Comparative risk study of hydrogen and gasoline dispensers for vehicles

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Abstract

This paper describes an investigation into the acceptability of installing hydrogen dispensers in public areas based on risk assessments. Because gasoline dispenser risks have been widely accepted for many years, they were used as a benchmark in this study to analyze the risks of hydrogen dispensers. More specifically, we performed risk assessments for both hydrogen and gasoline dispensers and then compared and analyzed the results. We began the process by creating models for both hydrogen and gasoline dispensers that represented their various specifications and elements. Next, potential accident scenarios for each dispenser model were identified by failure mode effect analysis (FMEA) and hazard and operability study (HAZOP). The risks of each scenario were then qualitatively evaluated and the results were organized into risk matrices. By comparing the results of both hydrogen and gasoline dispensers with and without existing safety measures, the appropriateness of their safety measures were validated. Furthermore, by comparing the results of hydrogen and gasoline dispenser safety measures, it was confirmed that the risk levels of the two types were practically equivalent. Therefore, we concluded that the risks involved with installing hydrogen dispensers in public areas can be considered acceptable.

Keyword: Hydrogen dispenser, risk assessment, hazard and operability study, failure mode effect analysis

1. Introduction

Gasoline, diesel, and liquefied petroleum gas (LPG) are currently the most commonly used vehicle fuels. However, in recent years, the practical use of hydrogen as an alternative secondary energy source has been advancing because of concerns over air pollution, global warming, and the need to reduce foreign oil dependency due to national energy security concerns. In Japan, more than 80 hydrogen fueling stations have been established since the first such station opened in 2002. According to the Energy Innovation Strategy (2016) roadmap issued by the Ministry of Economy, Trade and Industry (METI) in Japan, it is estimated that the number of hydrogen fueling stations will expand to 320 sites by 2025. Similar efforts are being carried out in major European countries and the United States (US).

Since all such vehicle fuels are combustible liquids or gases, each must be handled carefully, and the parties concerned must allow for new risks arising from fuel diversification. In a report that summarizes the safety characteristics of hydrogen when compared to gasoline, it was noted that hydrogen has a wide flammability range and a low minimum ignition energy, but that the gas dissipates quickly and its lower flammable limit is four times higher than that of gasoline[1,2]. There have been numerous studies that focused on the safety aspects of hydrogen handling, including its production, storage, transportation, transfer, and use. For example, accident records have been

analyzed for hydrogen fueling stations[3], production and storage facilities, and power plants[4]. Additionally, risk assessments have been carried out with qualitative methods[5–9], quantitative techniques[10–13], integrated methods[14–16], and the potential effects of hydrogen releases and resulting explosions have been analyzed via computational fluid dynamics (CFD)[17–19]. There has also been an experimental study on hydrogen explosions[20–22], and research aimed at the establishment of relevant codes and regulations, safety distances, and facility layouts[23–26]. Fig. 1 shows the outline of a typical hydrogen fueling station, which normally consists of a dispenser, accumulator, and compressor. It should be noted here that, because of their large inventories, many prior studies aimed at reducing the risks of hydrogen stations targeted the compressors and accumulators, but there has been little focus on dispensers.

Dispensers are infrastructure that supply fuel to vehicles, and are therefore essential devices in any motorized society. They are also equipped with measuring instruments used for commercial fuel transactions, and are thus indispensable for general economic activity. As for their risk assessments, there are some notable points that are different from other equipment. For example, it must be considered that they are often used by drivers who are not educated in specialized safety procedures. Moreover, consumers with diverse backgrounds get very close to dispensers for refueling. It is difficult to predict and regulate their behavior unlike operators. Especially, dispensers are directly operated by members of the public at self-service filling stations. Furthermore, fueling stations are often installed in urban areas. Dispensers are accessible to everyone on the open road. Thus, accidents such as a fire or an explosion would cause a severe impact. All of these factors mean that it is necessary to evaluate specialized risks for dispensers because they have characteristics that are different from other devices.

In this study, the risks involving gasoline dispensers, which have been generally accepted for many years, were set as benchmarks for analyzing the risks of hydrogen dispensers, and risk assessments were carried out for both dispenser types. However, since results of such risk assessments cannot be compared in general terms, we applied the same method, criteria, and working group to each dispenser in an effort to identify and focus on differences in the risk levels involved in dispensing both fuels. Then, by conducting risk assessments with and without existing safety measures, we validated the adequacy of existing safety measures related to each dispenser. Furthermore, to reveal risks specific to hydrogen dispensers and confirm whether the risks involved with installing hydrogen dispensers in public areas could be considered acceptable, the results of the assessments for each dispenser were analyzed.

2. Risk assessment method

Since safety measures cannot be applied against risks that have not been identified, it is clearly necessary to start by identifying and recognizing any and all potential risks. Accordingly, we

integrated the failure mode and effects analysis (FMEA) with the hazard and operability study (HAZOP) in our examination of each dispenser type in order to comprehensively identify potential accident scenarios. FMEA is a risk assessment technique that was developed for use in the US aerospace industry in the 1950s, and is now widely used in many industries to evaluate system hazards by assuming failure modes for various elements of a system.

On the other hand, HAZOP is a technique developed by Imperial Chemical Industries (ICI) in the United Kingdom (UK) for safety evaluations of its chemical plant. The HAZOP implementation manual was first issued in 1977, and the technique has since been generalized. HAZOP is a brainstorming method used to evaluate hazards with guide words. More specifically, by applying guide words, deviations from the normal state of a process can be presumed, and then potential accident scenarios can be identified and analyzed. In this research, we began by extracting potential accident scenarios that would result from the failure of system components by FMEA, and then used the HAZOP procedure to evaluate hazards caused by external factors such as earthquakes and neighboring fires, which are difficult to find with FMEA alone.

Risk assessments were performed on each potential accident scenario. The severity and the frequency of each scenario was qualitatively evaluated with both methods using the same risk assessment techniques discussed in Refs. [6,7,9]. Tables 1 and 2 show the criteria for the ranking of each potential accident scenario. The severity rank is categorized according to the magnitude of human injuries, as this is considered to be the most significant factor in determining the magnitude. Note that distinctions were made for human injuries inside and outside the station site because people outside the site do not directly benefit from the dispenser. After conducting risk assessments for each scenario with and without existing safety measures, the assessment results were analyzed using risk matrices.

3. Dispenser descriptions

To represent various specifications, the structures, components, and operating conditions of each dispenser type were investigated, after which models for each fuel were constructed.

3.1 Hydrogen dispenser

Although there are both on-site and off-site hydrogen stations, there are no notable differences in their specifications of dispensers. In both types, hydrogen is condensed by a compressor and then stored in accumulators. Finally, the hydrogen is refueled to a vehicle through a dispenser. In the hydrogen dispenser model shown in Fig. 2, the pressure is maintained at 82 MPa, the maximum flow rate is 5 kg/min, the delivery temperature is -40°C, and the ambient temperature varies from -20 to 40°C. The component materials are specialized for hydrogen resistance. To endure the high pressure of 82 MPa, cone and thread fittings are used between devices. The dispenser model is divided into

three parts. The dotted line shows the upper stream section that is within the housing, and where the pressure is 82 MPa and the temperature is around 20°C. The long dashed and dotted line shows the lower stream section, where the pressure is also 82 MPa, but where the temperature is maintained at -40°C. The hose unit section, which is located inside the lower stream section, is contained within the long dashed and double-dot lined box. This movable unit is located outside the housing.

Hydrogen is introduced from the accumulator to the dispenser by differential pressure through the main valve, which is a normally open manual valve of a type commonly used for installation and maintenance. A filter is used to block foreign particles during the transfer. Hydrogen passes through the flow meter where the mass of the flowing gas is measured. The heat exchanger is used to cool the hydrogen in order to control the temperature rise that results from adiabatic compression during high-speed filling within the specification range of a fuel cell vehicle (FCV) tank. The shutoff valve is normally closed and it opens only while filling. When the emergency stop button is pressed during filling, the shutoff valve is closed. In addition, the temperature and pressure are monitored by the pressure gauge (PI) and the thermometer (TI). The shutoff valve is closed if the pressure or temperature exceeds the set value. The filling protocol is based on the SAE International J2601 standard[27].

Eventually, hydrogen is transferred to the tank of an FCV through the hose unit, which consists of a safety coupler, hose, and nozzle. The safety coupler is one of the safety measures. If an FCV is accidentally driven away from the dispenser while the nozzle is still connected to the vehicle, there is a possibility that the dispenser will rupture and a large amount of hydrogen could leak. In order to prevent this, the safety coupler is designed to separate intentionally at a specific location in order to protect the entire structure. When that occurs, both sides of the separation are instantly sealed to prevent hydrogen leakage. Also, an excess flow valve is installed between a dispenser and an accumulator, and inventory of a dispenser is less than 1 liter. Hence, the amount of leakage is very small if the dispenser ruptures.

The safety valve opens when the preset pressure level is exceeded, so releasing hydrogen safely from the upper part of the dispenser into the atmosphere. This feature prevents the dispenser from rupturing due to an erroneous pressure increase. The function of the depressurizer valve is to release the pressure between the shutoff valve and the nozzle from 82 MPa to atmospheric pressure after filling is complete. Without this feature, the nozzle could not be detached from an FCV. In this case, the depressurized hydrogen is also safely discharged to the atmosphere from above the dispenser.

Next, the existing safety measures used in hydrogen stations were investigated and organized in order to assess the overall safety of the dispensers. The measures were classified as those intended to reduce risk frequency and risk severity, after which each was evaluated and classified as either "highly effective" or "effective to some extent". Furthermore, we categorized whether each safety

measure was effective in terms of risk "prevention", "detection", or "mitigation". These results are shown in Table 3. For example, firewall and safety distance, which are designed to prevent fires from spreading to neighboring facilities in the event of an accident or explosion, were classified as highly effective measures for reducing risk severity and effective measures for risk mitigation. Firewalls are implemented in the site boundary between a station and other properties due to reduce the risk for third parties. Also, a station is adjacent to open road as vehicles need to access for refueling, and safety distance is applied to the boundary between the station and road.

In addition, the leak detector and shutoff valve inside a dispenser were found to be highly effective safety measures for reducing risk severity, as well as being effective for risk detection and prevention. When the leak detector is triggered, the dispenser shutoff valve is closed automatically, thereby reducing the amount of the leakage and minimizing the scale of any resulting fire or explosion. Therefore, they were classified as highly effective measures for reducing the degree of risk severity. The shutoff valve can also be actuated by the emergency stop button installed in the dispenser. Meanwhile, representative safety measures for reducing risk frequency include the use of explosion proof electronics and the features designed to eliminate static electricity. These safety measures are effective for risk prevention because the frequency of fires and explosions is reduced by removing ignition sources. Applied methods for removing static electricity include grounding the dispenser, using conductive material in the hose unit, and using antistatic clothing for operators.

3.2 Gasoline dispenser

Gasoline is a volatile liquid fuel that has been widely used for many years. The fuel has a relatively low flammable limit and it can be easily ignited. Gasoline station equipment is roughly divided into an underground tank and a dispenser. In the model shown in Fig. 3, the pressure is 0.3 MPa, the maximum flow rate is 40 L/min, and the ambient operating temperature is from -20 to 40°C. As you can see in the figure, our gasoline dispenser model is divided into two parts. The dotted line shows the inside housing section, while the long dashed and dotted line shows the hose unit section, which is a movable unit outside the housing.

Gasoline is pumped up from the underground tank by the pump inside the dispenser. When the pump is in the off state, the check valve prevents the internal gasoline from returning to the underground tank. The shutoff valve is normally closed and opens only during refueling. When the emergency stop button is pushed during refueling, the shutoff valve is closed. An installed meter measures the volume of flowing fuel. Gasoline is supplied to the vehicle being refueled through the hose unit. As with the hydrogen dispenser, a safety coupler is incorporated into the hose unit.

The existing safety measures of gasoline service stations were investigated and the results of our evaluation are shown in Table 4. One significant difference between gasoline and hydrogen is that a person can detect the smell of gasoline. Thus, when leaks are detected by smell or visual

inspection, fuel discharge can be stopped by pressing the emergency stop button installed in the dispenser. Moreover, since gasoline is generally pumped upward from an underground tank, the supply of gasoline stops if there is loss of power, or if the dispenser malfunctions.

4. Results and Discussion

4.1 Risk assessment result of hydrogen dispenser

First, FMEA was conducted for the hydrogen dispenser model, from which 42 scenarios were identified. Of these, 16 were potential accident scenarios and the other 26 were scenarios that could cause minor issues such as negligible function loss, but would not lead to accidents. A sample FMEA sheet is shown in Table 5. One characteristic failure mode in high pressure hydrogen handling equipment is the loosely fastened parts in the joints incorporated between devices for assembly and maintenance. It was assumed that the safety measures did not work at all when the progression of scenarios was examined. This means that hydrogen could leak to the outside if fastened parts become loose. The most undesirable scenario in this failure mode would be that the leaked hydrogen ignites, thereby causing a fire or explosion. The result of a qualitative risk assessment performed on this scenario without safety measures found that the severity rank was IV (significant), and its probability rank was taken to be iv (probable).

Next, risk levels with existing safety measures were evaluated. Effective safety measures for each step of the scenario were organized and compiled into the FMEA sheet. Our evaluation found that the occurrence frequency of loosely fastened parts could be reduced by the use of an appropriate joining method and proper maintenance. Additionally, leakage amounts could be suppressed and the risk severity degree would be reduced by the applications of a leak detector and a shutoff valve. Moreover, ignition frequency could be reduced by using explosion-proof electronics and static electricity removal, and if fire or explosions did occur, the severity of the accident could be mitigated by safety distance, firewalls, fire extinguishing equipment, and emergency call units.

The rule for ranking down by applying safety measure is as follows. The risk is decreased by one rank if there is one "highly effective" safety measure or two safety measures that are "effective to some extent". The minimum level by ranking down is I (negligible) in severity and i (improbable) in frequency even if there are more safety measures. Therefore, the result of our qualitative risk assessment with existing safety measures was ranked at I (negligible) in severity, and its frequency was ranked at ii (Remote). The risk level was reduced to a level as low as reasonably practical.

As a result of implementing HAZOP, 12 potential accident scenarios, all of which could lead to accidents, were extracted. In this target model, pressure and temperature were set as the process parameters, while the guide words were set to "more" and "less". Brainstorming was done by combining these words. For example, "pressure decrease" was derived by a combination of "pressure" and "less". Next, the "pressure decrease" trigger was examined. This identified scenarios

focused on external factors such as earthquakes, vehicle crashes, and flying objects propelled by strong winds. Moreover, "temperature rise" was derived by the combination of "temperature" and "more". Triggers leading to "temperature rise" and identified scenarios such as onsite fires, nearby site fires, and rising ambient temperatures were investigated. As with the FMEA study, effective safety measures for each step of the scenario were organized and compiled into HAZOP sheets, after which qualitative risk assessments with and without existing safety measures were conducted.

Table 6 shows the HAZOP sheet related to earthquakes. The most undesirable trigger in this scenario is that the dispenser could rupture and large amounts of hydrogen could leak, ignite, and cause a fire or explosion. Without safety measures, the severity rank was V (severe) and the frequency rank was iii (occasional). Earthquakes are natural disasters, and thus not avoidable, but dispensers are constructed with earthquake-resistant designs as safety measures to reduce the likelihood that this scenario will progress to severe accidents. Additionally, there are safety measures that can be used to decrease the severity of such events, such as the combination of a seismometer and shutoff valve. By applying the ranking down rule, the severity was ranked at I (negligible) and the probability rank was i (improbable). These results confirmed that risk levels were appropriately reduced by implementation of existing safety measures.

The results of the risk matrices for our model hydrogen dispenser with and without the existing safety measures, are shown in Fig. 4. Focusing on scenarios where the risk was high before safety measures were applied, we found that all the fire or explosion scenarios were initially induced by hydrogen leakage. Typical leakage modes are loosely fastened parts, equipment destruction, and malfunctions involving safety valves and safety couplers. There are also damage modes peculiar to hydrogen, such as hydrogen embrittlement, in addition to damage modes involving corrosion, fatigue, and wear. However, when the risk matrices without safety measures were compared with those obtained when appropriate safety measure were applied, it was confirmed that the existing safety measures reduced risk levels to an acceptable degree. Furthermore, various redundant safety measures are commonly applied to safeguard against scenarios leading to fire or an explosion, which provides a significant strengthening influence.

4.2 Risk assessment result of gasoline dispenser

Next, FMEA was implemented for the gasoline dispenser models and 32 scenarios were extracted, 19 of which were scenarios that could lead to accidents. The other 13 scenarios could lead to failures without accompanying accidents. As a result of implementing HAZOP, 12 potential accident scenarios were identified. As with the hydrogen dispenser model, qualitative risk assessments were conducted with and without existing safety measures, the results of which are shown in Fig 5.

A characteristic scenario was leakage initiated by overfilling a vehicle. Since the pipe leading

to the gasoline tank is larger than the refueling nozzle, a firm seal is not produced during refueling. Hence, gasoline refueling nozzles are equipped with a mechanical sensor that triggers an automatic shutoff valve when the tank is full. However, if these functions do not work correctly at time when the operator is not closely monitoring the dispenser, leakage could result and initiate further accident scenario steps. Safety measures created in response to this scenario include an emergency stop button and a shutoff valve that could reduce an amount of leakage, and thus the resulting risk severity. Ignition sources are removed by using explosion proof electronics and controlling static electricity. Moreover, as in the case of the hydrogen dispenser model, the risk severity is mitigated by the installation of fire extinguishing equipment, firewalls, and safety distance.

4.3 Comparative discussion between hydrogen and gasoline dispensers

Next, the hydrogen and gasoline dispenser risk matrices were compared. Focusing on conditions without application of safety measures, it was found that the hydrogen dispenser risk level is almost same in comparison with gasoline dispensers. High pressure hydrogen gas leaks could cause jet fires with a long flame length, and there is a high severity risk that such fires could spread to outside facilities although a hydrogen flame emits low radiant heat. On the other hand, gasoline leaks could cause gasoline pool fire which has wide area effects with relatively high intensity of sustained thermal load. Furthermore, as explained previously, hydrogen has a wide flammability range and low minimum ignition energy. However, the stoichiometric concentration of hydrogen in air is 29.5 vol. % and that of gasoline in air is 1.8 vol. %. As for the minimum ignition energy, the minimum ignition energy of hydrogen is at around the stoichiometric concentration of hydrogen. Meanwhile, the stoichiometric concentration of gasoline in air, which is 1.8 vol. %, has almost same ignition energy as 12 vol. % of hydrogen in air. Therefore, it is noted that it might be easy to reach stoichiometry combustion with gasoline in air, compared with hydrogen in air. In addition, hydrogen has a relatively high leakage frequency due to the characteristic damage and leakage modes resulting from hydrogen embrittlement and high-pressure operations.

Importantly, it must also be remembered that hydrogen leaks are often difficult to detect by a person because the gas is invisible and odorless, although leaks might be identified by noise in some cases. Such leaks can also be detected since a leak detector is installed in upper part of inside a dispenser. Note that if hydrogen leaks from the hose unit, persons nearby might be exposed to the substance. However, even though the hydrogen is stored at -40°C , there is little potential for frostbite because the gas diffuses rapidly.

Turning to the risk matrices examined when the safety measures were applied, we confirmed that the risks of both dispensers were reduced to levels that were as low as practical. Hence, the existing safety measures for both dispensers were validated as sufficient. Of the two types, the risk

levels of our hydrogen dispenser model without any safety measures applied were considered to be higher than the gasoline model because it is operated under high pressure conditions, and due to the other characteristics noted above. Nevertheless, we also confirmed the risk levels of each dispenser types with existing safety measures applied were essentially equivalent. Therefore, the risks involved with installing hydrogen dispensers in public areas can be considered acceptable.

5. Conclusions

Although it is difficult to establish absolute risk acceptance criteria for a new technical system, this study aimed at evaluating the risks of one such system, a hydrogen dispenser, by comparing it with gasoline dispensers which have been in widely accepted use for many years. The safety of dispensers has always been a matter of great concern to the public especially as they are accessible to everyone. At the start, authors built dispenser models for both hydrogen and gasoline, which represent extensively varying specifications. A total of 28 and 31 potential accident scenarios related to the hydrogen and gasoline dispenser models were respectively identified by the integrated method of FMEA and HAZOP. Next, qualitative risk evaluations were conducted for each scenario and the results were organized into risk matrices. By comparing the risk matrices for hydrogen dispensers with and without existing safety measures, the appropriateness of safety measures related to hydrogen dispensers was confirmed. From the comparative analysis of the risk matrices for hydrogen and gasoline dispensers with safety measures, we found that the existing safety measures were effective and the risk levels were practically equivalent. Therefore, we concluded that the risks related to installing hydrogen dispensers in public areas can be considered acceptable.

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Table 1: Criteria for severity
*from references [5], [6] and [8]

Level Description		Definition
V	Severe	Severe damage to building and facilities outside the site Fatalities outside the site
IV	Significant	Significant damage to building and facilities outside the site Fatalities inside the site
III	Moderate	Moderate damage to building and facilities outside the site Injuries outside/inside the site
II	Minor	Minor damage to building and facilities outside the site Minor injuries outside/inside the site
I	Negligible	Negligible damage to building and facilities outside the site Negligible injuries outside/inside the site

Table 2: Criteria for frequency
*from references [5], [6] and [8]

Level Description		Definition
IV	Probable	Likely to occur several times in lifetime of one station. About once in several years or more.
III	Occasional	Likely to occur once in lifetime of one station. About once in several decades.
II	Remote	Unlikely to occur in lifetime of one station. About once in several hundreds years.
I	Improbable	Possible, but the probability is extremely low. About once in several thousands years or less.

Table 3 Assessment sheet for safety measures of hydrogen stations

Name	Objective	Explanation	Prevention	Detection	Mitigation	Effectiveness	Target
Appropriate joint method	To prevent leakage of high pressure substance	Use of cone and thread joint	○			To some extent	Frequency
Appropriate material	To prevent hydrogen embrittlement and corrosion	Use of materials for hydrogen resistance	○			To some extent	Frequency
Explosion proof electronics + Removal of static electricity	To remove ignition sources	Use of explosion proof electronics, antistatic earth of dispenser (hose unit) and antistatic cloth for operators	○			Highly effective	Frequency
Label for key-off during refueling	To prevent erroneous drive	Implementation of a label for key-off during refueling	○			To some extent	Frequency
Maintenance (daily and periodic)	To maintenance devices	Maintenance of devices	○			To some extent	Frequency
Protection of dispensers	To protect a dispenser from collision	Implementation of guard poles	○			Highly effective	Frequency
Safety valve	To prevent destruction from over pressure	Implementation of a safety valve	○			Highly effective	Severity
Seismic design	To protect a dispenser from earthquake	Seismic design	○			Highly effective	Frequency
Seismometer + Shut off valve	To stop operation for earthquake	Implementation of a seismometer and an emergency shut off system	○			Highly effective	Severity
Shut off valve of accumulator	To shut off leaking	Implementation of a shut off valve	○			Highly effective	Severity
Tag for operating valve	To prevent error in operation	Implementation of tags for operating valve	○			To some extent	Frequency
Monitoring pressure + Shut off valve	To stop operation for over pressure	Implementation of a pressure gage and an emergency shut off system	○	○		Highly effective	Frequency
Monitoring temperature + Shut off valve	To stop operation for over temperature	Implementation of a temperature gage and an emergency shut off system	○	○		Highly effective	Frequency
Excess flow valve	To stop operation for excess flow	Implementation of excess flow valve		○	○	Highly effective	Severity
Flame detector + Shut off valve	To detect flame	Implementation of flame detectors		○	○	Highly effective	Severity
Leak detector and alarm + Shut off valve	To detect leaking	Implementation of leak detectors and alarm		○	○	Highly effective	Severity
Emergency call unit	To make emergency call	Implementation of a telephone and a speaker			○	To some extent	Severity
Emergency stop button + Shut off valve	To stop refueling	Implementation of emergency stop buttons and an emergency shut off system			○	Highly effective	Severity
Fire extinguishing equipment	To extinguish fire	Implementation of extinguishments and sprinklers			○	To some extent	Severity
Firewall + Safety distance	To stop propagation of fire	Implementation of firewalls and safety layout of devices			○	Highly effective	Severity

Table 4 Assessment sheet for safety measures of gasoline stations

Name	Objective	Explanation	Prevention	Detection	Mitigation	Effectiveness	Target
Explosion proof electronics + Removal of static electricity	To remove ignition sources	Use of explosion proof electronics, antistatic earth of dispenser (hose unit) and antistatic cloth for operators	○			Highly effective	Frequency
Indication of a vehicle position	To prevent a car crash	Indication of a vehicle position	○			To some extent	Frequency
Label for engine stop during refueling	To prevent erroneous driving	Implementation of a label for key-off during refueling	○			To some extent	Frequency
Maintenance (daily and periodic)	To maintenance devices	Maintenance of devices	○			Highly effective	Frequency
Protection of dispensers	To protect a dispenser from collision	Implementation of an island	○			Highly effective	Frequency
Seismic design	To protect a dispenser from earthquake	Seismic design	○			Highly effective	Frequency
Odor	To detect leaking	Leak detection by a person		○		To some extent	Frequency
Seismometer + Shut off valve	To stop operation for earthquake	Implementation of a seismometer and an emergency shut off system		○	○	Highly effective	Severity
Emergency call unit	To make emergency call	Implementation of a telephone and a speaker			○	To some extent	Severity
Emergency stop button + Shut off valve	To stop refueling	Implementation of emergency stop buttons and an emergency shut off system			○	Highly effective	Severity
Fire extinguishing equipment	To extinguish fire	Implementation of extinguishment			○	To some extent	Severity
Firewall + Safety distance	To stop propagation of fire	Implementation of firewalls and safety layout of devices			○	Highly effective	Severity
Open space	To secure a space for extinguishment	Implementation of open space			○	To some extent	Frequency

Table 5 Example of FMEA sheets of hydrogen dispenser

Component	Main valve
Failure mode	Loose fastening part

	Scenario	Safety measures for severity	Safety measures for frequency
1	Loose fastening part		Appropriate joint method Maintenance
2	Leakage	Leak detector + Shut off valve Excess flow valve (Emergency stop button + Shut off valve)	
3	Ignition		Explosion proof electronics + Removal of static electricity
4	Fire or explosion	Firewall + Safety distance Fire extinguishing equipment Emergency call unit	

	Severity	Frequency
Without safety measures	(IV) Significant	(iv) Probable
With safety measures	(I) Negligible	(ii) Remote

Table 6 Example of HAZOP sheets of hydrogen dispenser

Section	Inside dispenser housing
Deviation	Less pressure
Trigger	Earthquake

	Scenario	Safety measures for severity	Safety measures for frequency
1	Earthquake	Seismometer + Shut off valve	
2	Dispenser rupture		Seismic design
3	Leakage	Shut off valve of accumulator Excess flow valve	
4	Ignition		Explosion proof electronics + Removal of static electricity
5	Fire or explosion	Firewall + Safety distance Fire extinguishing equipment Emergency call unit	

	Severity	Frequency
Without safety measures	(V) Severe	(iii) Occasional
With safety measures	(I) Negligible	(i) Improbable

Figure

Fig. 1: Outline of a hydrogen station

Fig. 2: Hydrogen dispenser model

Fig. 3: Gasoline dispenser model

		Frequency			
		i	ii	iii	iv
Severity	V		8	1	
	IV		7		2
	III		7		3
	II				
	I

		Frequency			
		i	ii	iii	iv
Severity	V				
	IV				
	III				
	II	5			
	I	16	7		

(a)

(b)

Fig. 4: Risk matrices of hydrogen dispenser
 (a) without safety measures
 (b) with safety measures

		Frequency			
		i	ii	iii	iv
Severity	V		4	3	
	IV		7	3	1
	III		6	6	
	II		1		
	I				

(a)

		Frequency			
		i	ii	iii	iv
Severity	V				
	IV				
	III				
	II	6	1		
	I	21	3		

(b)

Fig. 5: Risk matrices of gasoline dispenser
 (a) without safety measures
 (b) with safety measures