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Navigating Risks: The Imperative of Research in CIT and Hazmat Transport Security

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Abstract

The transportation of hazardous materials and valuables, exemplified by cash-in-transit, poses significant risks. Valuables transportation is prone to robbery, while hazmat transport faces accidents and potential material release, endangering the populace and the environment. This paper emphasizes the importance of researching risk mitigation in this domain, highlighting recent scholarly insights. It identifies research gaps, including the need for enhanced risk assessment models and the consideration of multimodal transportation. The manuscript advocates for interdisciplinary collaboration and innovative methodologies to fortify route security and minimize risks in CIT and hazmat transportation.

Keywords

Hazardous Materials, Valuables Transportation, Cash-In-Transit, Risk Mitigation, Route Security.

1. Introduction

The transportation of hazardous materials (hazmat) and valuables involves inherent risks, compelling stakeholders and researchers to devise methods to mitigate these risks and enhance route security. Hazardous materials, as defined by the US Department of Transportation (2022), encompass substances such as combustible, explosive, oxidizing, toxic, biohazard, radioactive, and corrosive materials that threaten people, properties, and the environment. Valuables include banknotes, coins, gold, jewelry, and special pharmaceutical items, collectively called cash-in-transit (CIT).

CIT and the transportation of hazmat involve several types of risk: valuables are extremely susceptible to robbery, and hazmat transportation is vulnerable to accidents and the release of the material transported, potentially exposing the population and the environment to such materials. In addition, the incidents described can occur at any phase of the transportation process (loading, transit, and unloading), and the consequences of such incidents are catastrophic. Annually, tens of thousands of accidents in the transportation of hazardous materials in the US are reported, accounting for 0.38% of the total number of transportation accidents on highways and 5% of the accidents on railroads yearly (Table 1). The total damage caused by such incidents amounts to tens of millions of dollars and hundreds of injuries per year (Table 2), and in significant cases, accidents in hazmat transportation can cause tens of millions of dollars per case in damage (Table 3). Therefore, such accidents are categorized as low-probability-high-consequence events. Most high-consequence accidents in transporting hazardous materials are related to combustible liquids, specifically petroleum, gasoline, and fuel oil (U.S. Department of Transportation, 2024). It is also observed that railroad accidents

that are related to hazmat account for a higher percentage of all railroad accidents in the US, that the total amount of damage caused by railroad accidents related to hazardous materials is similar to hazmat accidents that occur on the road, and that the accidents of the transportation of hazardous materials by railroad can be as catastrophic as, if not more than, hazmat transportation on the road.

In most countries, even though more transactions are occurring digitally, the total value of cash in circulation is still rising rapidly. Amidst the GDP growth, the total value of cash as a percentage of total GDP in Japan, Korea, and Mexico grew by 2 percent from 2019 to 2022. For the US, the cash in circulation has steadily amounted to 9% of the total GDP. In several countries, such as Japan and India, the total value of cash in circulation is consistently maintained in double digits, demonstrating that cash is still in high demand and widely used. (Table 4). With demand for cash and cash in circulation still growing steadily, the significance of the study of the routing problem in CIT is still warranted. Additionally, the rise in the number of robberies and attacks on banks and armored vehicles (Table 5) calls for better risk mitigation approaches to be developed to minimize the risk of such incidents.

1.1 Objectives

This research has two main objectives: First, to illustrate the significance of conducting research on risk mitigation for the transportation of hazmat and valuables, and second, to summarize the recent research trend in such areas. In recent years, the total damage and casualties of hazmat transportation remained high, prompting different stakeholders (government, corporations, and academia) to develop and invest in approaches to minimize the risk involved. Additionally, cash circulation and usage have been shown to still be increasingly high. Both of these factors further emphasize the significance of developing and refining risk mitigation approaches in the context of CIT and hazmat transportation.

2. Literature Review

We investigated and categorized two research aspects: risk equity measures and risk mitigation approaches. Papers from 2000 were collected and screened. The key findings and observations are discussed in the following sections.

2.1 Risk Equity Measures

Much research in hazmat transportation routing problems has incorporated risk equity measures into their models to ensure that the total risk of the route is distributed evenly across the nodes and arcs.

Gopalan et al. (1990), one of the earliest studies to consider risk equity measures, developed a model for hazardous materials to be transported from a single origin to a single destination with total transportation risk minimized and distributed the risk evenly throughout the route traveled. Since then, several methods of measuring risk equity have been developed. Carotenuto et al. (2007) proposed the Risk equity index (EI) and the Restricted risk equity index (REI), which are measurements that represent the variation coefficient of the risk imposed on the population around the links used in the route. The main difference between EI and REI is that while EI considers all the links used in the network, REI only considers the risk deviation of the set of links used in the route or routes selected.

Fontaine, Crainic, Gendreau, and Minner (2020) proposed measures similar to the EI to calculate the average and maximum deviation to the mean, the average difference between all population centers, and the maximum difference between two population centers. Additionally, to avoid the effect that the risk of some population centers would increase when the level of the total risk of the network is not considered, they also proposed another risk equilibrium measure that considers social bounds. Another method to ensure risk equity is to minimize or limit the overlapping rate. Dadkar, Jones, and Nozick (2008) considered the minimization of the overlapping rate between pair of routes used to ensure that risk is distributed evenly in the network. In their study, geographical diversity was defined to be the largest overlap between any two paths in the set of paths selected, and the relative importance of the maximum value of the composite measure mean in comparison to the maximum percentage of overlap was also defined to represent the trade-off between performance and geographical diversity. Dell'Olmo, Gentili, and Scozzari (2005) as well as Martí, Luis Gonzáles Velarde, and Duarte (2009), proposed dissimilarity measures to spread the risk among the selected routes. After a set of routes between an OD pair is selected by an optimization algorithm, a buffer zone

that represents the area of impact of a hazmat incident is considered. The dissimilarity is then calculated based on the buffer zones and their intersections.

2.2 Risk Mitigation Approaches

In the transportation of hazmat and valuables, three main approaches to risk mitigation are commonly employed: security enhancement through improved emergency response, diversification to increase the unpredictability of routes, and failure mode and effects analysis (FMEA).

The first approach involves enhancing emergency response measures. Tarantilis and Kiranoudis (2004) were among the earliest researchers to propose a risk-minimizing model for the transportation of valuables by reducing the distance between the location of the vehicle in the route and police stations. Similarly, Xu et al. (2013) proposed a model in which the route used cannot exceed the maximum service distance of the emergency response resources that are available.

Route diversification presents a second approach to risk mitigation. Ngueveu et al. (2013) presented the *m*-peripatetic vehicle routing problem (VRP) for cash logistics in which each path can only be used at most once during m periods, thus no edge is repeated among different days, thereby enhancing transportation security through route unpredictability. Another means to foster the unpredictability of the routes used is by diversifying arrival times. Yan et al. (2012) considered a constraint that formulated the concept of similarity in space and time by defining a parameter in which the route that is chosen for the current day will have a small maximum allowable similarity to the routes used in the preceding day. Michallet et al. (2014) formulated a VRP with irregular visit times by considering soft time windows and time spread constraints, imposing a time difference between the arrival times of vehicles to a specific location over the periods. Hoogeboom & Dullaert (2019) further generalized the arrival time variability by using customer-specific diversification parameters rather than using the same parameter for all customers. It is noted that while the approach of enhancing emergency response is considered for both the transportation of hazmat and valuables, diversification is the risk mitigation approach that is unique to CIT problems due to the nature of the items being transported.

The third approach, failure mode and effects analysis (FMEA), is the most frequently utilized method. In this approach, the risk of the selected route is often defined as the function of three main variables, namely occurrence/probability (measuring the probability of occurrence of an accident/robbery), vulnerability (measuring the probability that the robbery is going to be successful), and exposure (measuring the potential damage or loss that the robbery or accident is going to cause). Zhang, Wang, He, Yang, and Guan (2018) modeled the risk of hazmat transportation by considering the volume of hazmat on the link, damage per unit amount of hazmat, and population exposure. Fontain et al. (2020) calculated the risk of hazmat transportation based on population node rather than network's arc. The risk that a population center is exposed to is calculated based on various factors: volume of hazmat transported in the influence area of the population center, accident risk, potential influence factor, and population size. It is also important to note that since this model doesn't associate the perceived risk with arcs anymore, all of the modes that are used to transport the hazmat that are within the influence area have to be considered altogether. Fallahtafti et al. (2019) formulated the risk of cash transportation by considering different characteristics of the road used, such as type of road segment, number of lanes, traffic congestion, and light signals. In addition, Fallahtafti et al. (2021) measured the risk that the vehicles are exposed to in both echelons as a function of the total travel time of each vehicle and the amount of cash that each vehicle carries. In recent years, more research has shifted focus to another mode of transportation: drones. Both Zandieh et al. (2023) and Zandieh et al. (2024) modeled VRP in CIT using drones as the mode of transportation, with the security of the route also enhanced by real-time drone surveillance. Drones will be deployed and conduct ground surveillance for a specific period before the ground vehicle is scheduled to leave the bank. During the transport, if the drones detect a threat in a link, re-optimization will occur.

6. Conclusion

In conclusion, the transportation of hazardous materials and valuables inherently carries significant risks, often classified as low-probability, high-consequence events, including robbery and accidents. This risk is underscored by a persistent increase in cash demand, sometimes outpacing GDP growth, and a concerning rise in accidents involving hazardous materials and valuables. These trends highlight the pressing need for improved risk mitigation strategies to address mounting monetary losses and human casualties, emphasizing the ongoing relevance and significance of

refining approaches in this domain, which garners attention from stakeholders across government, business, and academia.

Our study underscores the critical importance of researching risk mitigation approaches for CIT and hazmat transportation. With the continued high circulation of cash and significant costs associated with hazmat accidents, refining risk measurement methodologies is imperative to minimize the impact of such incidents. Additionally, while traditionally routing problems only consider a single mode of transportation, recent research (Han et al., 2023; Li et al., 2021) has shifted focus to consider multimodal transportation in routing problems in hazardous materials to enhance the flexibility and reliability of the route or network, alongside drone utilization. Emerging trends also highlight the integration of machine learning and artificial intelligence in optimization algorithms, signifying an evolving landscape in transportation logistics that necessitates further interdisciplinary collaboration and innovative methodologies to fortify route security.

Furthermore, accidents involving hazardous materials on railroads can have equally catastrophic outcomes as those on roads, emphasizing the need for enhanced risk assessment and mitigation strategies. While traditional risk assessment models prioritize monetary values, there is a clear gap in considering environmental impacts such as carbon dioxide emissions or fuel usage. Addressing this gap is vital for developing comprehensive risk mitigation strategies that ensure the sustainability and safety of transportation systems. Government agencies have been implementing stricter regulations and investing in advanced emergency response systems to enhance safety. Similarly, businesses, such as logistics companies, are increasingly adopting technologies like AI and drones to enhance risk oversight, ensure route security, and optimize delivery efficiency, while corporations like UPS and FedEx are integrating AI-driven route optimization to enhance security and efficiency. Academia plays a crucial role by developing comprehensive risk assessment models and conducting interdisciplinary research that incorporates both economic and environmental impacts. Collaborative efforts among these stakeholders are crucial for enhancing the safety, efficiency, and sustainability of transportation systems.

Table 1. Number of accidents by transportation mode (U.S. Department of Transportation, 2024)

Mode	Total				Hazmat				Hazmat/Total (%)			
	2019	2020	2021	2022	2019	2020	2021	2022	2019	2020	2021	2022
Road	6,756,084	5,251,006	6,102,936	N/A	20,684	19,879	23,116	23,405	0.31	0.38	0.38	N/A
Rail	10,114	7,424	7,806	8,505	413	372	396	367	4.08	5.01	5.07	4.32
Water	7,299	7,818	6,992	6,593	6	2	5	5	0.08	0.03	0.07	0.08

Table 2. Hazmat transportation damages (in dollars) by mode (U.S. Department of Transportation, 2024)

Mode	2018	2019	2020	2021	2022	2023
Air	75,099	64,891	6,000	15,420	61,660	3,000
Highway	92,134,193	74,910,386	28,556,366	26,192,899	25,630,852	32,693,104
Railway	22,158,533	17,404,584	27,350,076	22,024,656	23,932,821	10,737,387
Water	32,500	15,100	1,750	0	3,500	218,000
Total	114,400,325	92,394,961	55,914,192	48,232,975	49,628,833	43,651,491

Table 3. High-consequence hazmat incidents in the U.S (U.S. Department of Transportation, 2024)

Mode	Year	City/Location	Type	Material	Transportation Phase	Damages ($)
Road	2018	Mishawaka, IN	Combustible liquid	Gasoline	In transit	17,017,646
Road	2018	Ayer, MA	Combustible liquid	Fuel oil	Unloading	12,402,500
Road	2017	Detroit, TX	Flammable gas	Propane	In transit	4,273,606
Road	2015	Walpole, IL	Combustible liquid	Gasoline	In transit	7,933,399
Road	2014	Jackson, WY	Flammable gas	Propane	Unloading	2,895,000
Railroad	2015	Mount Carbon, WV	Combustible liquid	Crude Oil	In transit	23,456,560
Railroad	2020	Draffin, KY	Combustible liquid	Alcohols	In transit	10,200,000
Railroad	2021	Newark, DE	Corrosive	Sulfuric Acid	Unloading	4,592,090
Railroad	2021	New Castle, DE	Corrosive	Sulfuric Acid	Unloading	2,097,000
Railroad	2022	Harmar, PA	Combustible liquid	Petroleum	In transit	7,925,000
Railroad	2023	Livingston, KY	Combustible liquid	Molten Sulfur	In transit	4,821,434
Water	2017	Pass Christian, MS	Compressed gas	Ammonia Anhydrous	In transit	5,400,000

Table 4. Cash in Circulation and GDP (Bank for International Settlements, 2024)

Country	GDP (in billion $)				Cash in Circulation (in billion $)				Cash/GDP (%)			
	2019	2020	2021	2022	2019	2020	2021	2022	2019	2020	2021	2022
Australia	61.89	79.34	77.64	73.64	1,387.96	1,363.04	1,656.01	1,720.26	4.46	5.82	4.69	4.28
Brazil	69.83	71.32	60.85	64.76	1,873.47	1,476.46	1,649.53	1,918.98	3.73	4.83	3.69	3.37
Canada	76.57	89.03	95.85	93.43	1,743.54	1,656.27	2,007.72	2,161.02	4.39	5.38	4.77	4.32
India	342.76	390.47	421.28	408.61	2,854.52	2,675.80	3,174.12	3,464.52	12.01	14.59	13.27	11.79
Indonesia	57.17	63.98	67.52	66.27	1,119.29	1,060.48	1,186.60	1,318.74	5.11	6.03	5.69	5.03
Japan	1,084.30	1,196.94	1,103.46	985.18	5,119.51	5,057.16	5,029.32	4,254.73	21.18	23.67	21.94	23.15
Korea	108.93	135.53	140.96	138.76	1,650.12	1,645.58	1,815.97	1,671.93	6.60	8.24	7.76	8.30
Mexico	92.17	106.40	119.40	137.67	1,337.12	1,208.07	1,368.96	1,529.19	6.89	8.81	8.72	9.00
South Africa	11.79	12.09	11.10	10.72	389.19	338.58	419.90	404.53	3.03	3.57	2.64	2.65
United Kingdom	98.12	101.81	113.85	103.45	2,848.64	2,699.05	3,141.68	3,047.72	3.44	3.77	3.62	3.39
United States	1,807.67	2,089.14	2,236.67	2,309.02	21,902.40	22,024.50	24,654.60	26,408.40	8.25	9.49	9.07	8.74

Table 5. CIT incidents in the U.S. (FBI, 2024)

Violation involving armored carriers	2016	2017	2018	2019	2020	2021	2022
Violations	36	41	34	24	25	28	33
Injuries	14	7	6	3	0	0	8
Death	3	4	2	2	0	0	2
Hostages	0	0	1	0	0	0	3

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Biographies

Alireza Fallahtafti earned his Ph.D. in Industrial and Systems Engineering from Ohio University and now holds a faculty position at Case Western Reserve University. With extensive experience in the industry, his expertise spans operations, supply chain management, and analytics. Alireza's teaching interests cover a range of topics including Supply Chain and Logistics optimization, Analytics (Descriptive, Predictive, and Prescriptive), Simulation, Visualization, and Project Management. In research, he focuses on applying machine learning and optimization methods to address practical challenges like supply chain risk and decision-making under uncertainty. His significant contributions to academia include numerous publications in prestigious international conferences and journals. Additionally, he actively serves as a reviewer for esteemed international journals and plays pivotal roles on technical committees for conferences. His outstanding achievements have garnered widespread recognition and accolades from both academic and industrial communities.

Tan Khoa is currently a senior student at Weatherhead School of Management, Case Western Reserve University. He is mainly interested in conducting research in operation research and risk minimization in transportation.