Identification of Factors Causing Hydrogen Transportation Accidents

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1. Introduction

Hydrogen has been attracting attention as an alternative fuel from the government and the public. This is because hydrogen is an environmental friendly and renewable energy source with high utilization efficiency, and it is also abundant in our environment. However, hydrogen has its drawbacks, such as high energy content, low ignition energy, and fast burning speed. In order to promote and enhance hydrogen as an alternative fuel in the future, it is necessary to study the risks in hydrogen transportation by proposing an integrated approach to identify the factors causing hydrogen transportation accidents. The proposed approach differentiates from the extant literatures by considering the relationships between the contributing factors and the effects in hydrogen transportation accidents, which can reduce the complexity in accident analysis.

2. Research Approach

The framework of this research is presented in **Fig. 1**. At the first stage, accident cases of hydrogen transportation are extracted from the databases[1)2)3)4)5)]. At the second stage, the associated accident chains are formulated, and the statics on its contributing factors and effect types are conducted. At the third stage, relationship analysis on the contributing factors and effect types are conducted, and their occurrence frequency are also determined. Hazardous factors can then be identified. At the final stage, recommendations are suggested for safety hydrogen transportation.

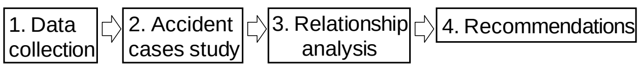

Fig. 1 Research framework

3. Data Collection

In data collection, 101 accident cases are extracted from the databases, in which 64 cases are from Japan and 37 cases are from overseas. The cases cover hydrogen transportation accidents that occur between the production of hydrogen and the usage of hydrogen, such as accidents occur during filling hydrogen from tanks to cryogenic liquid tanker trucks for hydrogen delivery, transporting hydrogen from one place to another place, filling hydrogen in refueling hydrogen station, etc.

4. Accident Cases Study

4.1 Formulating the Accident Chains

Accident chain is a clearly written sequence from first cause to final result of an accident[6)], and it can help to understand the order of events, factors and results of an accident and the relationships between them. In this research, accident chains are developed by extracting useful information from the descriptions of each accident case, so 101 accident chains are formulated from the accident cases. **Fig. 2** shows an example of an accident chain formulated from a collision case between a tractor-semitrailer and a pickup truck.

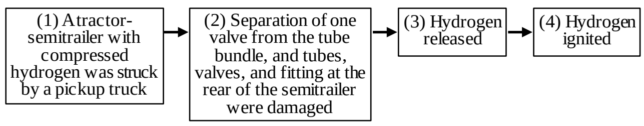

Fig. 2 An example of accident chain

4.2 Identifying the Contributing Factors and Effects

From the identified accident chains, 17 contributing factors are found, i.e. Design Flaw, Equipment Failure, Fatigue, Human Error, Improper or Inadequate Safety Measures, Inadequate Equipment, Inadequate Inspection or Maintenance, Inadequate Management of Change, Inadequate System Oversight, Manufacturing Defects, Material Incompatibility, Operation Induced Damage, Recognition Error, Standard Operating Procedure (SOP) Failure, Training Issue, Vehicle collision, and Weather. Moreover, 6 effect types (i.e. the result of an accident) are

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identified, i.e. Damage to Surroundings, Explosion, Fire, Human Damage, Leakage, and Service Damage. The identified contributing factors and the effects types are the keywords that commonly found in the accident chains. Statistical analysis is then conducted to investigate the occurrence frequency of the contributing factors and the effect types, and the results are presented in **Fig. 3** and **Fig. 4**, respectively.

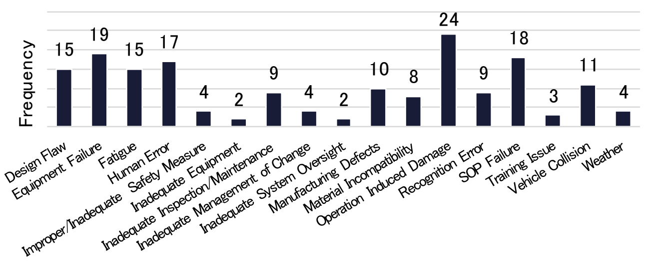

Fig. 3 Frequency of the occurrence of contributing factors

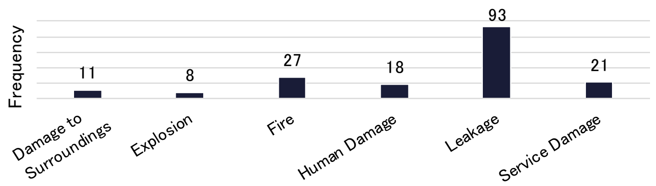

Fig. 4 Frequency of effect types

From the results, the characteristics of the collected accident cases are revealed. The total number of occurrence of contributing factors and effect types is 174 and 178, respectively. The most frequent contributing factor is Operation Induced Damage (24), and the most frequent effect type is Leakage (93) that account for more than 50% of the total number of occurrence of effect types.

5. Relationship Analysis on Hydrogen Accidents

5.1 Evaluating the Significant Factors

In this research, factor analysis is adopted to determine the significant factors. Significant factors are those contributing factors that directly related to the causes of an accident. Factor analysis can investigate the underlying variable relationships, and the significance of individual variables. In conducting factor analysis by SPSS, the weighted least square method is used for factor extraction, and the direct oblimin method is adopted for solution of rotation. In the rotated factor pattern, those factors that have significant rotated value are interpreted as significant factors in this research. From SPSS factor analysis (**Table 1**), the results show that five factors are extracted, i.e. Equipment Failure, Fatigue, Human Error, Manufacturing Defects, and Vehicle Collision. All these five factors have significant values (0.463, 0.977, 0.900, 0,969, and 0.561) in relation to each underlying variable and each contributing factor, therefore they are the significant factors in causing hydrogen transportation accidents.

Table 1 Result of factor analysis from SPSS

Rotated factor pattern	Factors				
Contributing factor	1	2	3	4	5
Equipment Failure	−0.897	−0.094	−0.214	−0.109	**0.463**
Fatigue	0.265	0.004	0.173	**0.977**	0.098
Human Error	0.214	−0.279	**0.900**	−0.217	0.164
Manufacturing Defects	0.093	**0.969**	−0.054	−0.266	0.300
Vehicle Collision	**0.561**	−0.379	−0.454	−0.226	0.421

5.2 Predicting the Relationship Probability

A network diagram is constructed as shown in **Fig. 5**, in which the nodes represent the contributing factors and the effect types while the links represent their relationships. Therefore in the network diagram, there are 23 nodes and 77 links.

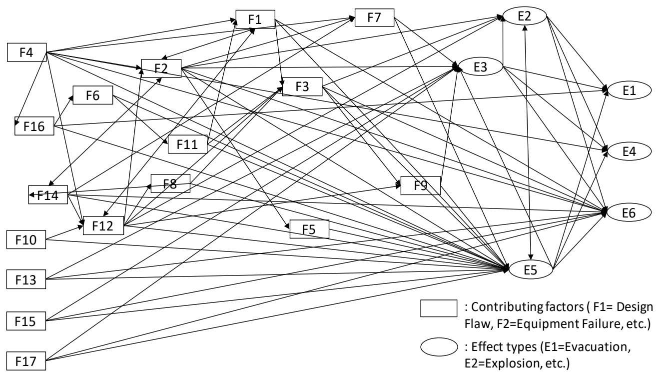

Fig. 5 Relationships between contributing factors and effect types

According to the identified accident chains, the occurrence frequencies of each link can be counted, and the probabilities of each link in the network diagram can then be calculated. From the calculated link probabilities, the route probability that is the probability of a path from a contributing factor to an effect type can further be calculated. Then, the relationship probability that represents the degree of impact of each contributing factor to each effect type is calculated by adding all route probabilities between a pair of a contributing factor and an effect type, and the results are shown in **Fig. 6**. The contributing factors that has a high relationship probability to an effect type is interpreted as a high probability factor, which means the contributing factor has a high impact on an effect type. For example in Fig. 6, Vehicle Collision has the highest relationship probability to Damage to Surroundings, so Vehicle Collision as a high probability factors. Similarly, Equipment Failure, Fatigue, Human Error, Operation Induced Damage, Recognition Error, SOP Failure, and Training Issue are also interpreted as high probability factors to Explosion, Fire, Human Damage, Leakage, and Service Damage, respectively.

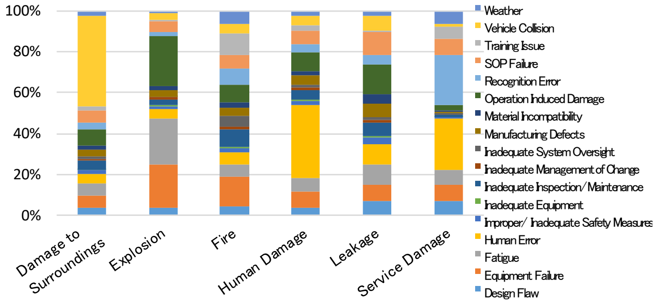

Fig. 6 The impact of each contributing factor to each effect type

5.3 Determining the Frequency of Occurrence

The occurrence frequency of each contributing factor is determined by counting the frequency of a contributing factor that will result in an effect type in an accident chain. By counting the frequency, it can help to reveal the actual occurrence of each contributing factor and how often it results in an effect type. The results of the determined occurrence frequency of each contributing factor to an effect type are shown in Fig. 7. The contributing factor that has a high counting number to an effect type is interpreted as a high frequency factor. For example, Vehicle Collision has the highest number to Damage to Surroundings, so Vehicle Collision is interpreted as a high frequency factor. Similarly, Equipment Failure, Human Error, Material Incompatibility, Operation Induced Damage, Recognition Error, and SOP Failure are also interpreted as high frequency factors to Explosion, Fire, Human Damage, Leakage, and Service Damage, respectively.

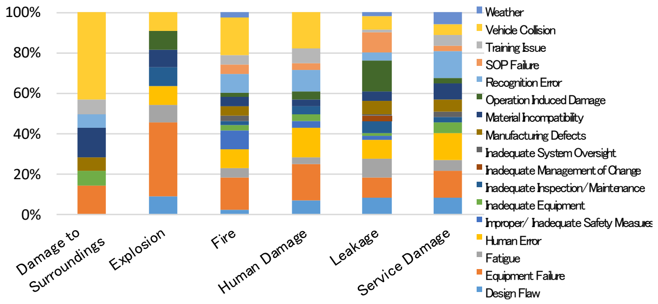

Fig. 7 The occurrence frequency of each contributing factor for each effect type

5.4 Identifying the Hazardous Factors

From the results of relationship analysis, hazardous factors for hydrogen transportation accident are identified. Hazardous factors are defined as those factors that have big influence on causing a hydrogen transportation accident, so the factors should (i) significantly relate to the causes of an accident, (ii) have high relationship probability between factors and effects, and (iii) have high frequency of occurrence in hydrogen transportation accident. Therefore as shown in Table 2, Equipment Failure, Human Error, and Vehicle Collision are identified as hazardous factors because they all fulfill the three above-mentioned requirements.

Table 2 Summary of relationship analysis results

Contributing factors	Significant Factor	High Probability Factor	High Frequency Factor
Design Flaw			
Equipment Failure	○	○	○
Fatigue	○	○	
Human Error	○	○	○
Improper/ Inadequate Safety Measures			
Inadequate Equipment			
Inadequate Inspection/ Maintenance			
Inadequate Management of Change			
Inadequate System Oversight			
Manufacturing Defects	○		
Material Incompatibility			○
Operation Induced Damage		○	○
Recognition Error		○	○
SOP Failure		○	○
Training Issue		○	
Vehicle Collision	○	○	○
Weather			

○ : Significant factor, High probability factor, High frequency factor

6. Recommendations for Safety Usage of Hydrogen

In order to promote safety hydrogen transportation, it is recommended to reduce or eliminate those identified hazardous factors. The recommendations for safety hydrogen transportation are listed in Table 3. The recommendations are made according to the study of the accident cases and the results from relationship analysis. For example, it is recommended to apply strict design standards to reduce Equipment Failure. This is because there is a high probability and strong relationship between Design Flaw and Equipment Failure as revealed from the relationship analysis. Similarly, Vehicle Collision is frequently followed by Leakage, it is then necessary to design or strengthen the resistance of the hydrogen transporting tank. For Human Error, it can be reduced by acting with multiple people so as to have a good communication among then before an accident occurs.

Table 3 Recommendations for safety

Hazardous factor	Recommendations
Equipment Failure	・Make strict design standards ・Develop a system that will not lead accidents even if the Equipment Failure occurs ・Make a rule that restricts the use of fire sources near the equipment ・Make a system in which the safety device works promptly so that it will not be a fire or explosion when Leakage due to Equipment Failure occurs
Human Error	・Act with multiple people ・Make checklists that describe the action to be done for confirmation of action ・Make a system that can cancel the action and confirm the action if the Human Error occures
Vehicle Collision	・Make standards of vessel that do not lead to effect types even if accident occurs, such as strengthening vessel for against external shocks, and fixing it securely

7. Conclusion

In this research, hydrogen transportation accidents are analyzed, and their associated accident chains are formulated. Based on the formulated accident chains, 17 contributing factors and 6 effect types are identified. Factor analysis is then conducted to identify the significant factors. Moreover, a network diagram is constructed to analyze the relationships between the contributing factors and the effect types, in which the probability of each link as well as the route probabilities are calculated. High probability factors and high frequency factors are then identified. Hazardous factors are further defined and interpreted, and they are Equipment Failure, Human Error, and Vehicle Collision. Finally, recommendations for minimize the risk of hazardous factors are suggested for safety hydrogen transportation.

In this research, factors causing hydrogen transportation accidents have been identified. Therefore, this research will be useful for promoting safety transportation of hydrogen. Furthermore, this research proposes an integrated approach that aggregates the analysis results to reveal the relationships between factors and effects of accidents, and the complexity in accident analysis can then be reduced. Despite the significance of this research, there are still opportunities for further enhancements, such as improving the uncertainty in formulating the accident chains or identifying the contributing factors, increasing the number of sample size of accident cases, inviting practitioners to discuss the details of accidents or involve in the development of accident chains.

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