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Research Article

A Safety Function Deployment Approach to Risk Management of HazMat Highway Transportation

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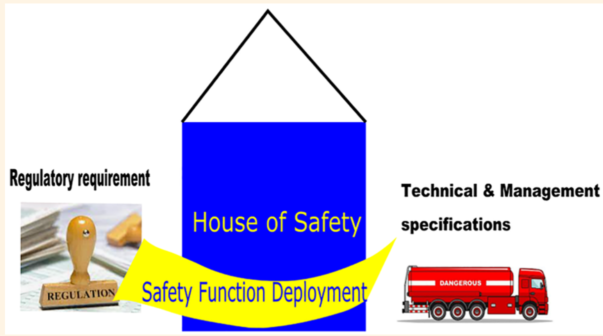
ABSTRACT: Various methods have been developed to ensure the safe transportation of hazardous materials (HazMat). These methods span from conventional statistical methods to modern risk management approaches. An essential question is how to establish the linkages between the regulatory requirements and the safety measures. The analysis of historical data from the past accident report databases would limit our focus on the specific incidents and their causes. Thus, we may overlook some critical elements in risk management, including regulatory compliance, expert opinions, and suggestions. It is necessary to develop a systematic approach that can translate the regulatory requirements of HazMat transportation into specified safety measures (both technical and administrative) to support the risk management. This study develops a structured and transparent method that integrates the quality function deployment (QFD) and risk assessment, namely, safety function deployment (SFD), to identify potential risks and find critical safety barriers for HazMat highway transportation. The proposed method is demonstrated by a hypothetical case study. The approach can serve as a tool to map the safety requirement into specific safety barriers to minimize the risk of HazMat highway transportation.



KEYWORDS: *HazMat transportation, quality function deployment, safety, risk assessment*

1. INTRODUCTION

Hazardous materials (HazMat) are substances that would pose a reasonable risk to lives or the environment if released without precaution. These substances usually include toxic chemicals, fuels, biological and nuclear wastes, and other chemical, biological, and radiological agents.[1,2] HazMat transportation accidents have led to enormous human life losses and imposed considerable damage to both the economy and the environment. According to the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration, four out of five HazMat Road transportation accidents led to severe consequences.[3] For example, in April 2019, in a northern suburb of Chicago, a farm tractor with two 1000 gallon tanks of fertilizers was pulled and leaked significant amounts of anhydrous ammonia into the air. More than 50 people were rescued from different injuries, including chemical burns to the lungs, damage of speech impairments, and vision.[4] HazMat transportation accidents are not rare in rapid-developing countries, such as China, and have caused significant damage to that country's international image and an enormous loss to its economy.[5] Figure 1 presents the variation of the number of HazMat transportation accidents of different transportation modes in the period of 1990 to 2018 in the U.S.A.[6] This shows that highway HazMat transportation accidents occurred the most frequently.

The Transportation Statistics Annual Report 2020 shows that "Truck/Highway Transportation" is the transportation mode, followed by "rail", "water", and "air, air & truck", that shipped and will ship the largest amount of freight.[7] However, the specific data on weight of hazardous material shipments by transportation mode is not available. According to the National of Statistics China, highway transportation is the most commonly used way of HazMat transportation in China.[5,8] This possibly leads to a more significant number of HazMat transportation accidents than other means of transportation. For the world's two largest economies and others, tremendous effort is needed to enhance HazMat highway transportation safety. Thus, this paper will focus on the risk management of HazMat highway transportation.

HazMat highway transportation accidents can cause severe impacts on public safety, human health, and the environment due to the intrinsic properties of HazMat. The primary risk

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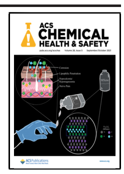

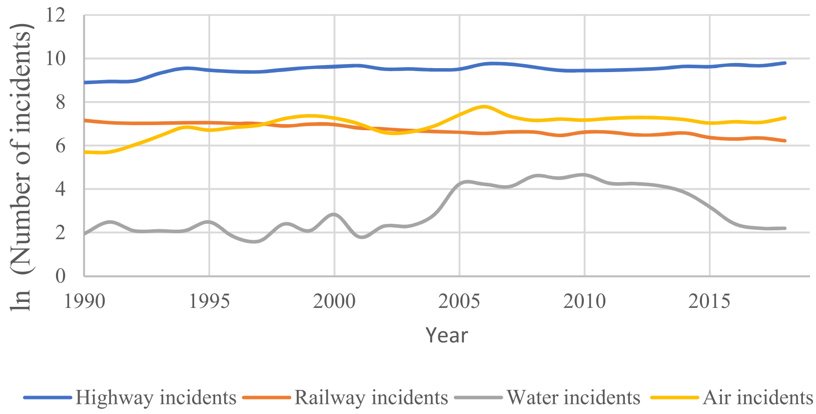

Figure 1. Natural logarithm of HazMat accidents from 1990 to 2018.[6,9]

factors of these accidents include human, vehicle, packing, transportation facilities, road conditions, and environmental conditions.[10] The causes of HazMat highway transportation accidents are complex. They may vary from human errors to severe weather conditions.[11] Various approaches have been applied to the risk assessment of HazMat transportation, which includes conventional statistical methods,[12] the F−N curve,[13] the event tree,[14] and the Bayesian network.[15] Chakrabarti and Parikh have proposed a risk-based approach to the HazMat transportation route evaluation by considering the probability of the collision accident and its consequences.[16] A more advanced quantitative risk assessment model was developed by Weng et al.[14] for evaluating HazMat transportation accident risk. Zhong et al. have investigated the vulnerability of the HazMat highway transportation network by quantifying the Impact Strength of each link in the entire network.[17] Most studies in the literature on HazMat highway transportation focus on the development of risk assessment methods. However, these methods cannot provide a systematic and transparent process to translate the regulatory requirement and corporate policy into safety measures for HazMat transportation. A robust approach is needed to facilitate the process of mapping out the specific safety measures from regulatory requirements for proper implementation of these requirements.

Even though strict standards and regulations have been applied, HazMat highway transportation accidents continue to occur. This indicates that there could be a gap between the well-developed standards and regulations and the proper implementation of them. To bridge the gap, this paper proposes a new safety management approach that supports the development of safety measures according to the regulatory requirements or corporate policies. The proposed approach adopts the quality function deployment (QFD) method to develop a safety function deployment (SFD) approach based on the risk management framework. This approach will help to deploy safety requirements for prevention and mitigation measures for safe HazMat transportation.

The rest of the paper is organized as follows. Section 2 gives an overview of the basic concepts of QFD and other risk assessment techniques. The methodology is presented in Section 3. Section 4 demonstrates the application of the proposed method. Finally, Section 5 concludes the paper and recommends future work.

2. QUALITY FUNCTION DEPLOYMENT

Since the proposed approach was developed based on a conventional QFD model, this section will introduce some basics. QFD is a structured matrix cross-functional methodology designed to collect customer requirements and translate them into technical specifications.[18] The methodology is supported by the graphical tool named House of Quality (HoQ). The tool consists of a series of "rooms" or matrices to identify and translate the phases of customer needs as qualitative requirements into technical, quantitative specifications in QFD. The conventional method includes four stages:

- Product definition: Engineering characteristics
- Product development: Parts characteristics and specifications
- Process realization: Key process operations, manufacturing, and assembly processes
- Process quality control and delivery: Production requirements

The brief definitions of each section of the matrix are listed below:

- *The section "WHATs"*: This room is a duly organized list of requirements or needs from the customer.
- *Importance Factor*: The technical importance rating is used to determine the priorities for each requirement. The weight or importance factor can be calculated based on the analytical hierarchy process (AHP).[18] This method is used to compare the numerous options or indices pairwise based on experts' subjective judgments.
- *HOWs:* This section of HoQ includes the design features and technical requirements to satisfy customer requirements.
- *Main Room:* This section demonstrates how the ranked correlation of effectiveness of every HOW fulfills each WHAT. This can be accomplished using a different scale to indicate weak, medium, and strong relationships between customer and design requirement pairs.[18] The absolute technical importance rating is then calculated based on the sum of the weighted columns of every requirement the relationship measures of jth engineering design requirement.
- *Roof*: This part of the matrix is applied to determine the correlation of design requirements between each other.
- *Relative Importance*: This section represents the results calculated by the sum of every column multiplied by the importance factors. The numerical values are presented as discrete numbers. The obtained data is used to rank each HOW and determine potential improvements.

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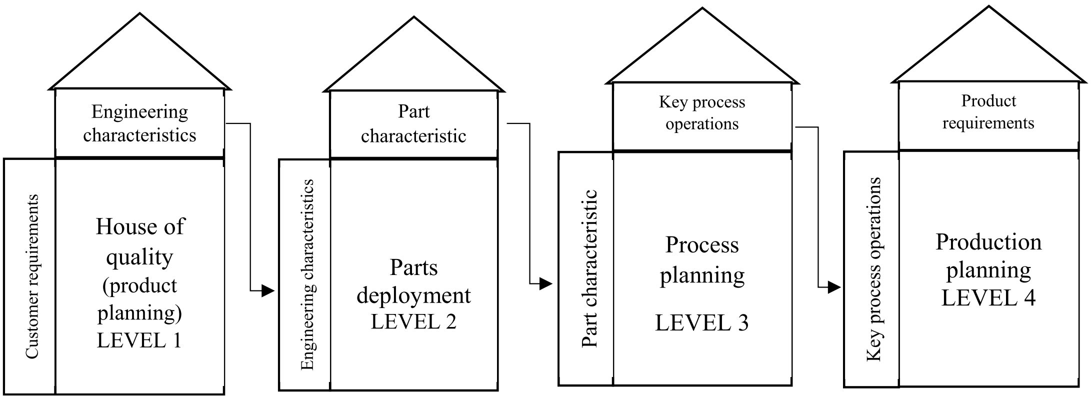

Figure 2. Phases of a conventional QFD.[19]

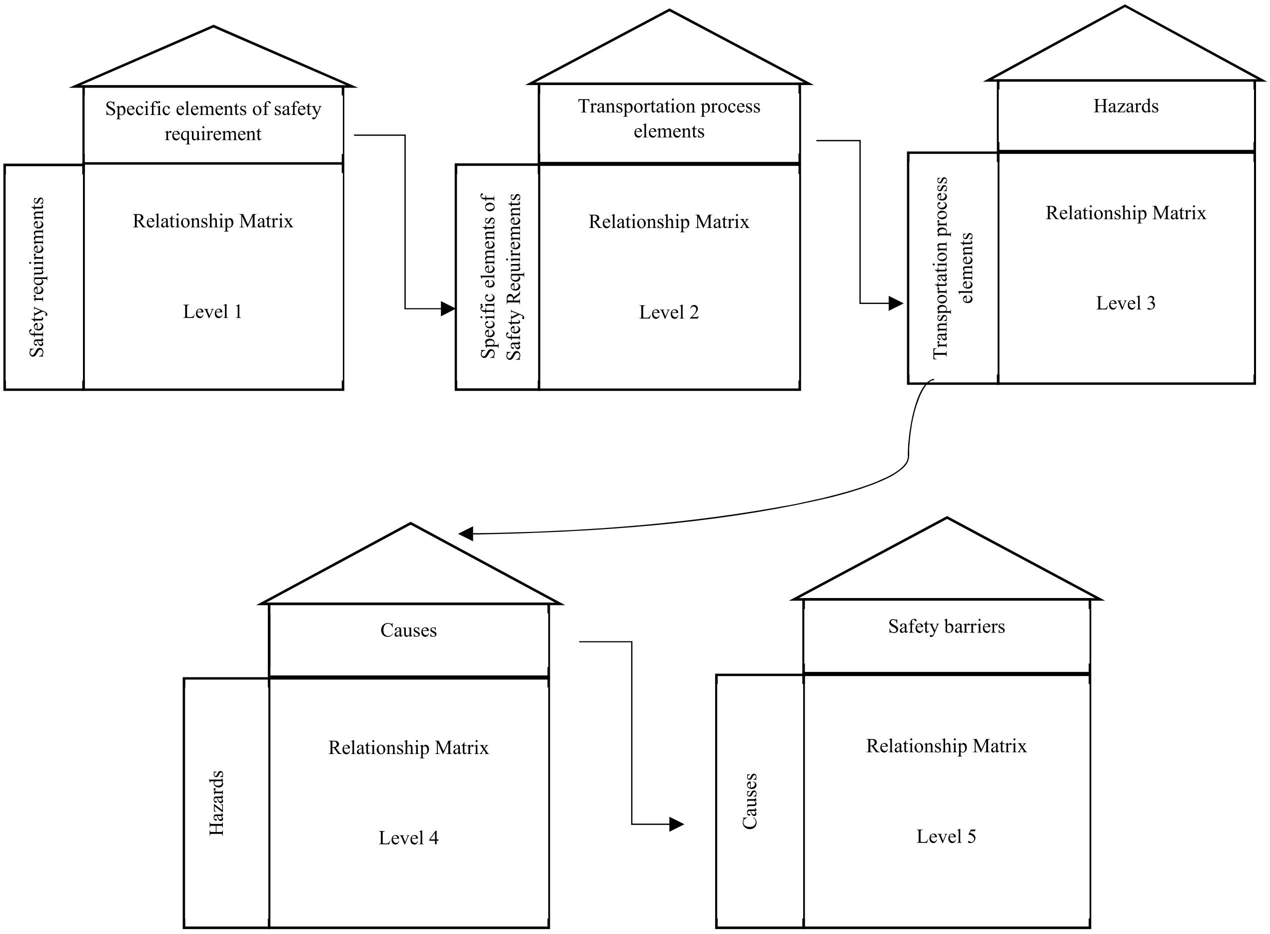

Figure 3. SFD model for the HazMat highway transportation process.

- *Lower Level*: This section identifies more specific target values for technical specifications relating to the HOWs used to satisfy the voice of the customer.

Figure 2 gives a graphical description of a conventional QFD.

Osorio Gomez and Espana used ontologies and fuzzy QFD to support operational risk management in the supply chain.[20] QFD has also been integrated with a probabilistic approach to rate engineering characteriscs.[21] Eleftheriadis et al. combined BIM with QFD to support decision-making in building structural design.[22] QFD was used by Bolar et al. to prioritize infrastructure user expectations.[23] Braglia et al. proposed a method called House of Safety (HoS) for the risk assessment during the machinery design stage.[24] They have demonstrated the usefulness of HoS to structure the selection of appropriate technical solutions to manage the risk caused by human misbehaviors. Inspired by Braglia et al.,[24] this paper proposes a series of HoSs to constitute an SFD approach for HazMat highway transportation risk management.

3. METHODOLOGY

The proposed SFD approach aims to translate the safety requirements for HazMat transportation into risk prevention or mitigation measures at each stage of transportation. This graphical tool visualizes the safety requirements and their

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importance weighting, engineering characteristics, technical elements, and correlation of transportation process elements, hazards, their causalities, and prevention or mitigation actions incorporated into five HoSs. This process produces a score for each HazMat transportation characteristic that combines the importance factors of safety requirements and the strength of the relationships. The following steps can be conducted to develop the SFD. The proposed SFD model is generic and was not developed for specific contexts.

3.1. House of Safety. The first step is to define the SFD architecture that specifies the HoSs. Level 1 HoS identifies the general safety requirements necessary to satisfy the safe shipment of hazardous materials. The safety requirements section lists the desired attributes of a safe transportation process with weights (indicating the importance) for each requirement. The design characteristics section contains a list of particular safety elements of those requirements. The center of the house contains a relationship matrix between the safety requirements and their specific elements. Experts may define the strength of the relationship. The Level 2 HoS indicates how the identified transportation process elements can be divided into subcategories. The Level 3 HoS demonstrates how the transportation process elements influence the occurrence of the hazard. Level 4 HoS provides the relationship between hazards and causal factors. The causes are then transferred to the WHATs section to formulate the safety barriers in the transportation characteristics section in Level 5 HoS. Figure 3 presents the SFD model for risk management of HazMat highway transportation.

3.1.1. Level 1—General Safety Requirements for HazMat Highway Transportation. The goal of safety management is to reduce the number of fatalities and injuries caused by HazMat-related incidents. The general safety requirements for the transportation process include basic safety, packaging safety, driver safety, journey safety, loading and unloading safety, and security.

- *Basic safety* consists of several critical factors common for all types of transportation modes, such as detailed information about hazardous materials and the complete inspection of the vehicle. The hazardous materials table provides detailed information about HazMat, including the shipping name, class, ID number, label, and packaging requirements. Shipping papers are passports providing pertinent information about the cargo, which may include the shipping name of the material, ID number, hazard class and division, packaging group, and the total amount of freight.
- *Packaging safety* includes the labeling and marking procedures. The packaging (separated into bulk and nonbulk) depends on the capacity of the vehicle and the type of transported material. For example, liquid materials can be packed in a nonbulk manner if the maximum capacity of the vehicle is 119 gallons or less or bulk packaging if it is greater than 119 gallons (450 L). Another component of packaging safety is a hazard warning symbol. This is a colored and symbol-coded label displayed on the vehicle that provides notification. There are two types of labels: the primary one, which indicates the most dangerous materials, and subsidiary labels for other less hazardous substances. Placarding is a compulsory element of all vehicles that transport hazardous materials. These are strictly regulated. For instance, in the European Union, chemical packaging and labeling are subject to the requirements of REACH (1907/2006/EC) and CLP (1272/2008/EC) regulations.
- *Driver safety* has several requirements for drivers, for example, passing all qualification courses according to the company regulations and standards and the awareness of state regulations for hazardous materials transportation. Also, the procedures of medical check-ups and the absence of bad habits are strictly controlled.
- *Journey safety* is sophisticated actions including disclosure of information on the cargo transported, the destination, maintaining regular contact with dispatchers, and staying on specified delivery routes.
- *Loading and unloading safety* covers the loading and unloading of the cargo, which are among the most dangerous parts of the transportation. There are particular regulations for thorough and safe procedures. For example, equipment should, if possible, be spotted on level grade and 25 feet (8 m) from any vent that emits vapors. All types of packages must be secured against shifting and segregation. The cargo with information placed on a package must be loaded according to the labeled requirements, remaining in the correct position and shipment conditions. Every package and trailer must be checked for the absence of any ignition sources.
- *Security* has only recently been called to people's attention. HazMat highway transportation is attractive and vulnerable to terrorists.

3.1.2. Level 2—Elements of Safety Requirements and Transportation Process Elements. HazMat transportation is a complex process that involves the joint actions of logistics companies, transportation agencies, and administrative officials. This HoS includes safety requirements as "customer requirements attributes" in a QFD and transportation process elements as a part of the HOWs section. The matrix demonstrates how the elements of the transportation process interact with the safety requirement elements. The vehicle, driver, and plan are three primary factors contributing to the safe transportation process.

3.1.3. Level 3—Transportation Process Elements and Hazards. Level 3 HoS indicates how the transportation process elements contribute to the hazard occurrence. The hazards might have resulted in human fatalities and serious injuries, environmental damages, cargo damage, explosions and fire, and damage to the facilities and properties.

3.1.4. Level 4—Hazards and Causes. The causal factors can be divided into groups according to their source types, such as the failures of all procedures related to the cargo, technical and mechanical failures of the transportation mode, operational failures induced by human errors, weather conditions, and geographical features of transportation routes. The degree of influence of the causal factors on the hazard occurrence is identified and demonstrated in a relationship matrix.

3.1.5. Level 5—Causes and Mitigation Measures. In this HoS, the causal factors from Level 4 are transferred to the WHATs section, and safety measures are incorporated into the HOWs section. The relationship matrix determines the importance factors of each safety barrier and identifies how they effectively cope with a set of hazard causes. Level 5 HoS is the final matrix in the proposed model.

3.2. Uncertainties in SFD. The implementation of the proposed SFD requires subjective judgements obtained from surveys or questionnaires. Thus, uncertain information is

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inevitable and inherent in the proposed approach. The conventional methods based on the 1−3−9 or 1−5−9 ranking scale may lead to two essential types of uncertainties in survey data: inconsistent information with varying responses of experts and vague descriptions.

Considering those limitations, rough set theory is selected to approximate vague description by means of the boundary region of a set. Rough set is a formal approximation of a crisp set using a target set and provides the lower and upper estimates. The lower approximation is a combination of positively classified objects belonging to the target set. In contrast, the upper approximation is a number of objects considered as a member of the target group.[19] More details about the use of the rough set in QFD can be found in the work of Yang et al.[25] The rough sets will be applied to deal with the uncertainties in SFD.

4. AN EXAMPLE

This simple and general example was developed primarily based on the information and accident reports published on the Web

Table 1. An Example of the Experts' Evaluation Results of the Relative Importance

Transportation process element (W_i)	Decision maker (DM)		
	DM_1	DM_2	DM_3
Shipping papers (W_1)	5	7	9
Vehicle control checklist (W_2)	9	7	9
Freight analysis (W_3)	7	7	9

Table 2. Evaluation Results in Rough Numbers

Transportation process element (W_i)	Decision maker (DM)		
	DM_1	DM_2	DM_3
Shipping papers (W_1)	[5,7]	[7,7]	[7,9]
Vehicle control checklist (W_2)	[8,9]	[7,8]	[8,9]
Freight analysis (W_3)	[7,8]	[7,8]	[8,9]

site of the U.S. Department of Transportation.[6] These reports constitute the primary source of information used to perform the case study to demonstrate the proposed method. For illustrative purposes, the assessment results were calculated based on hypothetical surveys and expert opinions. The proposed approach provides a practical tool and transparent process to map out safety measures based on regulatory requirements for HazMat highway transportation. To the authors' knowledge, it is the first of its kind with application to HazMat highway transportation. Thus, the results could not be compared with those achieved by other methods in the literature.

At the Level 1 HoS, we started with the general safety requirements, namely, basic safety, packaging safety, driver safety, journey safety, loading and unloading safety, and security. We identified the specific element of each safety requirement. The following provides the list.

Table 4. WHAT−HOW Relationships in Rough Numbers

WHATs	HOWs			
Basic Safety	Basic Safety	Packaging Safety	Journey Safety	Loading and Unloading Safety
Shipping papers (W_1)	[6,7]	[6,8]	[0,0]	[0,0]
Vehicle control checklist (W_2)	[6,7]	[2,3]	[5,7]	[3,4]
Freight analysis (W_3)	[5,7]	[6,7]	[1,2]	[6,7]

Table 5. Correlation between HOWs in Rough Numbers

WHATs	HOWs			
Basic Safety	Basic Safety	Packaging Safety	Journey Safety	Loading and Unloading Safety
Basic safety	[9,9]	[8,9]	[0,0]	[3,5]
Packaging safety	[9,9]	[9,9]	[0,0]	[8,9]
Journey safety	[0,0]	[1,2]	[9,9]	[0,0]
Loading and Unloading safety	[8,9]	[7,8]	[0,0]	[9,9]

Table 6. Adjusted WHAT−HOW Relationship Considering the Correlation between HOWs

WHATs	HOWs			
Basic Safety	Basic Safety	Packaging Safety	Journey Safety	Loading and Unloading Safety
Shipping papers (W_1)	[102,135]	[48,72]	[0,0]	[27,45]
Vehicle control checklist (W_2)	[96,126]	[63,90]	[72,99]	[27,36]
Freight analysis (W_3)	[15,32]	[55,67]	[6,14]	[0,0]

Table 7. List of Hazards

No.	Hazard
H1	Technical failure (e.g., mechanical defects)
H2	Damage to the automation system
H3	Operating system failure (human errors, e.g., the failure of the driver)
H4	Inadequate certification test of cargo
H5	The operating system failure of a logistic company
H6	Severe weather conditions
H7	Improper packaging
H8	Improper cargo loading
H9	Lack of personnel emergencies trainings
H10	Ignition of freight inside the unit load device

- *Basic Safety*
  (1) S1: Information about transported HazMat
  (2) S2: Technical inspections and characteristics of the vehicle
- *Packaging Safety*
  (1) S1: Chemical and physical properties of HazMat

Table 3. Rough Number of HOWs at Level 2 HoS

WHATs	HOWs												
	Basic Safety		Packaging Safety					Journey Safety		Loading and Unloading Safety			
Basic Safety	SS1	SS2	SS1	SS2	SS3	SS4	SS5	SS1	SS2	SS1	SS2	SS3	SS4
Shipping papers (W_1)	[9,9]	[3,5]	[7,9]	[6,8]	[6,7]	[7,7]	[6,7]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
Vehicle control checklist (W_2)	[7,7]	[6,8]	[2,3]	[2,3]	[3,4]	[1,3]	[2,4]	[6,8]	[3,5]	[6,8]	[0,0]	[0,0]	[7,9]
Freight analysis (W_3)	[6,8]	[5,6]	[4,6]	[5,6]	[8,9]	[6,7]	[5,6]	[2,3]	[0,0]	[5,7]	[6,7]	[6,8]	[5,7]

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Table 8. Detailed Description of Identified Hazards and Causal Factors

H1. Technical failure	
Hazard effect/description	This hazard includes possible mechanical failures of the vehicle. Mechanical failures directly affect the independent critical systems necessary for crew survivability and road safety.
Causal factors	- Defective component or device
	- Malfunction of the truss assemblies and control systems
	- Control cable tension and elevator function
	- Inappropriate maintenance
	- Incorrect sensors set
H2. Failure of the automation system	
Hazard effect/description	The failure of the automation control system may lead to catastrophic consequences with human fatalities and injuries. The speed of the vehicle and brake operation are the most frequent types of hazards during the transportation process. The failure of one of them may result in vehicle collisions and leakage.
Causal factors	- Defective component or device
	- Errors on signal displays, audio control panels
	- Software failure
	- Outdated methodology
	- Alarm system defect
	- Brake failure
H3. Operating system failure (human errors, e.g., the failure of the driver)	
Hazard effect/description	Human error is the element that, more than any other, characterizes the link between operation and accident.
Causal factors	- Lack of specialized training for drivers and crew
	- Not fully competent personnel
	- Medical conditions of the driver
	- Errors during the evacuation procedures
	- Psychological conditions of the crew
	- Inadequate procedure
H4. Inadequate certification test of cargo	
Hazard effect/description	The collection of detailed information about transported cargo plays a crucial role in safety procedures. All types of cargo must be documented and certified with certain administrations.
Causal factors	- The discrepancy of documents with the actual cargo
	- Overweight
	- Transportation of prohibited HazMat
	- Not awareness of staff on the type of cargo
H5. The operating system failure of a logistic company	
Hazard effect/description	The policy of the company, as well as a management system, plays a crucial role in accident prevention. The company must spend a lot of effort to keep all safety regulation procedures and requirements.
Causal factors	- Poor safety culture
	- Unclear corporate policy
	- Lack of proper risk management system
H6. Severe weather conditions	
Hazard effect/description	The weather conditions may be one of the main reasons for transportation incidents. Untimely response to meteorological changes can lead to disaster.
Causal factors	- Freezing
	- Turbulence zone
	- Storm, thunder

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Table 8. continued

H7. Improper packaging	
Hazard effect/ description	Most of the accidents related to hazardous materials occurred due to labeling inconsistencies. Each type and class of dangerous goods require certain storage conditions. Failure to comply with these conditions may result in fire or damage to the cargo.
Causal factors	- Wrong class of hazardous material
	- Overweight
	- Marking and labeling errors
	- Lack of certification
	- Human error
H8. Improper cargo loading	
Hazard effect/ description	There are strict cargo loading procedures, nonfulfillment of which may lead to various kinds of consequences.
Causal factors	- Wrong class of hazardous material
	- Human error
	- Inconsistency of loading and storage conditions
H9. Lack of personnel emergencies trainings	
Hazard effect/ description	During an emergency, how quickly passengers will be rescued depends on crew members. Uncoordinated crew work, loss of time during an evacuation may lead to the injuries or even deaths of several people.
Causal factors	- Human error
	- Uncoordinated crew and captain actions
	- Lack of training
	- Psychological conditions of the crew members
H10. Ignition of freight	
Hazard effect/ description	Hazardous materials transported in special containers may contain ignition sources inside, which may occur due to internal and external factors.
Causal factors	- Human error
	- Improper storage conditions
	- Presence of ignition source

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Table 9. List of Safety Barriers

	Risk mitigation approach[a]	Code	Safety barrier
H1. Technical failure (mechanical defects)	4	SB1	Appropriate and continuous maintenance program
	3	SB2	System diagnosis and proof testing
	3	SB3	Autonomous integrity monitoring
H2. Failure of the automation system	4	SB1	Appropriate and continuous maintenance program
	3	SB2	Continuing system diagnosis and proof testing
	3	SB3	Autonomous Integrity monitoring
	2	SB4	Development of software to supply vehicle with emergency control and response systems
H3. Operating system failure (human errors, e.g., the failure of the driver)	3	SB5	Regular personnel training
	3	SB6	Emergency preparation training
	3	SB7	Tightening the rules of medical check-up and the psychological conditions of the crew
H4. Inadequate certification test of cargo	4	SB8	Double check-up of shipping papers
	4	SB9	Freight analysis
	3	SB10	Training for courier services on the conditions of cargo clearance and penalties, liability for noncompliance
H5. The operating system failure of a logistic company	2	SB11	Development of modern immediate response system
	3	SB12	Development of culture and policy of the company
	4	SB13	Development of risk and safety management regulations
H6. Heavy weather conditions	4	SB14	True data summaries
	3	SB15	Constant monitoring of the vehicle by dispatchers
	3	SB16	Timely cancellation or stop of trip in bad weather
H7. Improper packaging	4	SB8	Double check-up of shipping papers
	3	SB17	Double-check of courier services at the airport
	4	SB18	Certification and total inspection of cargo
	3	SB19	Proper marking and labeling
H8. Improper cargo loading	4	SB8	Double check-up of shipping papers
	3	SB19	Proper marking and labeling
	3	SB20	Cargo separation and storage following the requirements
	3	SB21	Certification and total inspection of cargo
H9. Lack of personnel emergencies trainings	3	SB5	Regular personnel training
	2	SB22	Development of advanced emergency evacuation tools
	3	SB7	Tightening the rules of medical check-up and the psychological conditions of the crew
H10. Ignition of freight	3	SB19	Proper marking and labeling
	3	SB23	At least two rounds of technical inspections
	3	SB17	Double-check of courier services at the airport
	4	SB18	Cargo analysis

[a]Note: 1, attempt to reduce the damage caused by an accident; 2, attempt to reduce the likelihood that a hazard results in an accident; 3, attempt to reduce the likelihood that a hazard occurs; 4, attempt to eliminate a hazard.

   (2) S2: Type of packaging
   (3) S3: Packaging tests
   (4) S4: Identification of the degree of risk
   (5) S5: License
- *Journey Safety*
   (1) S1: Each vehicle has a fully equipped spill/containment kit
   (2) S2: Road analysis
- *Loading and Unloading Safety*
   (1) S1: Must be secured against shifting, including relative motion between packages
   (2) S2: Follow hazmat segregation factors
   (3) S3: Personnel must remain within certain distance, e.g., 25 feet (8 m)
   (4) S4: Handbrake set while loading and unloading

At the Level 2 HoS, these specific elements of safety requirements were translated into transportation process elements. For instance, two particular elements of *Basic Safety*—"Information about transported HazMat" and "Technical inspections and characteristics of the vehicle"—were converted into the actual transportation process element, including shipping papers, vehicle control checklist, and freight analysis. They were also evaluated at this level. Table 1 provides an example of the expert evaluation results. The evaluation of importance was conducted by a 1 to 9 assessment scale, where 1 is very low, 3 is low, 5 is moderate, 7 is high, and 9 is very high. The evaluation results were then converted into rough numbers. Table 2 presents the results. Below is an example to show how we calculated the rough numbers to represent the preference of DM1 concerning shipping papers.

$\underline{\lim}(5) = R(C_1) = 5$

$\overline{\lim}(5) = (R(C_1) + R(C_2) + R(C_3))/3 = (5 + 7+9)/3 = 7$

Rough number (RN) for DM1 wrt shipping papers: RN (5) = [5,7]

To integrate the weights, the following process was applied.

$RN(W_1) = ([5,7] + [7,7] + [7,9])/3 = [6,8]$

$RN(W_2) = ([8,9] + [7,8] + [8,9])/3 = [8,9]$

$RN(W_3) = ([7,8] + [7,8] + [8,9])/3 = [7,8]$

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Table 10. Importance Factors of HOWs

Level 1	IF	Level 2	IF	Level 3	IF	Level 4	IF
Basic safety	[34,51]	Type of vehicle	[6,23]	Destroyed freight/ Cargo fire	[9,38]	H1. Technical failure	[3,18]
Packaging safety	[35,52]	Mechanical properties of the vehicle	[7,11]	Explosion	[12,45]	H2. Damage of the automation system	[2,20]
Driver safety	[23,36]	Compliance with all traffic standards	[4,9]	Release of chemicals	[17,55]	H3. Operating system failure	[9,43]
Trailer safety	[30,52]	Proper inspection and monitoring of the vehicle	[5,13]	Vehicle collision	[28,70]	H4. Inadequate certification test of cargo	[6,34]
Journey safety	[26,55]	Physical conditions of driver	[5,11]	Management failures	[41,71]	H5. The operating system failure of logistic company	[11,4]
Unloading and Loading safety	[63,78]	Working experience	[16,22]			H6. Heavy weather conditions	[1,19]
Security	[44,52]	Qualification of driver	[26,37]			H7. Improper packaging	[7,44]
		Emergency training	[15,31]			H8. Improper cargo loading	[15,56]
		The general plan for HazMat transportation	[16.37]			H9. Lack of personnel emergencies trainings	[25,72]
		Emergency plan	[21.32]			H10. Ignition of freight	[3,33]
		Proper route plan	[8.25]				
		Cargo transportation area information	[11.17]				

Table 11. Importance Factors of the Safety Barriers

Level 5—Safety barriers	IF
SB1. Appropriate and continuous maintenance program	[1,19]
SB2. Continuing system diagnosis and proof testing	[1,20]
SB3. Autonomous Integrity monitoring	[1,20]
SB4. Development of a program to supply vehicle with emergency control systems	[1,24]
SB5. Regular personnel training	[1,20]
SB6. Emergency preparation training	[1,17]
SB7. Tightening the rules of medical check-up and the psychological conditions of the crew	[0,13]
SB8. Double check-up of shipping papers	[1,27]
SB9. Freight analysis	[1,30]
SB10. Training for courier services on the conditions of cargo clearance and penalties, liability for noncompliance	[1,22]
SB11. Development of modern immediate response system	[1,26]
SB12. Development of safety culture and policy of the company	[2,38]
SB13. Development of risk and safety management regulations	[2,33]
SB14. True data summaries	[2,43]
SB15. Constant monitoring of the vehicle by dispatchers	[2,42]
SB16. Timely cancellation or stop of trip in bad weather	[2,38]
SB17. Double check of courier services	[3,51]
SB18. Cargo analysis	[4,57]
SB19. Proper marking and labeling	[5,62]
SB20. Cargo separation and storage in accordance with the requirements	[8,70]
SB21. Certification and total inspection of cargo	[11,80]
SB22. At least two rounds of technical inspections	[14.86]
SB23. Development of advanced emergency evacuation tools	[18,89]

Table 3 presents the calculated results of the rough numbers of HOWs. Table 4 gives the WHAT−HOW relationship at the level. Table 5 provides the correlation between HOWs in rough numbers. Finally, the WHAT−HOW relationship was adjusted based on the correlation between HOWs. They are presented in Table 6. Yang et al. provided a more detailed calculation process of the correlation matrix and how they can be used to adjust the WHAT−HOW relationship.[25]

At the Level 3 HoS, we identified the hazards associated with the transportation process elements. Table 7 provides the list.

At the Level 4 HoS, the causal factors of each hazard were identified and are listed in Table 8.

Eventually, at Level 5 HoS, the safety barriers were identified and are presented in Table 9.

Then, we calculated the importance factors (IFs) of HOWs at Level 1 to Level 4 (Table 10) using the method developed in Yang et al.[25]

The above table shows that, at Level 1, "security" and "loading and unloading safety" may have more influence on the risk management of the HazMat highway transportation. The importance factors of Level 2 indicate that driver experience and qualification are essential. The critical causal factors are operating system failure, failure of the operating system of the whole company, lack of personnel emergency training, and improper cargo loading.

Eventually, all the safety barriers listed in Table 9 were ranked. Table 11 presents their importance factors. The results provide some insight into critical safety barriers that must be well implemented.

5. CONCLUSIONS

The proposed SFD approach has provided a framework that can identify the proper safety measures according to the safety requirements for HazMat highway transportation. The framework was developed by incorporating risk assessment elements into the skeleton of QFD adapted to the risk management of all stages of HazMat highway transportation. The proposed work represents a systematic approach capable of analyzing incidents and hazards in different scenarios and for each mode. Furthermore, this framework can help formulate essential safety barriers to prevent and mitigate HazMat highway transportation accidents.

The proposed SFD method for risk management of HazMat highway transportation is characterized by several advantages compared to other approaches in the literature:

- It is a structured approach that can help map safety requirements into safety barriers/measures in a transparent step-by-step process.
- It effectively integrates the QFD and risk assessment to identify and prioritize best measures to ensure HazMat transportation safety.

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- It can be used as a brainstorming tool for a cross-functional team working on risk management of HazMat highway transportation.

The case study identified the top five essential safety barriers/measures for safety management of HazMat highway transportation. They are

- Development of advanced emergency evacuation tools
- At least two rounds of inspections
- Certification and total inspection of cargo
- Cargo separation and storage in accordance with the requirements
- Proper marking and labeling

Since the proposed approach has not been tested via a real-world case, the current study remains theoretical. Future work will be devoted to real-world case studies to gain more practical insights.

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Notes

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