SAFETY SYSTEM DESIGN FOR MITIGATING RISKS OF INTENDED HYDROGEN RELEASES FROM THERMALLY ACTIVATED PRESSURE RELIEF DEVICE OF ONBOARD STORAGE

Zhiyong Li and Ke Sun
Institute for Built Environment and Energy Engineering, Jiaxing University,
No.56 South Yuexiu Road, Jiaxing City, P.R. China
E-mail: z.li@mail.zjxu.edu.cn

ABSTRACT

All vehicular high-pressure hydrogen tanks are equipped with thermally-activated pressure relief devices (TPRDs), required by Global Technical Regulation. This safety device significantly reduces the risk of tank catastrophic rupture by venting the hydrogen pressure outside. However, the released flammable hydrogen raises additional safety problems. Japan Automobile Research Institute has demonstrated that in the vehicle fire event, once the TPRD opens, the hydrogen fires will engulf the whole vehicle, making it difficult for the drivers and passenger to evacuate from the vehicle. This paper designs a new safety system to solve the evacuation problem. The safety system includes a rotatable pressure relief device with a motor, a sensory system that consists of infrared sensors, ultrasonic radar and temperature sensors, a central control unit and an alarm device. The new design of the pressure relief device allows the system actively adjusting the release direction towards void open space outside the vehicle to minimize the risks of hydrogen fires. The infrared sensors located at the roof of the vehicles collect info inside the vehicle and the ultrasonic radar detect the region outside the vehicle. Temperature sensors tell when to trigger the alarm and set the motor in standby mode, and the central control unit determines where to rotate based on the info from the infrared sensors and ultrasonic radars. A control strategy is also proposed to operate the safety system in an appropriate way. The cost-benefit analysis show that the new safety system can significantly reduce the risks of intended hydrogen releases from onboard pressure relief devices with total cost increases by less than 1% of the vehicle cost, making it a good cost-effective engineering solution.

1.0 INTRODUCTION

With the significant improvement of hydrogen fuel cell technologies in the past two decades, the large scale commercialization of hydrogen use for transport is approaching. A clear signal is that the automobile companies' optimistic attitude and actions. For example, Toyota is upping its production capacity for hydrogen-powered cars after the company announced that it expects hydrogen car sales to increase ten-fold from 2020. Whereas global sales of hydrogen fuel cell vehicles currently stand at around 3,000 a year, Toyota has said that it expects more than 30,000 hydrogen vehicles to be sold annually during the 2020s [1]. This number is expected to continue booming thereafter. According to a new research report by Global Market Insights, global fuel cell electric vehicle market share is projected to surpass 300,000 units by 2024 [2]. In China, the number of fuel cell vehicles is expected to reach 10,000 by 2020 and 2,000,000 by 2030, according to the blue book of development of China hydrogen industries and infrastructures [3].

With the growing number of hydrogen fuel cell vehicles, the safety issues would become a public concern. Hydrogen has been widely used in industrial field for over one hundred years, but not in consumers' environment in a large scale before. Hydrogen introduces hazards that are different from those of gasoline and diesel fuels. Onboard hydrogen is mostly stored in high compressed condition with pressure up to several hundreds of atmospheric pressure, despite a few cryogenic liquid hydrogen storage applications. The high pressure storage has the potential to cause catastrophic tank rupture. The result will be a violent depressurization from high pressure tank with a creation of a strong blast wave and a hydrogen fireball. Tank rupture tests conducted by USA Southwest Research Institute on a type 3 tank (wrapped composites with metallic liner) mounted under a sports utility vehicle [4] has demonstrated the extent of hazards associated with the tank rupture: the catastrophic rupture of a type 3 tank with a volume of 88 L at pressure of 31.8Mpa produced a hydrogen fireball with maximum diameter up to 24 meters and the blast wave carried aluminium liner fragments travelling over 40 meters.

To prevent such catastrophic events, a safety device called pressure relief device is required to be installed with the onboard hydrogen tank. The pressure relief device can reduce the overpressure inside the tank to avoid catastrophic rupture. Commonly all vehicular high-pressure hydrogen tanks are equipped with thermally-activated pressure relief devices (TPRDs), required by No.13 of Global Technical Regulation [5]. In an event of vehicle fire, if the temperature reaches more than 110 degree centigrade approximately, the TPRD will open and the compressed hydrogen will be released rapidly. This safety device significantly reduces the risk of tank catastrophic rupture by venting the hydrogen pressure outside. However, the released flammable hydrogen can raise additional safety problems such as hydrogen fires. An experiment conducted by Japan Automobile Research Institute [6] has demonstrated that once the TPRD opens, the hydrogen fire might engulf the whole vehicle in a very short time. This indicates that the driver and passengers cannot evacuate through doors of the vehicle when the TPRD opens.

As generally agreed and manifested in current regulation that TPRDs for fuel cell vehicles are required safety equipment as the benefit of preventing catastrophic tank rupture is vitally important. However, the side effect of TPRD cannot be neglected as the hydrogen fires introduced by TPRD are also deadly. The aim of this study is to reduce the harm of hydrogen fires caused by TPRD venting and solve the evacuation problem for the driver and passengers inside the vehicle.

2.0 SAFETY SYSTEM DESIGN FOR HYDROGEN RELEASE FROM TPRD

Hydrogen release from TPRD is an intended release as the system is designated to do so. For intended hydrogen release, it is possible to manipulate it as we know when and how it will occur. The essential idea of the safety system design is to actively control the release direction pointing to void open space before TPRD opens.

Currently automobile manufactures set TPRD vent pipe vertically downward as the default release direction, so that the hydrogen fire hazard zone can be localized in the vicinity of the vehicle. However the vertically downward hydrogen impinging on the ground will result in fire engulfment of the vehicle, making the evacuation of the driver and passengers difficult. If we could identify any void open space around the vehicle, then it will be unnecessarily to follow the default downward direction to vent hydrogen. Instead, let the hydrogen release towards the void open space to mitigate the fire intensity around the vehicle, so the driver and passengers would be able to evacuate.

Therefore, the questions for the safety system design will be: (1) would it be possible to change the release direction of TPRD vent pipe? (2) Would it be possible to monitor the outdoor environment around the vehicle to identify a void open space? (3) If so, which release direction would be good to balance the indoor safety and outdoor safety? i.e., an appropriate release angle enabling the evacuation of people inside the vehicle while not leading to large harm distance for people outside the vehicle.

2.1 Rotatable pressure relief device

To be able to change the release direction, a new rotatable pressure relief device is designed as shown in figure 1. It can be seen from the figure that the original TPRD vent exit is extended by introducing mechanical parts including a buffer region, an inducing region and a direction shift region. The liner of buffer region is made of foam aluminium which can capture the melted plug and divert the released hydrogen to the inducing region. The inducing region part sets two designated position. The default position is shown in figure 1, i.e., the pipe axis is from the left side of the vehicle to the right side of the vehicle. The other position is rotation of 90 degree and the pipe axis will be from the front of the vehicle to the rear of the vehicle. It is worth stating that the rotation design is not arbitrarily rotation at any angle but just two alternatives only, i.e. either to maintain its default position or to rotate 90 degree at one time and then keep the position (be locked). The rotation angle, β, is the appropriate release angle enabling the evacuation of people inside the vehicle while not leading to large harm distance for people outdoors. This angle will be investigated in Part 3 of this paper.

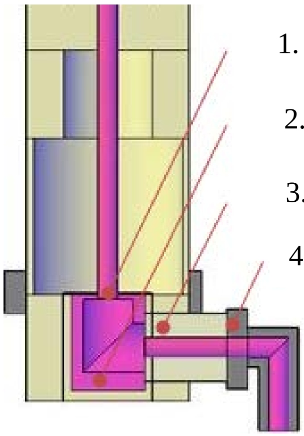

Figure 1 A schematic drawing of the new TPRD design for onboard hydrogen tank
(view from the rear of the vehicle toward the front of the vehicle)

2.2 Sensory and control system

The rotatable TPRD device require a system to inform it when and where to adjust release direction. The system should be able to collect the indoor and outdoor info of the vehicle and then make a decision automatically. To collect the info inside the vehicle, the system applies pyroelectric infrared sensors which can detect the indoor environment of the vehicle and tell whether there is any person inside the vehicle. To collect the info outside the vehicle, the system adopts ultrasonic radars to detect the outdoor environment and tell where the void space is located. In addition, temperature sensors are required to tell when to let the motor initiate to adjust release direction before TPRD activation. Table 1 lists the technical parameters of the sensors in the system.

Table 1 List of sensors of the safety system

	Pyroelectric infrared sensors	Ultrasonic radars	Temperature sensors
Detection Parameters	Distance < 7 m Detection angle 100°	Distance 0.05 m ~ 12 m Detection angle 85°	Distance 0.5 ~ 1 m Temperature range 40~115℃
Function	Detect people inside the vehicle	Detect void open space outside the vehicle	Detect ambient temperature around TPRD

A central control unit is also required to process the info collected and to send instructions to the motor and the alarm device. The flowchart of the safety system is shown in figure 2.

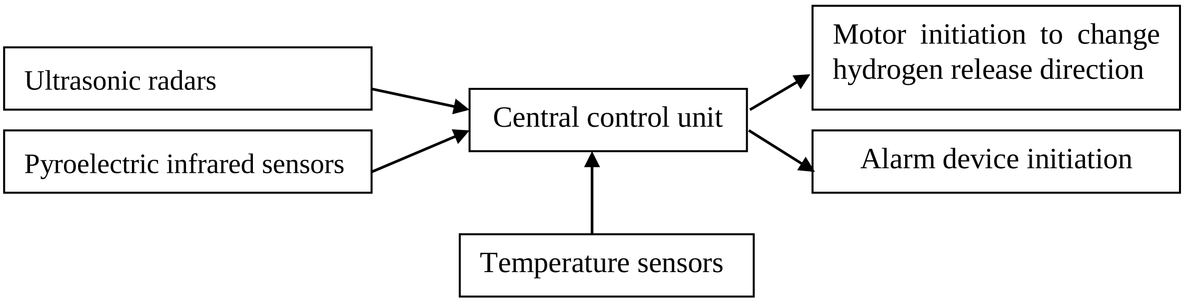

Figure 2 Flowchart of the safety system

2.3 System layout and operation

The safety system layout is shown in figure 3. Two temperature sensors are located near the TPRD to detect the ambient temperature around TPRD. Two pyroelectric infrared sensors are placed at the roof of the vehicle. One is above the front seats to detect the half space of the vehicle, and the other is above the rear seats to cover the rest of the space in the vehicle. There are three ultrasonic radars. One is located at the rear of vehicle to detect the backward space outside the vehicle. The other two are placed symmetrically at the left rear side and right rear side of the vehicle. The central control unit and the alarm are located in the middle of rear region near the temperature sensors.

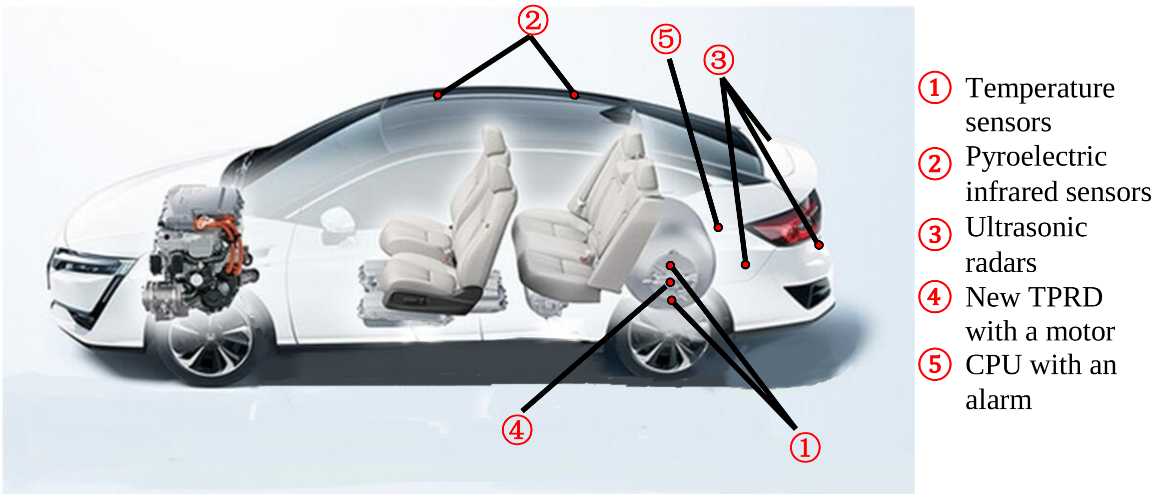

Figure 3 Layout of the safety system

The safety system operation strategies are developed, as shown in figure 4. If the high temperature is detected by sensor #1, then the safety system will be initiated with alarm beeping and motor in standby mode. If the info from the sensor#2 shows nobody inside the vehicle, then the vent direction will keep the default position and the motor will be turned off. If there are people inside the vehicle, then the info from sensor #3 is required to be collected. If backward space is void, then the motor will rotate the vent direction backward, and people are able to evacuate through any doors of the vehicle. If the backward space is not void, then the left side info needs to be collected. If the left side space is void, then the motor will rotate the vent direction leftward, and the left doors will be locked automatically. People should evacuate through right doors only. If the left side space is not void, then the right side info will be collected to judge where the rightward direction is safe to release. If so, the motor will rotate vent direction to rightward, and the right doors will be locked automatically. People should evacuate through left doors only.

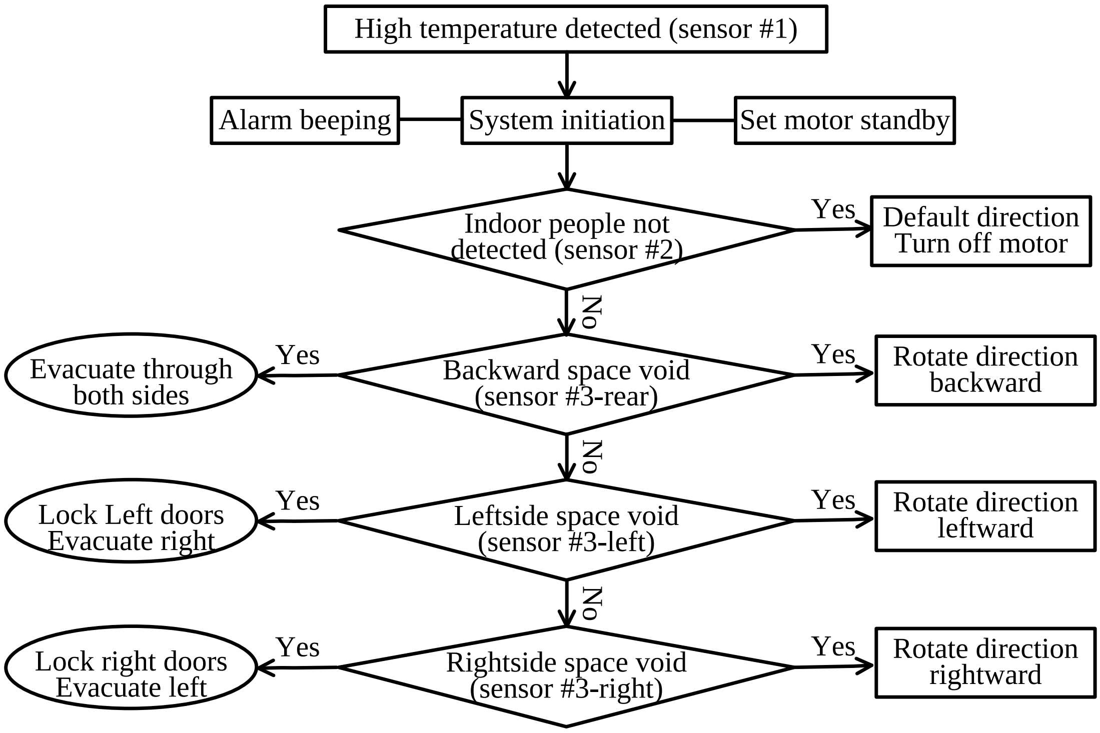

Figure 4 Safety system operation strategies

3.0 DETERMINATION OF VENT ANGLE

A good vent angle should be able to allow evacuation of people inside the vehicle while not leading to large harm distance for people outdoors. To determine the best angle, CFD simulations are carried out.

3.1 Vehicle and environment parameters

Hydrogen storage parameters are selected from the specification of the Honda Clarity [7] with parameters shown in table 2. The ambient pressure and temperature are assumed to be 1 atm and 20 °C, respectively.

Table 2 Hydrogen storage parameters of the fuel cell vehicle

Name	TPRD orifice (mm)	Pressure (MPa)	Inventory (Kg)
Honda Clarity	4.2	35	4

3.2 Blowdown model

Releases from high pressure hydrogen tank are under-expanded jets, where the pressure at the exit of the nozzle is above atmospheric pressure. Calculation of this expansion with complex shock structure from the nozzle exit to the Mach disk requires intensive computation. In many practical situations, it is not necessary to fully resolve these shock structures if the main concern is not the near field around the nozzle. Therefore, it is convenient for our study to substitute the under-expanded jet with an expanded one by applying the notional nozzle model that was introduced by Molkov et al. [8].

3.3 CFD modeling

During tank blowdown, the notional nozzle diameter will decrease with the dropping of pressure in the reservoir. It would be difficult to change the effective diameter during a CFD transient calculation. Instead, mass inflow can be treated as volumetric sources of mass, momentum, and energy in order to avoid having to constantly alter the effective diameter with the passing of time during the simulation. Using this approach the volumetric sources can equivalently reflect the changing parameters at the notional nozzle. This approach was validated against HSL experimental data [9] of hydrogen releases through a 3 mm diameter orifice.

Considering the viscous model implemented, the shear-stress transport (SST) k-ω model was applied in the turbulence calculations performed, as this model is known to allow for a more accurate near wall treatment than k-ε model. The SST k-ω model was developed by Menter [10] to effectively blend the robust and accurate formulation of the k-ω model in the near-wall region with the freestream independence of the k-ε model in the far field. For combustion modelling the eddy-dissipation model is applied. It is a turbulence-chemistry interaction model based on the work of Magnussen and Hjertager [11]. In this model, reaction rates are assumed to be controlled by the turbulence, so expensive Arrhenius chemical kinetic calculations can be avoided. The model is computationally cheap and effective for one or two step heat-release mechanisms.

3.4 Results and discussions

The simulation results are shown in Figure 5 below.

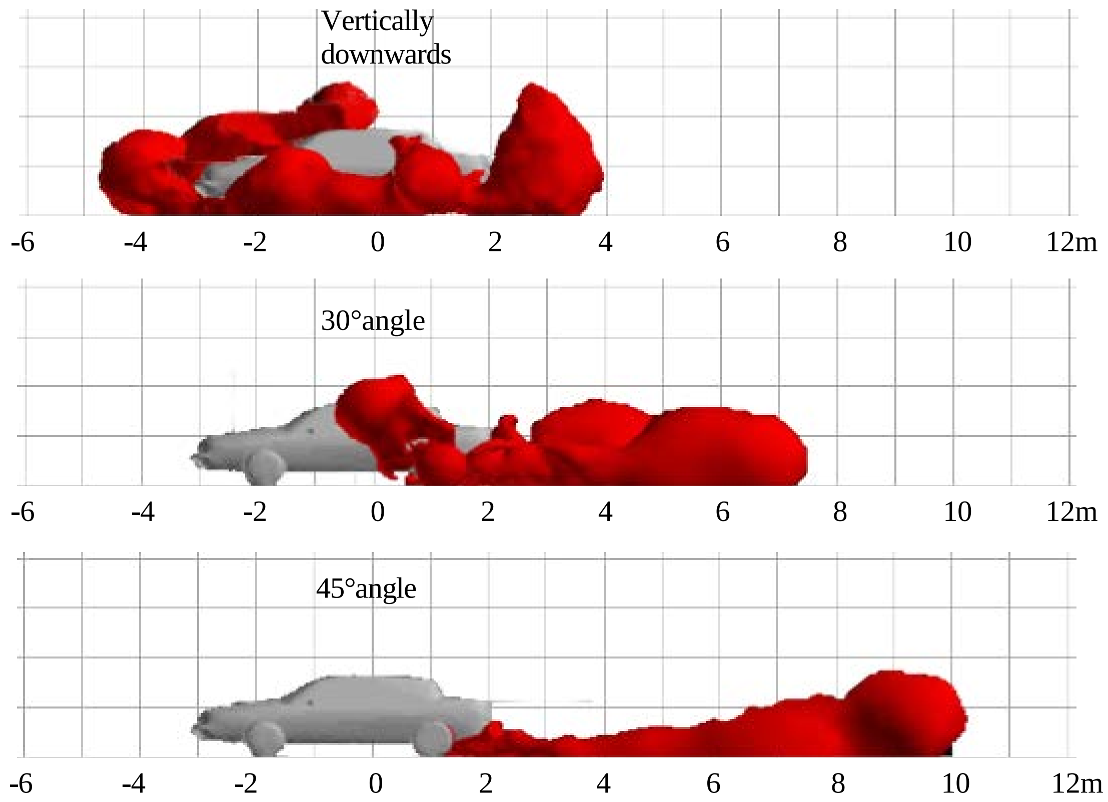

Figure 5 Hydrogen flames at different release angles

It can be seen from figure 5 that for the backward release, 30 degree angle is not sufficient as the hydrogen flame still reaches the rear door of the vehicle, making evacuation from the rear doors dangerous. The 45 degree is good enough as both the front doors and rear doors are clear to evacuate people inside. The side effect is also obvious: the hydrogen can travel distance as far as more than 10 meters. However, this is acceptable as the ultrasonic radar in the safety system can detect distance up to 12 meters, longer than the longest hydrogen flame. The backward release will occur only the ultrasonic radar detects void space within 12 meters. Further increase of the release angle is not recommended as the hydrogen flame distance would surpass the 12 m, out of the radar detection range.

4.0 COST-BENEFIT ANALYSIS

The estimated costs for the safety system are shown in table 3. The prices of sensors and other parts are investigated on the basis of market price available on online retailer websites. The fuel cell vehicle retail price is roughly $63,300 for Honda Clarity [12]. The total costs of the safety system vary from 235 USD to 460 USD, which takes up 0.37% and 0.72% of the total vehicle price.

Table 3 Cost estimation of the safety system

	Price(USD/item)	Number	Cost
Pyroelectric infrared sensors	5~10	2	10~20
Ultrasonic radars	10~20	3	30~60
Temperature sensors	20~30	1	20~30
CPU	15~30	1	15~30
Alarm	10~20	1	10~20
New TPRD	100~200	1	100~200
Other connection parts	/	/	50~100
Sum	/	/	235~460
Percentage over vehicle price	/	/	0.37%~0.72%

The benefit of the safety system can be evaluated in terms of successful evacuation probability. A fault tree analysis is performed, as shown in figure 6.

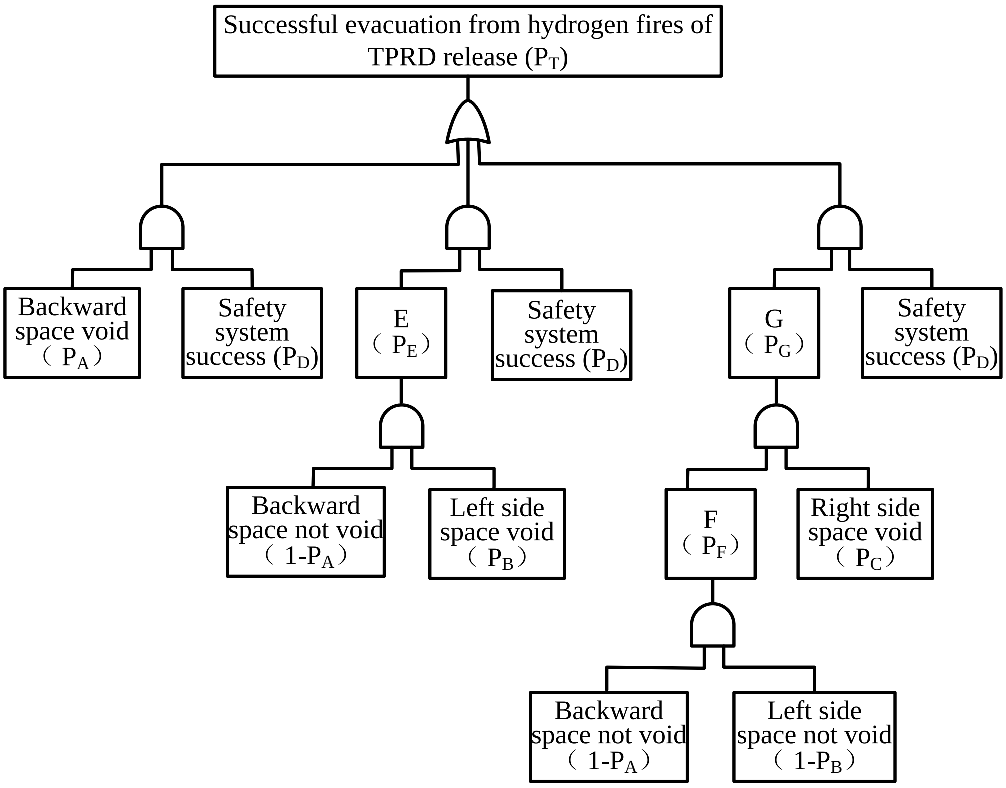

Figure 6 Fault tree analyses for successful evacuation

Assume the probability of void space is 50%, i.e., $P_A=P_B=P_C=0.5$, and the safety system failure rate is 1%, then the chance of successful evacuation PT will be:

$$
\begin{aligned}
P_T &= (P_A \cap P_D) \cup (P_E \cap P_D) \cup (P_G \cap P_D) \\
&= (P_A \cap P_D) \cup ((1 - P_A) \cap P_B \cap P_D) \cup ((P_F \cap P_C) \cap P_D) \\
&= (P_A \cap P_D) \cup ((1 - P_A) \cap P_B \cap P_D) \cup ((((1 - P_A) \cap (1 - P_B)) \cap P_C) \cap P_D) \\
&= P_A P_D + (1 - P_A) P_B P_D + (1 - P_A)(1 - P_B) P_C P_D \\
&= P_D((P_A + P_B + P_C) - (P_A P_B + P_B P_C + P_A P_C) + P_A P_B P_C) = 86.625\%
\end{aligned}
$$

This is a great improvement compared with the no chance of evacuation. This improvement may vary depending on whether the space around the vehicle is crowded or not. Table 4 lists the successful evacuation probabilities at different crowded level. It can be seen that even in the crowed region with the void space probability of only 0.3, the successful evacuation chance is almost 2/3. If the vehicle outdoor environment is not crowded with the void space probability of 0.8, then the successful evacuation rate will be over 98%.

Table 4 Successful evacuation probability at different ambient conditions

Conditions	P_A	P_B	P_C	P_T
Crowded	0.3	0.3	0.3	65.043%
Neutral	0.5	0.5	0.5	86.625%
Not crowded	0.8	0.8	0.8	98.208%

Overall, the new safety system can significantly improve the rate of successful evacuation from TPRD intended hydrogen releases, with total cost increases by less than 1% of the vehicle price.

5.0 SUMMARY

This paper presents a new safety system to solve the evacuation problem in the event of hydrogen releases from TPRD. The safety system includes a rotatable pressure relief device with a motor, a sensory system that consists of infrared sensors, ultrasonic radar and temperature sensors, a central control unit and an alarm device. The safety system is able to actively control the vent direction pointing to void open space before TPRD activation. The CFD simulation results indicate that the appropriate release angle is 45 degree and the angle should not be increased further. Mitigation strategies are also proposed to operate the safety system in an appropriate way. The cost-benefit analysis results show that the operation of the new safety system will significantly reduce the risks of intended hydrogen releases from onboard pressure relief devices with the total cost increases by less than 1% of the vehicle cost, making it a good cost-effective engineering solution.

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