A GIS-BASED RISK ASSESSMENT OF HYDROGEN TRANSPORT: A CASE STUDY IN YOKOHAMA, JAPAN

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ABSTRACT

Risk assessment of hazardous material transport by road is critical in considering the spatial features of the transport route. However, previous studies that focused on hydrogen transport were unable to reflect the spatial features in their risk assessments. Hence, this study aims to assess the risk of hydrogen transport by road considering the spatial features of the transport route, based on a geographic information system (GIS). This risk assessment method is conducted through a case study in Yokohama, which is an advanced city for hydrogen economy in Japan. In our assessment, the risk determined by multiplying the frequency of accidents with the consequence was estimated by road segments that constitute the entire transport route. The effects of the road structure and traffic volumes were reflected in the estimation of the frequency and consequence for each road segment. All estimations of frequency, consequence, and risk were conducted on a GIS compiled with the information regarding the road network and population. In the case study in Yokohama, the route for the transport of compressed hydrogen was virtually set from the near-term perspectives. Based on the case study results, the risks of the target transport route were assessed at an acceptable level under the previous risk criteria. The results indicated that the risks fluctuated according to the road segments. This implies that the spatial features of the transport route significantly affect the corresponding risks. This finding corroborates the importance of considering spatial features in the risk assessment of hydrogen transport by road. Furthermore, the discussion of this importance leads to the capability of introducing hydrogen energy careers, with high transport efficiency and transport routing to avoid high risk road segments, as risk countermeasures.

1. INTRODUCTION

In recent years, efforts to realize a hydrogen society in Japan have been accelerating. In this society, hydrogen is transported in trucks from the production and storage plants to the consumption areas. Hydrogen has dangerous physicochemical properties that include the risk of explosions or fires. Therefore, when an accident occurs, it can severely impact the surrounding area. In addition, it is predicted that as hydrogen consumption increases in the future, the quantity to be transported will increase, thereby increasing the demand that the hydrogen be transported safely. The hydrogen transport safety must be verified through risk assessments. However, hydrogen transport risk assessment [1–3] has received lesser attention than the risk assessment at hydrogen stations [4–22]. In Japan, which promotes a hydrogen society, the hydrogen-transport risk is not being assessed at all.

Because of the topographical restrictions, logistics in Japan are dependent on road transport. Therefore, hydrogen transport is mainly conducted by road. A major characteristic of road transport is that, unlike fixed facilities, such as production plants, the surrounding environment constantly changes. As a result, the spatial features of transport routes must be reflected in the hydrogen-transport risk assessment. However, past research on hydrogen transport risk assessment studied only virtual spatial features and not actual spatial features [1–3].

This study proposes a hydrogen-transport risk assessment method that considers actual spatial features, using a geographic information system (GIS) and traffic accident information. As spatial features, it considers the road structure, road-traffic volumes on the transport routes, and population density along these transport routes. In addition, this study includes a risk assessment case study in the city of Yokohama, Japan.

2. METHODOLOGY

2.1 Analytical framework

This section presents an overall image of the hydrogen transport risk assessment method. The risk assessment method establishes transport routes from the hydrogen production and storage plant to hydrogen stations, divides the routes into road segments, and estimates the risk (fatalities/year) using the information regarding hydrogen transport accidents for each segment. The given transport routes from the plant to the stations have their objective function set to minimize costs, based on the GIS, with road-network information provided by the Japan Digital Road Map Association [23]; this road-network information is inputted as spatial data. The risk (fatalities/year) of hydrogen transport accidents by road segment is represented by equation (1), as the product of the number of hydrogen transport trucks passing through the road segment, frequency of hydrogen transport accident scenarios, and consequence of the scenarios [24]. The above risk (fatalities/year) is calculated by GIS with the spatial features of the given road segment inputted as attribute data.

$$\mathrm{R_{is}} = \mathrm{T} \cdot F_{is} \cdot C_{is} \tag{1}$$

where *i* – road segment; *s* – accident scenario; *R* – risk (fatalities/year) of the hydrogen transport accident scenario; *T* – number of hydrogen transport trucks passing through the segment; *F* – frequency of hydrogen transport accident scenarios, (leaks/(truck per year)); *C* – consequence of the accident scenario, (fatalities/accident). Subsections 2.2 and 2.3 describe the methods for estimating the frequency of the hydrogen-transport accident scenario (*F*) and the accident's consequence (*C*), while considering the spatial features.

2.2 Frequency estimation

The frequency of the hydrogen-transport accident scenario (*F*) for each road segment is defined by equation (2), based on the "Guideline for Chemical Transportation Safety, Security, and Risk Management" by the Center for Chemical Process Safety of the American Institute of Chemical Engineering [25].

$$\mathrm{F_{ijs}} = \left\{a \cdot b_j \cdot \prod_k f_{ijk} + c_j \cdot (1-a)\right\} \cdot d_s \cdot D \cdot \lambda \tag{2}$$

where *i* – road segment; *j* – leakage scale; *k* – spatial-feature type of the transport route; *s* – hydrogen transport accident scenario; *λ* – frequency of leakage accidents by hydrogen transport trucks, leaks/(truck · km); *f* – spatial-feature factor of the transport route; *D* – transport distance, km; *a* – percentage of traffic accidents to total leak accidents; *b* – percentage of traffic accidents by leakage scale; *c* – percentage of other accidents by leakage scale; *d* – percentage occurrence of hydrogen-transport accident scenarios.

Because no information is available on the frequency of leakage accidents by hydrogen-transport trucks (*λ*), the annual frequency of leakage accidents by hazardous-material transport trucks is substituted. The frequency is defined by the following equation (3).

$$\lambda = \frac{la}{td \cdot ot} \tag{3}$$

where *la* – average annual number of leak accidents for hazardous material (leaks/year); *td* – average annual travel distance of the logistics truck; *ot* – average annual ownership number of the truck for hazardous material.

The percentage of traffic accidents to total leak accidents (*a*) and the average annual number of leak accidents for hazardous materials (leaks/year) (*la*) are obtained from the fire-service statistics [26] and the past accident cases compressed gas transport [27]. The percentage of traffic accidents by leakage scale (*b*) and percentage of other accidents by leakage scale (*c*) are obtained using the traffic accident cause data provided by the Institute for Traffic Accident Research and Data Analysis (ITARDA) [28]. The average number of trucks with annual ownership for hazardous materials (*ot*) is obtained using individual statistical data from the Automobile Inspection and Registration Information Association [29]. The average annual travel distance of logistics-trucks (*td*) is obtained from the actual situation of using cars by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT)[30]. The occurrence percentage of hydrogen transport accident scenarios (*d*) is obtained from the results of an inventory analysis in past research [1].

A unique feature of this study is that it sets the detailed spatial-features factors by quantification based on the traffic accident information. The spatial-feature factor of the transport route (*f*) represents the degree of contribution of a specific spatial feature to the accident frequency. The spatial-features factor is determined by equation (4), using traffic accident occurrence-point data provided by the ITARDA [28].

$$f_{kj} = \frac{AC_{kj}}{r_k \cdot r_j \sum_k \sum_j AC_{kj}} \tag{4}$$

where k – transport route's spatial-feature type; j– leakage scale; f – spatial-feature factor of the transport route; AC – number of logistics-truck traffic accidents k; r – logistics-truck traffic accident occurrence percentage.

Table 1 presents the results of estimating the spatial-feature factors for transport routes. The spatial features are broadly categorized as road structures and traffic volume. The road type, road shape, and topography surrounding the road are also considered, for a total of 24 spatial-feature types. The travel velocity is used as a representative index of the traffic volume, which can be expressed as a function of the average speed [31].

Table 1. Spatial-feature factors of a transport route

Spatial-feature type			Spatial-feature factor value		
			Large-scale leakage	Medium-scale leakage	Small-scale leakage
Road structure	Road type	National highway	1.26	1.14	0.97
		Major local road	0.80	0.91	1.02
		Ordinary prefectural road	0.78	0.95	1.02
		Ordinary municipal road	0.53	0.78	1.05
		Expressway	2.82	1.63	0.84
	Road configuration	Intersection	0.66	0.98	1.02
		Straight road (tunnel)	2.76	1.75	0.82
		Straight road (bridge)	1.73	1.35	0.92
		Level crossing	11.14	1.15	0.62
	Topography surrounding road	Urban (densely populated)	0.51	0.67	1.07
		Urban (other)	0.71	0.88	1.03
		Non-urban	1.68	1.41	0.91
Traffic volume	Travel velocity	Stopped	0.25	0.49	1.11
		Under 10 km/h	0.12	0.26	1.15
		Under 20 km/h	0.24	0.50	1.10
		Under 30 km/h	0.41	0.80	1.05
		Under 40 km/h	0.91	1.25	0.96
		Under 50 km/h	1.64	1.61	0.88
		Under 60 km/h	2.46	1.87	0.81
		Under 70 km/h	3.25	2.10	0.75
		Under 80 km/h	4.04	2.09	0.72
		Under 90 km/h	3.92	1.98	0.75
		Under 100 km/h	4.87	2.30	0.66
		Under 120 km/h	5.86	2.55	0.59

2.3 Consequence estimation

The consequence of the hydrogen transport accident scenario (C) (number of fatalities) for each road segment is defined in equation (5), based on past research [1]. This consequence is estimated by considering the spatial features and accounting for the population density surrounding the transport route.

$$C_{is} = c_s \times A_s \times P_i \tag{5}$$

where i – road segment; s – hydrogen transport accident scenario; A – area impacted by the accident scenario (km^2); P – population density surrounding the given road segment (number of residents/km^2); c – probability of fatality according to the hydrogen-transport accident scenario (number of fatalities/population).

The population density can be obtained using the national land numerical-information data-download service provided by the MLIT [32]. The probability of fatality is based on the probit values obtained from the probit model of fires and explosions. Probit models are defined by equations (6) and (7) [33]. The conversion from probit values to probability of fatality is defined in equation (8) [34].

$$Y_{s=1} = -14.9 + 2.56\ln\left(\frac{t_{s=1} \times I_{s=1}^{4/3}}{10^4}\right) \tag{6}$$

$$Y_{s=2} = -23.8 + 2.92\ln(P_{s=2}) \tag{7}$$

$$C_s = 50\left[1 + \frac{Y_s - 5}{|Y_s - 5|} erf\left(\frac{|Y_s - 5|}{\sqrt{2}}\right)\right] \tag{8}$$

where s – hydrogen-transport accident scenario (1: fire accident and 2: explosion accident); c– probability of fatality; Y – probit value; I – thermal radiation intensity, W/m^2; P – peak overpressure, Pa; t – exposure time, s. The area involved in the accident is estimated using the ALOHA hazard-modeling program, which was developed by the United States Environmental Protection Agency [35].

3. CASE STUDY

3.1 Object of the case study

The object of the case study was compressed-hydrogen-transport in Yokohama City, Japan, in the first half of the 2020s. Yokohama City was selected because it is attempting to popularize hydrogen energy (see Fig.1) [36]. The background maps shown in Figs. 1 and 2 can be obtained by the national land numerical-information data-download service provided by the MLIT [32]. The candidate hydrogen-energy carriers are compressed hydrogen, liquid hydrogen, organic hydride, and ammonia. At present, it is difficult to decide which energy carriers will be used widely in the future. Therefore, this study dealt with compressed hydrogen, which is now available in society, as the object hydrogen-energy carrier. The object period of the study is the first half of the 2020s, i.e., the relatively near future, when compressed hydrogen will likely be the major hydrogen form used.

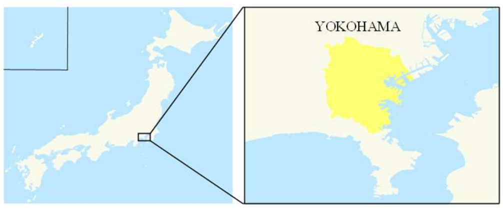


Figure1. Case study area of this study

3.2 Condition of Case study

The estimation conditions of this case study are explained below. Currently (2019), four permanent offsite-type compressed-hydrogen stations are located in Yokohama City. This case study focuses on compressed-hydrogen-transport from a hydrogen-production plant in an industrial district to these four stations, to assess the risk (fatalities/year) faced by the residents living in the districts along the routes, if a hydrogen-transport accident occurs. The consequences by the accidents to the residents in road segment with a tunnel can be ignored because the accidents are contained inside a tunnel. It has been hypothesized that in the first half of the 2020s, no new hydrogen stations will be established, thereby increasing the operating rates of the four stations.

The considered transport trucks are hydrogen-gas trailers equipped with multiple 45-MPa-class pressure vessels [37]. The transport frequency to the hydrogen stations was set as 60/year, based on the target-penetration rate of fuel-cell-powered automobiles set by the Ministry of Economy, Trade, and Industry [38]. As in past research, the hydrogen-transport accident scenarios were an explosion and a fire [1]. However, these accident scenarios are premised on a large-scale leak from one of the pressure vessels. The quantity leaked was classified as “major” in the leak-volume categorization set by the Sandia National Laboratories in the United States [39].

The frequency and consequence parameters needed to calculate the risk (fatalities/year) are summarized in Tables 2 and 3, respectively. The transport distance in Table 2 is the average transport distance of the four routes to the four hydrogen stations. The area involved in the accident in Table 3, as explained in subsection 2.3, was estimated using ALOHA. The ALOHA calculation conditions used for this task are listed in Tables 4 and 5. The probability of fatality in Table 3 ware set 1% and 10% respectively [1]

Table 2. Parameters for frequency estimation of hydrogen-transport accident scenarios

Parameter	Outline	Value
a	Percentage of traffic accidents to total leak accidents	30.80 (%)
$b_{j\,=\,Large\ scale\ leakage}$	Percentage of traffic accidents by leakage scale (large)	2.26 (%)
$c_{j\,=\,Large\ scale\ leakage}$	Percentage of traffic accidents by leakage scale (large)	10.00 (%)
$d_{s=1}$	Occurrence percentage of hydrogen-transport accident scenarios (fire)	0.59 (%)
$d_{s=2}$	Occurrence percentage of hydrogen-transport accident scenarios (explosion)	1.98 (%)
λ	Frequency of leakage accidents by hydrogen-transport trucks	7.54×10^{-9} (leaks /(truck·km))
D	Transport distance	14.96 (km)

Table 3. Parameters for consequence estimation of hydrogen-transport accident scenarios

Scenario	Physical quantity	Area involved in the accident (m^2)	Exposure time (s)	Probability of fatality (%)
Explosion (detonation)	12 (kPa)	4536	-	10
Fire (jet fire)	12.5 (kW/m2)	314	30	1

Table 4. ALOHA calculation conditions: Characteristic parameters of an explosion-accident scenario and a fire-accident scenario

Scenario	Item	Values entered
Explosion	Type of tank failure	Leaking tank; chemical is not burning because it escapes into the atmosphere
	Hazard type	Blast area of vapor cloud explosion
	Ignition time of vapor cloud (1 s to 60 min.)	Unknown
	Type of explosion	Detonation
Fire	Type of tank failure	Leaking tank; chemical is burning as a jet fire

Table 5. ALOHA calculation conditions: Common parameters of explosion and fire accident scenarios

Parameter item		Values entered	Source
Spatial information	City	Yokohama City (at North latitude 35º 26”, East longitude 139 º 38”)	
	Height above sea level (m)	1.8	[40]
Chemicals	Material	Hydrogen	
Weather conditions	Wind speed	3.5	[41]
	Wind direction	North	[41]
	Relative humidity (%)	67	[41]
	Surface roughness	Urban or Forest	
	Cloud cover (%)	7	[41]
	Air temperature (°C)	15.8	[41]
	Atmospheric stability	D	
	Inversion layer	None	
Compound-pressure vessels condition	Full length (mm)	3020	
	Diameter (mm)	436	
	Internal pressure (MPa)	45	
	Volume capacity (L)	300	
	Leakage quantity (kg)	17	
	Internal state	Gas	
	Leakage diameter (mm)	138	
	Internal temperature	Ambient temperature	

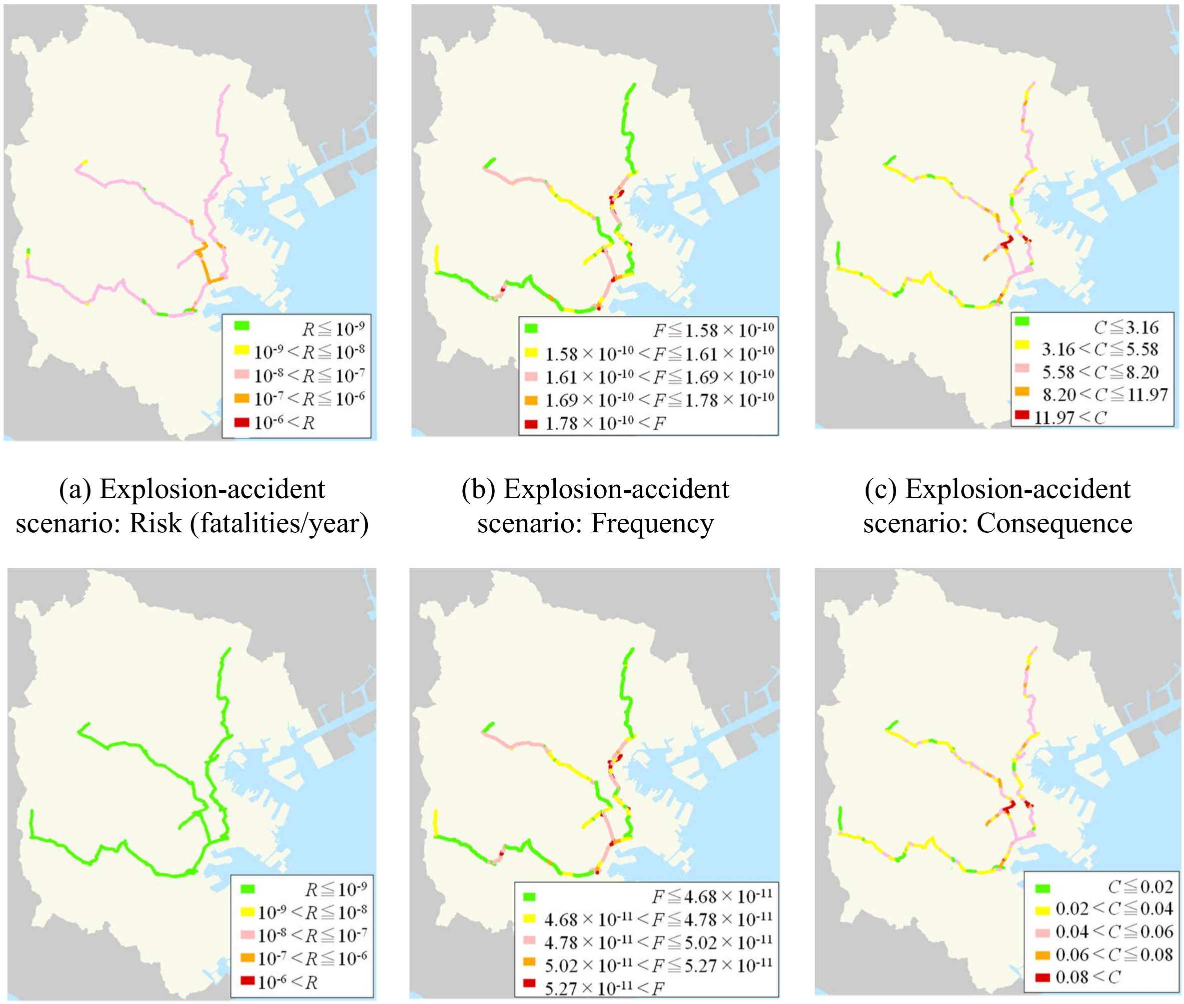
3.3 Result of case study

In this case study, the transport routes to the four hydrogen stations in Yokohama City were divided into 1,119 road segments, and the risks of explosion- and fire-accident scenarios were estimated for each road segment. The spatial distributions of the risk (fatalities/year) of these scenarios during the compressed-hydrogen transport in Yokohama City are illustrated in Figs. 2 (a) and (d). In addition, the spatial distributions of the frequency and consequence for (a) and (d) are shown in Figs. 2 (b)–(c) and (e)-(f).

Based on Figs. 2 (a) and (d), no road segments showed a risk that exceeded the acceptable risk standard of 10^{-6} fatalities/year proposed by the ISO [42]. The highest risk obtained for the explosion-accident scenario was from 10^{-7} to 10^{-6} fatalities/year, which was calculated for 139 road segments, which constituted 12.4% of the entire transport route. Far lower results were obtained in the fire-accident scenario in comparison with the explosion-accident scenario. The highest risk obtained for the fire-accident scenario was from 10^{-10} to 10^{-9} fatalities/year, which was calculated for 650 road segments, which constituted 58.1% of the entire transport route. Based on the above results, we can conclude that the risk of compressed-hydrogen-transport in Yokohama City in the first half of the 2020s can be assessed at an acceptable level.

Focusing on the impact of spatial features on the hydrogen-transport risk assessment reveals that the risk values differ at the order level between road segments, confirming that the impact of spatial features on the risk is very large. In addition, Figs. 2 (b)-(c) and (e)-(f) indicate the impact of consequences on the risk are higher than that of the frequencies. Hence, population density determining the consequences is detected as a key factor in the risk assessment.

The object of this case study is the transport routes to the four hydrogen stations. Even if a single road segment forms part of more than one transport route, the risk increases. An investigation of the duplication in this case study showed that, out of 1,119 road segments, there was one road segment on four transport routes, 29 road segments on three transport routes, 54 road segments on two transport routes, and 1,035 road segments on only one transport route. The above results revealed that 7.5% of all road segments increased the risk by forming part of more than one transport route.



(a) Explosion-accident scenario: Risk (fatalities/year)

(b) Explosion-accident scenario: Frequency

(c) Explosion-accident scenario: Consequence

(d) Fire-accident scenario: Risk (fatalities/year)

(e) Fire-accident scenario: Frequency

(f) Fire-accident scenario: Consequence

Figure 2. Spatial distributions of risk, frequency, and consequence of hydrogen transport in Yokohama City

4. CONCLUSION

This study proposed a method of assessing the hydrogen-transport risk by considering detailed spatial features related to the transport-route road structure, traffic volume, and population density, using GIS and traffic accident information. It included a case study that hypothesized the first half of the 2020s, i.e., the near future, and applied the proposed risk assessment method to compressed-hydrogen transport in Yokohama City, Japan.

While the risk (fatalities/year) of the explosion- and fire-accident scenarios during compressed-hydrogen transport in Yokohama City in the near future varied for each road segment, there were no risk (fatalities/year) that was over the acceptable risk.

This case study hypothesized the near future. In the distant future, it is predicted that the number of hydrogen stations and quantity of hydrogen-transported to them will increase, owing to the rise in hydrogen consumption. It is feared that in such a distant future, the hydrogen-transport risk will exceed the acceptable level. Judging from this case study, selecting high transport-efficiency hydrogen-energy carriers, such as, liquid hydrogen, organic hydrides, or ammonia, which reduce the hydrogen-transport itself, or selecting transport routes that avoid overlapping road segment with high risk and transport routes will be an effective risk countermeasure.

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REFERENCES

1. Gerboni, R. and Salvador, E., Hydrogen Transportation Systems: Elements of Risk Analysis, *Energy* **34**, No. 12, 2009, pp. 2223-2229.
2. Moonis, M., Wilday, A.J. and Wardman, M.J., Semi-Quantitative Risk Assessment of Commercial Scale Supply Chain of Hydrogen Fuel and Implications for Industry and Society, *Process Safety and Environmental Protection*, **88**, No. 2, 2010, pp. 97-108.
3. Lasn, K. and Echtermeyer, A.T., Safety Approach for Composite Pressure Vessels for Road Transport of Hydrogen. Part 1: Acceptable Probability of Failure and Hydrogen Mass, *International Journal of Hydrogen Energy*, 39, No. 26, 2014, pp. 14132-14141.
4. Kikukawa, S., Yamaga, F. and Mitsuhashi, H., Risk Assessment of Hydrogen Fueling Stations for 70 MPA FCVs, *International Journal of Hydrogen Energy*, **33**, No. 23, 2008, pp. 7129-7136.
5. Kikukawa, S., Mitsuhashi, H. and Miyake, A., Risk Assessment for Liquid Hydrogen Fueling Sations, *International Journal of Hydrogen Energy*, **34**, No. 2, 2009, pp. 1135-1141.
6. Casamirra, M., Castiglia, F., Giardina, M. and Lombardo, C., Safety Studies of a Hydrogen Refuelling Station: Determination of the Occurrence Frequency of the Accidental Scenarios, *International Journal of Hydrogen Energy*, **34**, No. 14, 2009, pp. 5846-5854.
7. LaChance, J., Risk-Informed Separation Distances for Hydrogen Refueling Stations, *International Journal of Hydrogen Energy*, **34**, No. 14, 2009, pp. 5838-5845.
8. Zhiyong, L., Xiangmin, P. and Jianxin, M., Harm Effect Distances Evaluation of Severe Accidents for Gaseous Hydrogen Refueling Station, *International Journal of Hydrogen Energy*, **35**, No. 3, 2010, pp. 1515-1521.
9. Zhiyong, L., Xiangmin, P. and Jianxin, M., Quantitative Risk Assessment on a Gaseous Hydrogen Refueling Station in Shanghai, *International Journal of Hydrogen Energy*, **35**, No. 13, 2010, pp. 6822-6829.
10. Haugom, G. P. and Friis-Hansen, P., Risk Modelling of a Hydrogen Refuelling Station Using Bayesian Network, *International Journal of Hydrogen Energy*, **36**, No. 3, 2011, pp. 2389-2397.
11. Kim, E., Lee, K., Kim, J., Lee, Y., Park, J. and Moon, I., Development of Korean Hydrogen Fueling Station Codes Through Risk Analysis, *International Journal of Hydrogen Energy*, **36**, No. 20, 2011, pp. 13122-13131.
12. Kim, J., Lee, Y. and Moon, I., An Index-Based Risk Assessment Model for Hydrogen Infrastructure, *International Journal of Hydrogen Energy*, **36**, No. 11, 2011, pp. 6387-6398.
13. Zhiyong, L., Xiangmin, P. and Jianxin, M., Quantitative Risk Assessment on 2010 Expo Hydrogen Station, *International Journal Of Hydrogen Energy*, **36**, No. 6, 2011, pp. 4079-4086.
14. Nakayama, J., Sakamoto, J., Kasai, N., Shibutani, T. and Miyake, A., Preliminary Hazard Identification for Qualitative Risk Assessment on a Hybrid Gasoline-Hydrogen Fueling Station with an On-Site Hydrogen Production System Using Organic Chemical Hydride, *International Journal of Hydrogen Energy*, **41**, No. 18, 2016, pp. 7518-7525.
15. Tsunemi, K., Yoshida, K., Yoshida, M., Kato, E., Kawamoto, K., Kihara, T. and Saburi, T., Estimation of Consequence and Damage Caused by an Organic Hydride Hydrogen Refueling Station, *International Journal of Hydrogen Energy*, **42**, No. 41, 2017, pp. 26175-26182.

16. Huang, Y. and Ma, G., A Grid-Based Risk Screening Method for Fire and Explosion Events of Hydrogen Refuelling Stations, *International Journal of Hydrogen Energy*, **43**, No. 1, 2018, pp. 442-454.
17. Dadashzadeh, M., Kashkarov, S., Makarov, D. and Molkov, V., Risk Assessment Methodology for Onboard Hydrogen Storage, *International Journal of Hydrogen Energy*, **43**, No. 12, 2018, pp. 6462-6475.
18. Hirayama, M., Shinozaki, H., Kasai, N. and Otaki, T., Comparative Risk Study of Hydrogen and Gasoline Dispensers for Vehicles, *International Journal of Hydrogen Energy*, **43**, No. 27, 2018, pp. 12584-12594.
19. Honselaar, M., Pasaoglu, G. and Martens, A., Hydrogen Refuelling Stations in the Netherlands: An Intercomparison of Quantitative Risk Assessments Used for Permitting, *International Journal of Hydrogen Energy*, **43**, No. 27, 2018, pp. 12278-12294.
20. Sakamoto, J., Misono, H., Nakayama, J., Kasai, N., Shibtani, T. and Miyake, A., Evaluation of Safety Measures of a Hydrogen Fueling Station Using Physical Modeling, *Sustainability*, **10**, No.11, 2018, pp. 3846.
21. Tsunemi, K., Yoshida, K., Kihara, T., Saburi, T. and Ono, K., Screening-Level Risk Assessment of a Hydrogen Refueling Station that Uses Organic Hydride, *Sustainability*, **10**, 2018, pp. 4477.
22. Gye, H., Seo, S., Bach, Q., Ha, D. and Lee, C., Quantitative Risk Assessment of an Urban Hydrogen Refueling Station, *International Journal of Hydrogen Energy*, **44**, No. 2, 2019, pp. 1288-1298.
23. Japan Digital Road Map Association, Digital Road Map Data, http://www.drm.jp/map/index.html, (in Japanese).
24. Zhang, J., Hodgson, J. and Erkut, E., Using GIS to Assess the Risks of Hazardous Materials Transport in Networks, *European Journal of Operational Research*, **121**, No. 2, 2000, pp. 316-329.
25. CCPS (Center for Chemical Process Safety of the American Institute of Chemical Engineering), Guideline for Chemical Transportation Safety, Security, and Risk Management, CCPS, New York, 2008.
26. Fire Department , Fire-Service Statistics, http://www.fdma.go.jp/neuter/topics/fieldList8_3.html (in Japanese).
27. High Pressure Gas Safety Institute of Japan, High Pressure Gas Safety Act Database, https://www.khk.or.jp/public_information/information/incident_investigation/hpg_incident/incident_db.html, (in Japanese).
28. Institute for Traffic Accident Research and Data Analysis, Traffic Accident Count Tool, http://www.itarda.or.jp/shukei/, (in Japanese).
29. Automobile Inspection and Registration Information Association, Individual Statistical Data, https://www.airia.or.jp/publish/book/individual.html, (in Japanese).
30. Ministry of Land, Infrastructure, Transport, and Tourism, Actual Situation of Using Cars http://www.mlit.go.jp/jidosha/iinkai/seibi/5th/5-2.pdf, (in Japanese).
31. Lighthill, M.J. and Whitham, G.B., On Kinematic Waves II: A Theory of Traffic Flow on Long Crowded Roads, Proceedings of the Royal Society A, **229**, 1955, pp. 317-345.
32. Ministry of Land, Infrastructure, Transport, and Tourism, the National Land Numerical-Information Data-Download Service, http://nlftp.mlit.go.jp/ksj/, (in Japanese).
33. Eisenberg A.N., Lynch, J.C. and Breeding, J.R., Vulnerability Model: A Simulation System for Assessing Damage Resulting From Marine Spills, DTIC Document, 1975.
34. CCPS (Center for chemical Process Safety of the American Institute of Chemical Engineering), Guideline for Chemical Process Quantitative Risk Analysis Second Edition, Safety, Security, and Risk Management, CCPS, New York, 2010.
35. United States Environmental Protection Agency (EPA), ALOHA Software, https://www.epa.gov/cameo/aloha-software.
36. Urban Development of "Future City" Yokohama and The City-to-City Collaborations, COP 23 Japan Pavilion, 2017, https://www.carbon-markets.go.jp/wp-content/uploads/2017/11/4_City_of_Yokohama.pdf)

37. Kawasaki Engineering Co., Ltd., Product List, https://www.khi.co.jp/corp/ke/product/hydrogen.html, (in Japanese).
38. Ministry of Economy, Trade and Industry, Basic Hydrogen Strategy Determined, https://www.meti.go.jp/english/press/2017/1226_003.html.
39. LaChance, J., Houf, W., Middleton, B. and Fluer, L., Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards, Sandia Report Sand, 2009-0847, 2009.
40. Geographical Information Authority of Japan, Map Information Provided by Geospatial Information Authority of Japan, https://maps.gsi.go.jp/, (in Japanese).
41. Japan Meteorological Agency, Past Weather Data, Common Year Value, https://www.data.jma.go.jp/obd/stats/etrn/view/nml_sfc_ym.php?prec_no=46&block_no=47670&year=&month=&day=&view=, (in Japanese).
42. ISO (2018) Draft international standard ISO 19880-1, Gaseous hydrogen – Fueling stations –, International Standard Organization