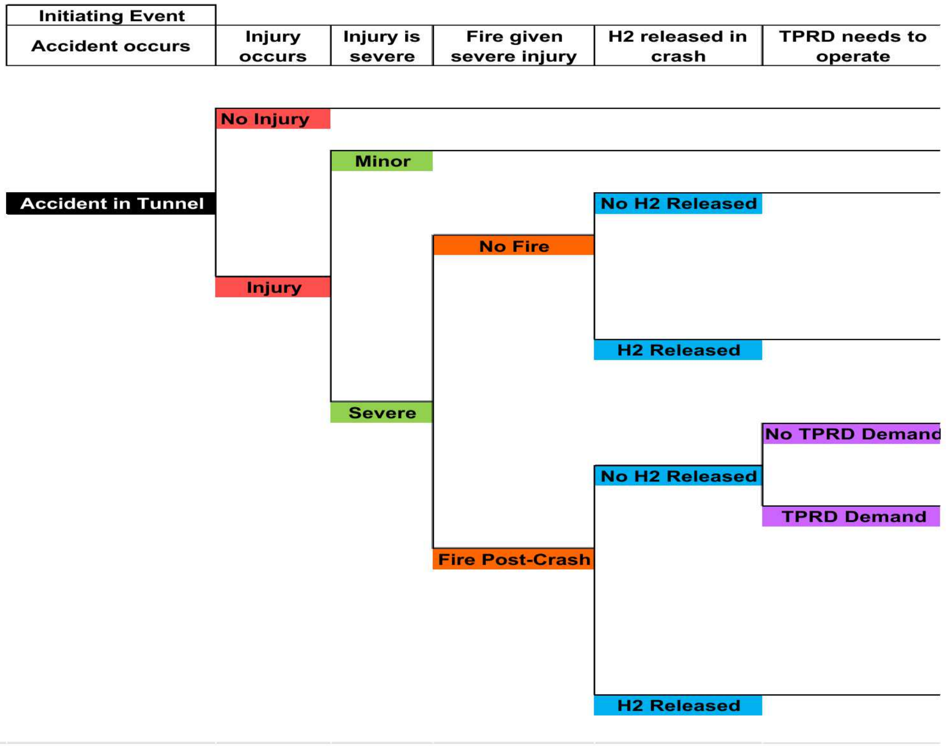


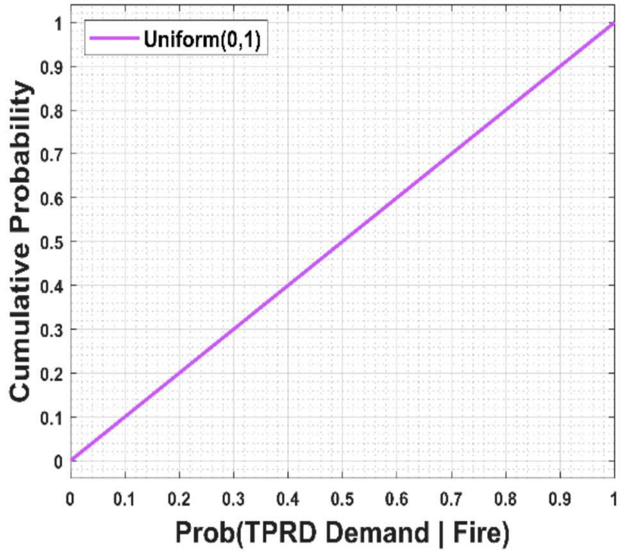
References: Pape D, Cox A (2015) Compressed Hydrogen Container Fueling Options for Crash Testing. National Highway Traffic Safety Administration, Washington, DC
Batelle Memorial Institute (2015) Crashworthiness Research of Prototype Hydrogen Fuel Cell Vehicles: Task Order 7 Project Report. National Highway Traffic Safety Administration, Washington, DC

Event Tree

Pressure Release Device Demand– Probability that hydrocarbon fire exposes thermally-activated pressure relief device (TPRD) on the H2 tank

- Actual crash specifics determine the extent of the fire and the proximity of the vehicle and pressure vessel to the fire; neither of these parameters are known
- Uniform distribution between zero and one was assumed due to high uncertainty



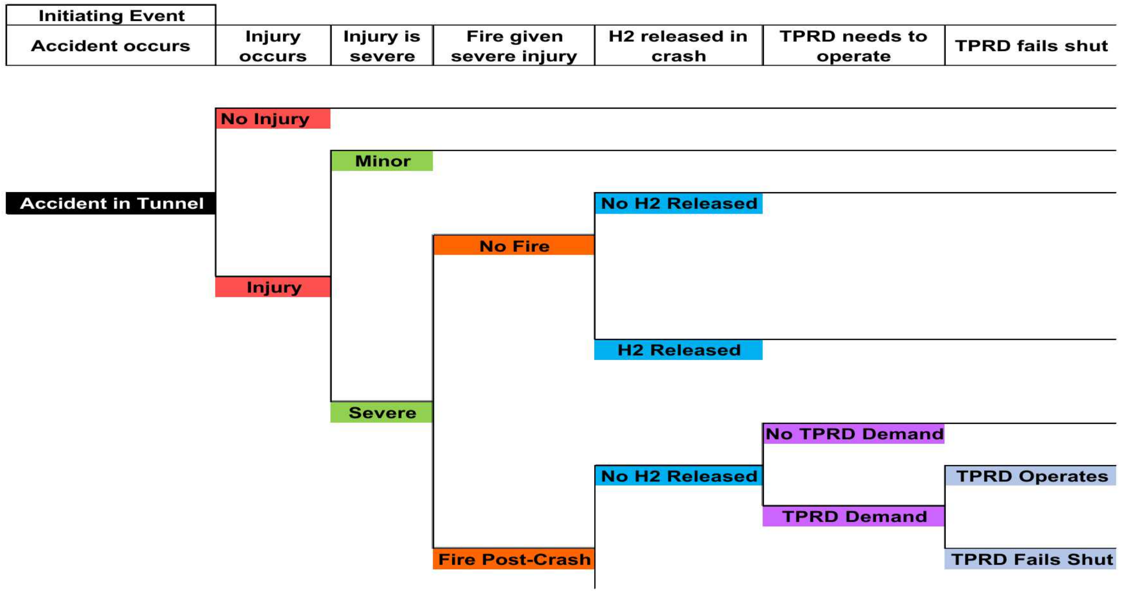


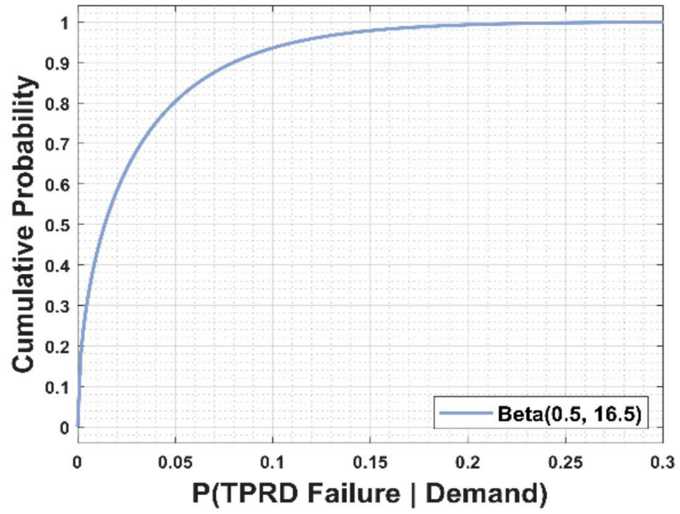
Event Tree

Pressure Relief Device Activation– Possibility that TPRD fails to operate on demand

- literature review was performed on pressurized hydrogen tank fire testing that included TPRDs
- Five sources of data were found
- Used Jeffrey's prior (0.5 event) because no failures were recorded

Source	TPRD Demands	TPRD Operation
Yamazaki	2	2
Suzuki	4	4
Zheng	1	1
Wyandt	6	6
Sekine	3	3





References: Koji Yamazaki YT (2017) Study of a post-fire verification method for the activation status of hydrogen cylinder pressure relief devices. IJHE, 42 (11):7716-7720

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. 2006 SAE World Congress, Detroit, Michigan, 4/3/2006 - 4/6/2006

Jinyang Zheng HB, Ping Xu, Honggang Chen, Pengfei Liu, Xiang Li, Yanlei Liu, (2010) Experimental and numerical studies on the bonfire test of high-pressure hydrogen storage vessels, . IJHE, 35 (15):8191-8198.

Weyandt N (2009) Compressed Hydrogen Cylinder Research and Testing in Accordance with FMVSS 304. Southwest Research Institute,

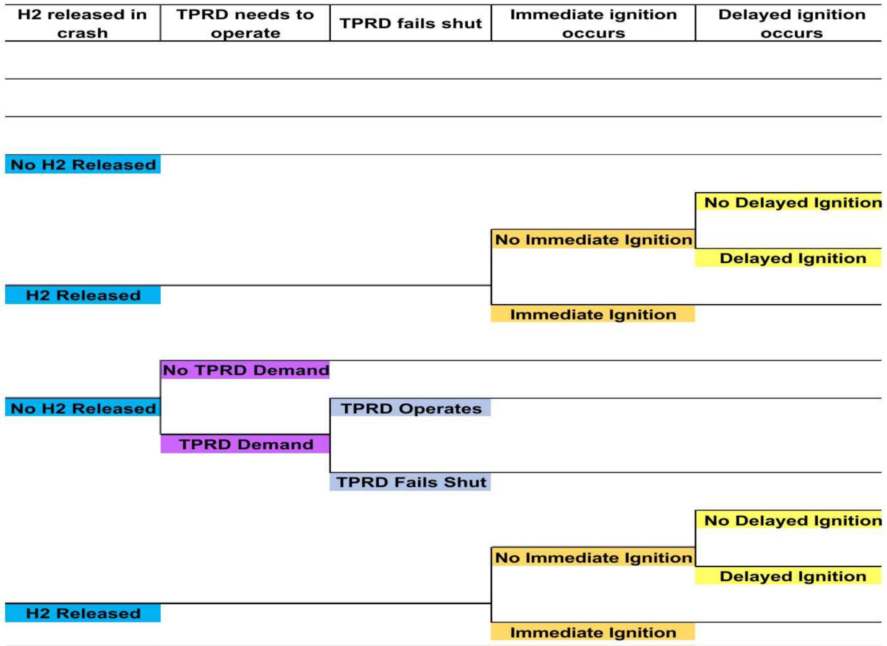
Seike M, Ejiri Y, Nobuyoshi Kawabata, Hasegawa M, Tanaka H (2014) Fire Experiments of Carrier loaded FCV in Full-Scale Model Tunnel - Estimation of Heat release rate and Smoke Generation Rate. Paper presented at the Third International Conference on Fire in Vehicles, Berlin, Germany, 10/1/2014 - 10/2/2014

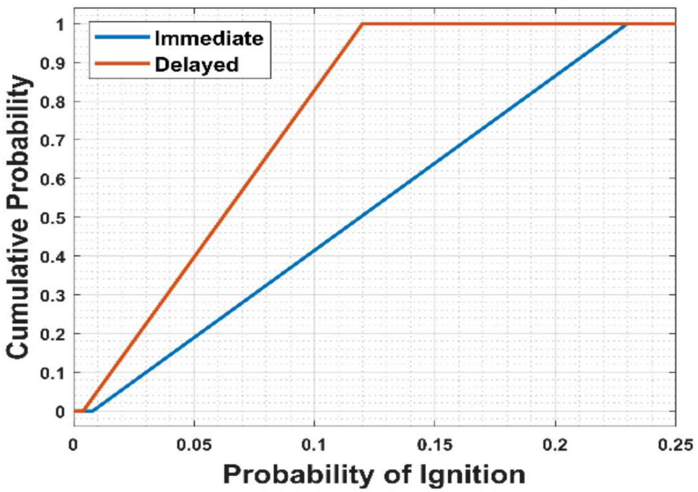
Event Tree

Hydrogen Ignition – Probability that released hydrogen will ignite

- Probabilities derived for the Canadian Hydrogen Safety Program by adapting non-hydrogen ignition values suggested in Cox, Lees, & Ang.
- Historically used for hydrogen quantitative risk assessment and to develop separation distances in NFPA
- Actual hydrogen release rate are incident specific - distributions for immediate and delayed ignition were defined as uniform between the bounding values in the table

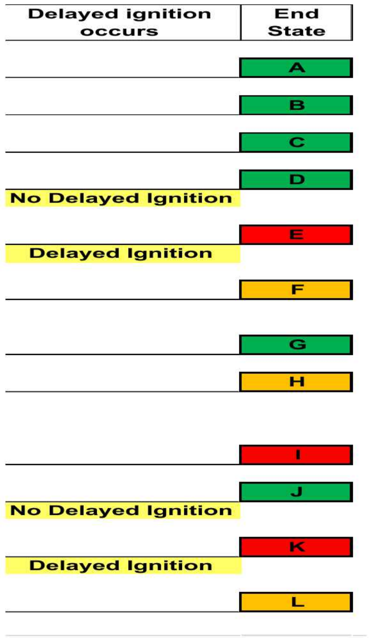
Hydrogen Release Rate (kg/s)	Immediate Ignition	Delayed Ignition
<0.125	0.008	0.004
0.125 - 6.25	0.053	0.027
>6.25	0.23	0.12
Average	0.098	0.049





References: Tchouvelev A, Hay D, Bénard P (2006) Quantitative risk comparison of hydrogen and CNG refuelling options. Final Technical Report to Natural Resources Canada
Cox, A. W, Lees, Frank P, Ang, M. L, Institution of Chemical Engineers and Inter-Institutional Group on the Classification of Hazardous Locations *Classification of hazardous locations*. Institution of Chemical Engineers, London, 1990.

Event Tree Results

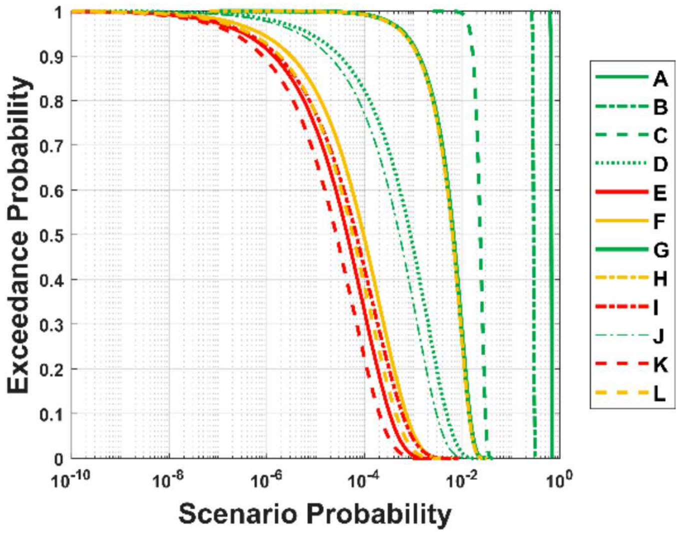


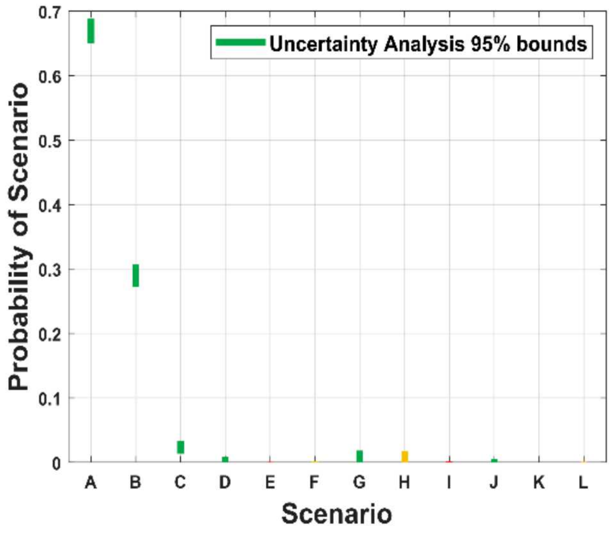
Legend for Branch Line Results

- Green: Hydrogen does not contribute to consequence of crash
- Yellow: Hydrogen does contribute to consequence
- Red: Hydrogen contributes to catastrophic consequence

Exceedance probability curves for each branch line show that the scenarios with the highest consequences from hydrogen have probabilities on the order of 1E-05 to 1E-04

Overwhelmingly, the most likely scenarios are those in which hydrogen does not significantly contribute to the consequences.





Scenario	Probability 95% Bounds	Probability Median Estimate	Median Frequency*	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

* per million vehicle kilometers

Discussion

What scenario(s) should be the basis of regulatory requirements?