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Exploring an Infrastructure Investment Methodology to Risk Mitigation from Rail Hazardous Materials Shipments

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***Abstract*—Railroad is one of the primary modes to transport hazardous materials (hazmat) in North America. For instance, Canadian railroads carried around 50 million tons of hazmat in 2018. Given the inherent danger of trains carrying hazmat, this study aimed at exploring a novel way towards mitigation of the associated risk. This study sought to investigate whether proper rail track infrastructure investment can mitigate the risk from hazmat shipments. To this end, a methodology was developed and then applied to the Canadian railroad network. The proposed three-step methodology captured the differing perspectives of rail carriers and regulatory agencies, and entailed (1) ascertaining the risk-level of various yards and links in the given railroad network, (2) specifying potential candidates for infrastructure investment, and (3) finding the optimum set of investment decisions. The proposed methodology was then applied to the Canadian railroad network to demonstrate that significant risk-reduction can be achieved by adding alternative rail-links around the riskiest locations (i.e. the network hot-spots), and also to show that risk-reduction function is non-linear with non-monotonous behavior. The study showed the possibility of significant hazmat risk reduction through alternative rail-links that could take traffic away from the network hot-spots. The methodology and the results from the Canadian case can be used by railroad companies and policy makers to estimate the value of potentially risk-reducing infrastructure investments.**

***Index Terms* — risk mitigation, railroad network, hazardous materials, infrastructure investment, optimization, transportation safety.**

I. Introduction

Hazardous materials (hazmat), though harmful to humans and the environment, are integral to the industrial lifestyle. However, they are rarely produced and consumed at the same location and thus they may need to be transported in significant volumes. Railroads carry a significant portion of hazmat shipments in North America. For instance, around 111 million tons of hazmat were carried by rail in the United States (U.S. Department of Transportation, 2012), and the same year's number for Canada was around 37 million tons, which reached almost 50 million tons in 2018 (Transport Canada, 2018). It is pertinent that the quantity of hazmat traffic on railroad networks is expected to continue increasing; this is in part due to the recent need to transport an increasingly large volume of crude oil from the Bakken shale formation regions in the United States and Canada to the refineries located along the southern and eastern coasts (Canadian Association of Petroleum Producers, 2019). In general, railroads are preferred over highways for both the long-haul and larger volumes of hazmat (Bagheri, Verma, & Verter, 2014). Fortunately, it is also one of the safest modes for transporting hazmat, thanks to a number of industry initiatives to reduce the frequency/probability of tank car accidents and the likelihood of release (Verma & Verter, 2013). However, the probability of catastrophic events resulting from multi railcar incidents does exist. For instance, on July 6th, 2013, a freight train derailed in the town of Lac-Mégantic (Quebec, Canada) spilling over six million liters of crude oil, and the resulting fire and explosion left 47 people dead.

Several initiatives have focused on the assessment and management (mitigation) of hazmat risk for rail shipments over the last two decades; we provide a state-of-the-art review in the next section. However, none of the initiatives can assuredly eliminate the possibility of catastrophic events because of two factors that are specific to railroad transportation infrastructure in North America: *first*, railroad was designed to connect population centers, and hence traverses populated areas; and *second*, the railroad network is sparse, which limits the routing options between two points. Note that the latter also rules out imposing tolls or closing links as a mechanism to mitigate hazmat risk as is possible for highway hazmat shipments (Bianco, Caramia, Giordani, & Piccialli, 2013), since the resulting network might not be connected. Creating new links, on the other hand, might increase routing options while maintaining connectedness. Thus, in this study, we make the first attempt to explore the potential societal benefit of rail-link infrastructure investment in terms of reducing the network-wide risk from rail hazmat shipments. More specifically, we investigate if providing routing choices around high-risk locations (i.e. network hot-spots) could lower hazmat risk? If viable, such an augmented network could result in a lower public risk that regulators desire, as well as better insurance rates and cleaner public image that railroad companies seek.

Besides the domain-specific aspects and the use of mathematical optimization, this work is inspired by a combination of two main theories: Cost-Benefit Analysis and Game Theory. The former is generally useful in evaluating infrastructure investment projects (Drèze & Stern, 1987), and the latter allows for analytical modeling of interactions among rational decision-makers (Osborne & others, 2004). Consequently, the proposed methodology consists of the following steps: *first*, conduct the risk assessment of the railroad network to identify high-risk links and network hot-spots; *second*, introduce alternative rail-links around each identified hot-spot; and *third*, for the given budget, determine the optimal investment strategy based on the idea of cost-benefit analysis as well as the presence of conflicting objectives/perspectives. The first step of the methodology entails solving a multi-commodity flow problem, the second step requires recreating the railroad network in a geographical information system (GIS) environment (ESRI 2016), whereas the final step makes use of the inputs from the previous two steps to determine the investment that brings about maximum benefit, i.e. maximum risk reduction in the given network. While we adopt the regulator's viewpoint in making risk-minimizing investment decisions, we also consider the cost-minimizing attitude of the railroad companies (carriers) in making routing decisions; therefore, both perspectives are captured in our modeling approach (Kara & Verter, 2004). The proposed methodology is applied to the realistic railroad network in Canada, and the resulting computational experiments demonstrate that hazmat risk can be reduced by investing in building rail-tracks that can take traffic away from the population centers, and that risk could be reduced only up to a certain level of investment. This study makes a four-fold contribution to the literature: *first*, explore a novel methodology to mitigate risk from rail hazmat shipments; *second*, identify high-risk rail-links and hot-spots in the Canadian railroad network based on a well-known risk measure; *third*, suggest a mechanism to propose alternative rail-links around the hot-spots; and *fourth*, given the interactive decision-making environment, build the risk reduction versus investment budget (i.e., benefit vs. cost) function to delineate point beyond which further investments would have no or negative impacts.

The remainder of this paper is organised as follows. Relevant literature is discussed in Section II. In Section III, a process view of the proposed methodology is presented, which is followed by its application to the railroad network in Canada in Section IV, where results are provided and discussed. Finally, conclusions and limitations are summarised in Section V.

II. Literature Review

The hazmat risk literature contains numerous studies with different modeling approaches in a variety of settings, for example, multi-criteria decision analysis in the context of hazardous facilities (Nivolianitou & Papazoglou, 2014), and quantitative modeling of hazmat shipments for modal choice (Mazzarotta 2002; Bury et al. 2017). In this paper, we organised the most relevant literature under three themes: the *first* part reviews risk assessment efforts for rail hazmat shipments; the *second* part briefly discusses risk management initiatives in the railroad domain; and, the *third* focuses on risk-reducing infrastructure investment and hazmat routing.

A. Risk Assessment of Rail Hazmat Shipments

Risk is most commonly defined as the product of the *probability* and the *consequence* of an undesirable event (Lowrance, 1976); in the hazmat transport literature, this is referred to as *traditional risk* (*TR*). For example, Verma (2011) used a traditional risk approach, where hazmat release from multiple sources and train-decile-based conditional derailment probabilities were incorporated into the risk assessment effort. It is pertinent that the usage of the traditional risk approach in the rail hazmat domain is limited, mainly due to the dearth of relevant data.

Attempts to overcome the abovementioned challenge resulted in the development of two alternative measures of risk: *incident probability* (*IP*), and *population exposure* (*PE*). The *IP* measure ignores consequence and is suitable only for hazmat with relatively small danger zones (Abkowitz, Lepofsky, & Cheng, 1992), and thus not appropriate to capture the "low-probability, high-consequence" feature of rail hazmat incidents. The *PE* measure focuses on the number of people potentially threatened by an undesirable consequence (Batta and Chiu 1988; Erkut and Verter 1995), and has been adapted for rail shipments (Verma & Verter, 2007). In this study, we make use of *PE* as the measure of risk and apply the dis-aggregation methodology proposed in the literature (Vaezi and Verma 2017; 2018) to estimate link-level hazmat volume. More recent risk modeling approaches include *value-at-risk* and *conditional value-at-risk* (Hosseini & Verma 2017*;* 2018), and we invite the readers to consult the related works for more details.

B. Risk Management (Mitigation) of Rail Hazmat Shipments

During the past three decades, various industry and academic studies have focused on risk mitigation measures, some of which have been adopted by the railroad industry to reduce the frequency of tank car accidents as well as the likelihood of release in case of an accident. Some studies focused on mitigating hazmat risk through safer tank-car designs (Barkan, Ukkusuri and Waller 2007; Saat and Barkan 2011), while other studies concentrated on the proper placement of hazmat railcars in the train as a way to mitigate risk (Thompson, Zamejc and Ahlbeck 1992; Cheng, Verma and Verter 2017). Moreover, the routing of hazmat railcars as a risk mitigation technique was studied by Glickman (1983), subsequently extended to consider competing perspectives of regulators and railroad companies (Verma 2009; Verma, Verter and Gendreau 2011). Finally, we invite the reader to consult recent risk management techniques proposed in the literature such as emergency response planning (Vaezi, Dalal, & Verma, 2021).

C. Risk-reducing Infrastructure Investment and Hazmat Routing

Infrastructure investment as a measure to mitigate/reduce the risk from rail hazmat shipments has only been briefly alluded to in the hazmat transport domain (Milazzo et al. 2002; der Vlies & Suddle 2008). It is important to recognise that the resulting values/benefits from certain infrastructure investment decisions would depend on interactions among two or more decision-makers, each with its own perspective/objective. In railroad transportation of hazmat, the regulator is usually concerned about transport risk whereas the carrier seeks to minimise routing costs while satisfying the safety requirements set by the regulator (Kara & Verter, 2004); therefore, the presence of a hierarchical (bi-level) setting is conceivable. As a result, a broader literature review revealed two main concepts/theories most relevant to this study:

Cost-Benefit Analysis, which is cited as a general method to assess infrastructure investment projects (Harangozó & Szerényi, 2012). Such analysis entails deciding which items to include as costs and benefits, assigning values to the included items, and arriving at a conclusion to support decision making (Quah & Toh, 2011).

Game Theory, which is used to analyze situations involving more than one decision-maker. A generalised version of a specific problem in game theory (i.e., Stackelberg game) is known as bi-level programming, which is capable of modeling the hierarchical relationship between two decision-makers with potentially conflictual objectives (Colson, Marcotte, & Savard, 2007).

Given the risk associated with hazmat shipments, the government makes use of regulatory policies such as *network design* and *toll setting* for the resulting global routing problems (Bianco et al., 2013). Kara and Verter (2004) introduced the idea of network design for truck hazmat shipments using a bi-level framework, where the government authority (regulator) imposes restrictions on the road network, i.e. closes some transport links to hazmat shipments, and the carriers then choose the routes. On the other hand, toll setting policy as a mechanism to discourage hazmat carriers from using certain road segments was first studied by Marcotte et al*.* (2009) and modeled as a bi-level program. As mentioned earlier, the sparsity of railroads in North America limits the routing options between two points; consequently, imposing restrictions or tolls would not make an effective risk mitigation strategy. However, the availability of new rail-links through appropriate infrastructure investment could motivate the railroad companies to use lower-risk routing options, as long as they are not costlier than the alternative(s). In this paper, we investigate the potential societal benefits (quantified by network-wide hazmat risk reduction) via such investment efforts while recognizing the bi-level nature of interaction among regulator and carrier.

III. Methodology

In this section, we provide the details of our methodology, which is then applied to the Canadian case in Section IV. The methodology, summarised in Fig. 1, consists of 3 steps. *Step 1* identifies the most sensitive spots (hot-spots) in the railroad network by solving a multi-commodity flow model whose solution is first used to compute population exposure risk at every rail-link in the network, and then to rank them. We provide the details in Section III.*A*. For each major hot-spot, *Step 2* identifies a set of new rail-links that could be added to provide alternative routes, and the pertinent details are outlined in Section III.*B*. Finally, for a given budget, *Step 3* incorporates information about the new rail-links and solves another routing problem on an augmented network, the details of which are outlined in Section III.*C*.

As mentioned before, the proposed methodology is inspired by the theory of cost-benefit analysis as well as game theory: The high-level methodology seeks to optimise risk reduction benefit given cost (budget), current situation, and available alternatives; further, the last step of the methodology captures the hierarchical interaction among the regulator's risk-minimizing and the carrier's cost-minimizing objectives. Such an interaction could be represented by a complex bi-level framework where the regulator solves the outer-level problem and the carrier solves the inner-level problem in an iterative manner (See Appendix A). However, for the sake of simplicity and intuition, an equivalent "enumerative" heuristic approach (Žerovnik, 2015) that finds the minimum-risk configuration by comparing *all* feasible alternatives is captured in Fig. 1 (Step 3).

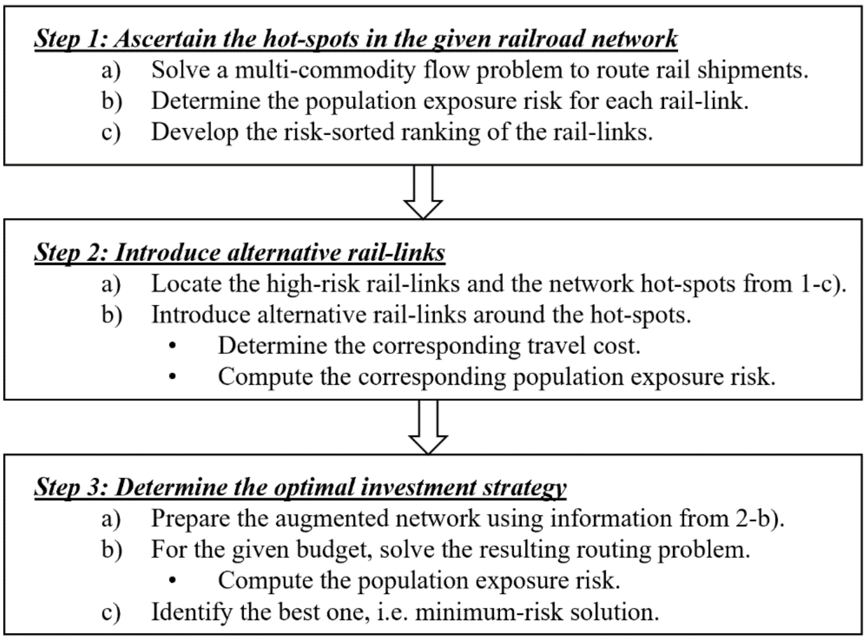

Fig. 1. Flowchart of the proposed investment methodology.

A. Ascertain the Hot-spots

In this subsection, we outline the steps needed to ascertain the hot-spots in the given railroad network. Note that railroad companies seek to minimise cost, which could be modeled as a multicommodity flow routing problem (Ford and Fulkerson 1962; Verma 2009). The details of this optimization program, named **(P1)**, are outlined in Appendix B.

The minimum cost flow solution obtained by solving **(P1)** is then evaluated for hazmat risk in the post-processing stage. In other words, given the shipment route, corresponding population exposure risk is computed using the technique developed in Verma and Verter (2007). More specifically, this would entail three levels of data processing: *first*, for the given number of hazmat railcars at a specific rail-link, a threshold envelope is created in Arc GIS (ESRI, 2016); *second*, the area common to the envelope and the underlying population census data are extracted; and *third*, the number of people in the extracted area would represent the population exposure risk. Once the evaluation is complete, the risk values are sorted so that a ranked list of the rail-links could be developed and the hot-spots could be identified.

B. Introduce Alternative Rail-links

For each hot-spot identified in the previous sub-section, a set of links that could provide alternative routes are proposed and mapped in Arc GIS. It is important to recognise the limitations associated with devising such alternatives and to understand that a given list of alternatives is rarely comprehensive. Next, the appropriate cost and associated risk of using the new links are estimated. For example, consider the rail network depicted in Fig. 2 where nodes *j* and *z* are requesting node *i* to provide hazmat shipments. Note that the existing network (i.e., solid arrows) would send both the shipments through the densely populated area to their respective destinations. However, if it were possible to add alternative rail-tracks such that the densely populated area could be circumvented, then the resulting network risk could be mitigated. Note that the associated insertion locations necessitate a thorough understanding of the current routes so that the post-insertion flow through the candidate is reduced or eliminated. Also, it is assumed that all the stakeholders affected by the building of alternative rail-tracks are on board, and that the regulators would be able to dissuade the railroad companies from using links traversing high-risk areas.

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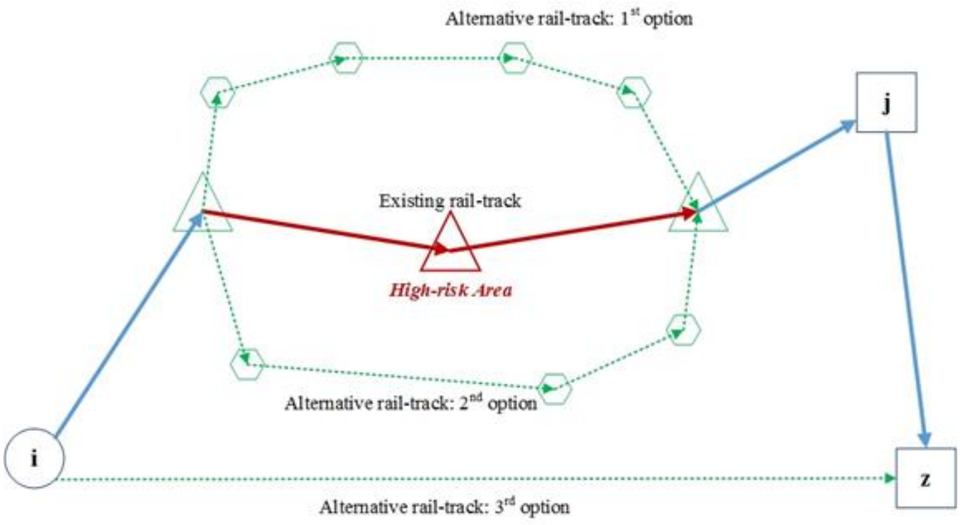

Fig. 2. Schematic of introducing alternative rail-links.

C. Determine the Optimal Investment Strategy

Transport cost and population exposure risk information about the alternative links are made available to the railroad company, which in turn would yield an augmented network for preparing the shipment plan. It should be clear that every time such alternatives are proposed for a candidate hot-spot, the railroad company needs to re-run the route planning model which could result in different routes for some shipments. While this iterative procedure could be analytically modeled in a generic bi-level framework (Appendix A), we stick to the simpler representation shown in Fig. 1. To sum, (1) the regulator starts with evaluating the network-wide risk and identifies the hot-spots, given that the railroad companies seek cost minimization; (2) the regulator identifies alternative rail-links around the hot-spots; and, (3) the regulator anticipates the routing behavior of the railroad companies (i.e. their cost-minimizing objective) in the potentially augmented network, and finds the optimal set of investment decisions that would result in minimum network-wide risk. It should be evident that this last step of the methodology involves solving an optimization problem like **(P1)**, but on an augmented network, where it is also possible to impose penalties to dissuade railroad companies from using high-risk links. We call this second problem **(P2)**. Finally, this step requires some post-processing to evaluate the network-wide risk given the investment budget.

IV. Results and Discussion

In this section, we apply the proposed infrastructure investment methodology to the railroad network in Canada. The resulting network, recreated in ArcGIS (ESRI, 2016), has 464 nodes and 470 arcs (=940 directed arcs). Next, we provide a basic outline about the model parameter estimation, and then analyse the reference case followed by an assessment of increment in infrastructure investment budget.

A. Estimation of Basic Model Parameters

Railcar routing cost was assumed at \$0.50 per train-mile (Ahuja, Goodstein, Mukherjee, Orlin, & Sharma, 2007), whereas the fixed cost to provide a train service is \$500 per hour (Verma, 2009) and includes the hourly rate for a driver, engineer, brakeman, and an engine. The average train speed of 22 miles per hour (Railroad Performance Measures, 2018), and train capacity of 100 railcars was assumed.

We focus on hazmat classes 2, 3, and 8 (i.e., *gases*, *flammable liquids*, and *corrosives*, respectively), which collectively account for 80% of the rail hazmat shipments in Canada (Provencher 2008; Vaezi & Verma 2017). Besides, we assume a bi-weekly shipment plan, since a freight train would need just under seven days to travel between the furthest locations in Canada. For each of the three hazmat classes, origin-destination pairing of shipments is accomplished using the railway carloadings data (Statistics Canada, 2017) and the allocation scheme developed in the literature (Vaezi & Verma, 2017). The analytics methodology maps the actual supply points as origins, and different population centers, production plants, oil refineries, and export terminals as the destinations; for instance, the demand in population centers is determined based on relative population density.

Finally, as alluded earlier, population exposure (*PE*) is used as the measure for hazmat risk. It is pertinent to recognise the limitations associated with this measure, i.e., excluded risk factors such as passenger traffic (Blackwell, 2011). According to *PE*, A population center is exposed if the aggregate concentrate level exceeds the critical level for the hazmat class being shipped (Verma & Verter, 2007). Consider three different trains with H_A, H_B, and H_C hazmat railcars; given a conservative approach, the population exposure risk would be a function of the maximum number of hazmat railcars moving over the given rail-link, i.e., $PE = f\{Max(H_{A,}, H_B, H_C)\}$. For the given number of hazmat railcars, the corresponding threshold distance (and therefore "red" threat zones, i.e. potentially lethal within 60 sec) can be computed using ALOHA software made available by the US Environmental Protection Agency (2016).

B. Solution

(P1) was solved in CPLEX 12.6.2.0 (IBM, 2020) using the 2016 country-wide aggregate hazmat volume information about the three classes in question. For visual prominence, the resulting solution is mapped on the railroad network in Canada in Fig. 3 and underlines the dominance of hazmat class 3 traffic. In an effort to more explicitly discuss the detailed output, we focus on the province of Ontario (Fig. 4). The size of the pie-chart indicates the relative share of hazmat traffic of the three classes in question over the corresponding rail-link. For instance, the circled rail-link connecting Batchewana and Sault Ste. Marie is carrying 87, 175, and 60 hazmat railcars belonging to classes 2, 3, and 8, respectively. In addition, further details about the train-type and consist is available. No unit trains used the specified link. However, freight trains where hazmat railcars were mixed with regular freight and with other classes of hazmat traversed this link, and whose details are indicated in the inset table. For example, a total of ten freight trains, on average, were carrying 4 hazmat class 2 railcars -and 96 cars with regular freight. Note that the detailed information about the train consist enables us to estimate hazmat risk on different rail-links across the network. If a conservative approach is adopted, then the most relevant information would be the maximum number of hazmat railcars in a single train, assuming that contents from all those railcars would be released in an incident. For the specific rail-link, the maximum number of hazmat railcars would be 34, i.e., the mixed train with 9 hazmat class 2 and 25 hazmat class 3 railcars. Simulation in ALOHA resulted in a threshold radius of 1678 meters, which was used to create a layer in ArcGIS and subsequently determine the population exposure risk of the impacted area. Similar train consist information, threshold radii determination, and population exposure risk estimation were done for each of the remaining 939 arcs of the railroad network in Canada. The top high-risk areas in the network are concentrated around the major population centers across Canada, i.e., Vancouver, Calgary-Edmonton, Winnipeg, Toronto, and Montreal. Note that the links leading to each population center correspond to over 70K people.

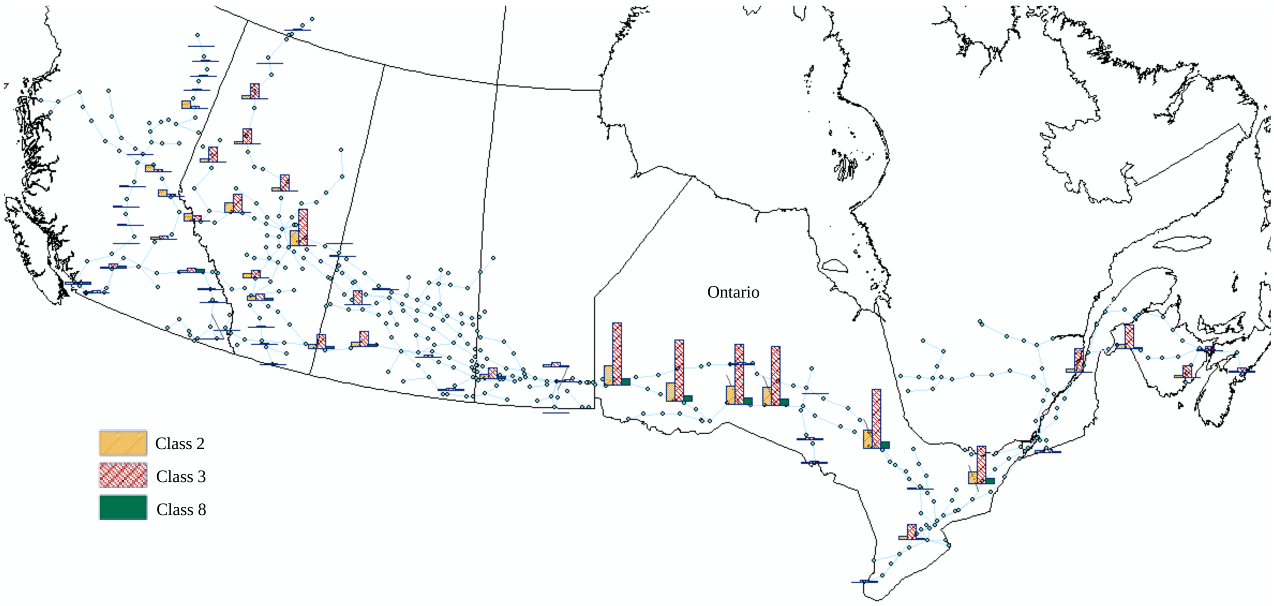

Fig. 3. Traffic distribution of the three hazmat classes over the railroad network in Canada.

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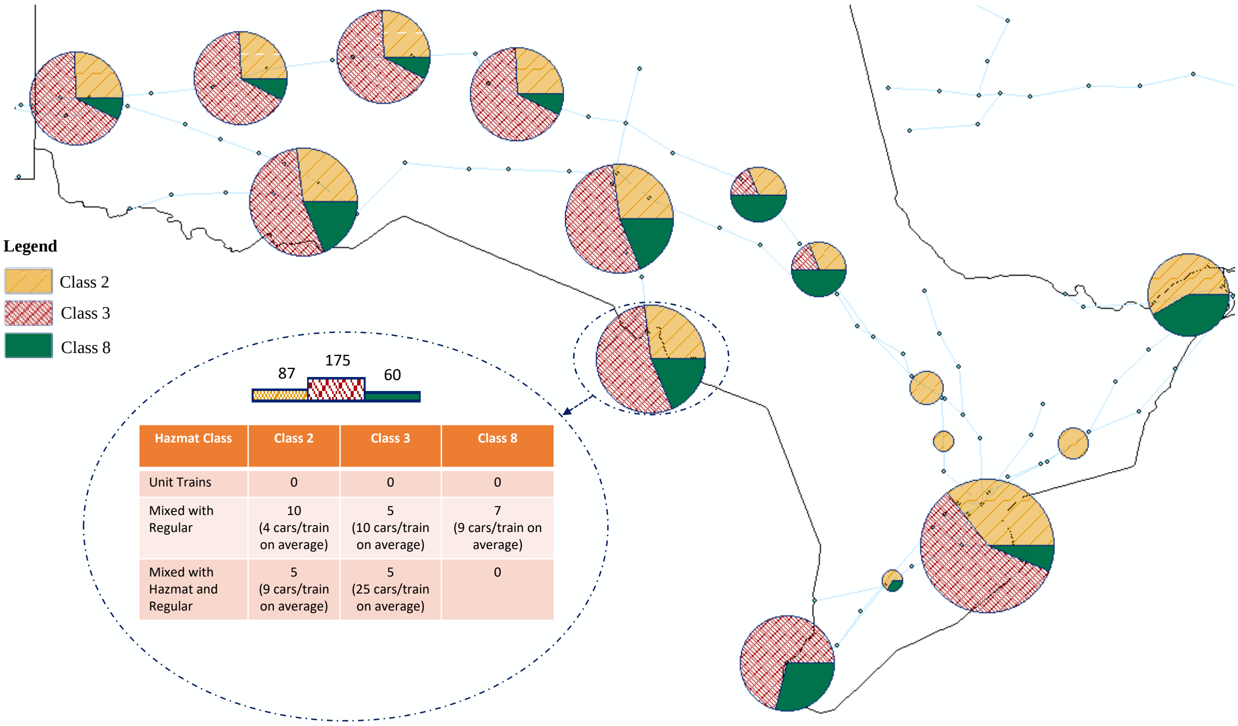

Fig. 4. Traffic distribution of three hazmat classes in the province of Ontario.

To facilitate the discussion about the infrastructure investment strategy, we focus on the top ten riskiest rail-links. Table I depicts the pertinent information about the ten links, all of which are in the provinces of Ontario (ON) and Quebec (QC), and near the two most populous cities in Canada, i.e., Toronto and Montreal. The second last column provides information about the total hazmat traffic on a given link (in terms of railcars) whereas the last column reveals the maximum number of hazmat railcars in a single train, and the latter is used to determine the population exposure risk in the third last column.

Given that the top ten high-risk links are all near Toronto or Montreal, alternative rail-tracks could be built around these two hot-spots to hopefully take traffic away from the adjacent high-risk links. For expositional reasons, we propose only ten alternative rail-links (e.g. six around Toronto as shown in Fig. 5); we demonstrate the investment methodology using only these ten alternative rail-links, and note that similar analyses can be conducted using any number of rail-links. We also assume that the available budget is enough to build only two new rail-links. Note that selecting two from the ten candidate rail-links implies evaluating $\binom{10}{2} = 45$ distinct investment strategies. However, before evaluating each solution to determine the optimal investment option, we briefly comment on how alternative links are conceived (selected) around a hot-spot.

Table I. Top ten high-risk links in the Canadian railroad network

Link		Province	Population Exposure Risk	Total hazmat traffic	Maximum hazmat railcars
Number	Name				
449	Toronto-Guelph Junction	ON	407,245	1,758	100
226	Toronto-Oshawa		394,716	4,491	
215	Toronto-Beaverton		393,504	6,757	
236	Montreal-Glen Robertson		387,298	182	23
456	Toronto-Scarborough		321,261	84	25
217	Toronto-Mississauga		315,639	1,185	57
466	Les Coteaux-Saint Luc	QC	301,941	4,353	100
465	Montreal-Saint Luc		189,487	3,643	
448	Toronto-Alliston	ON	177,579	12	4
255	Montreal-Drummondville	QC	162,087	2,941	100

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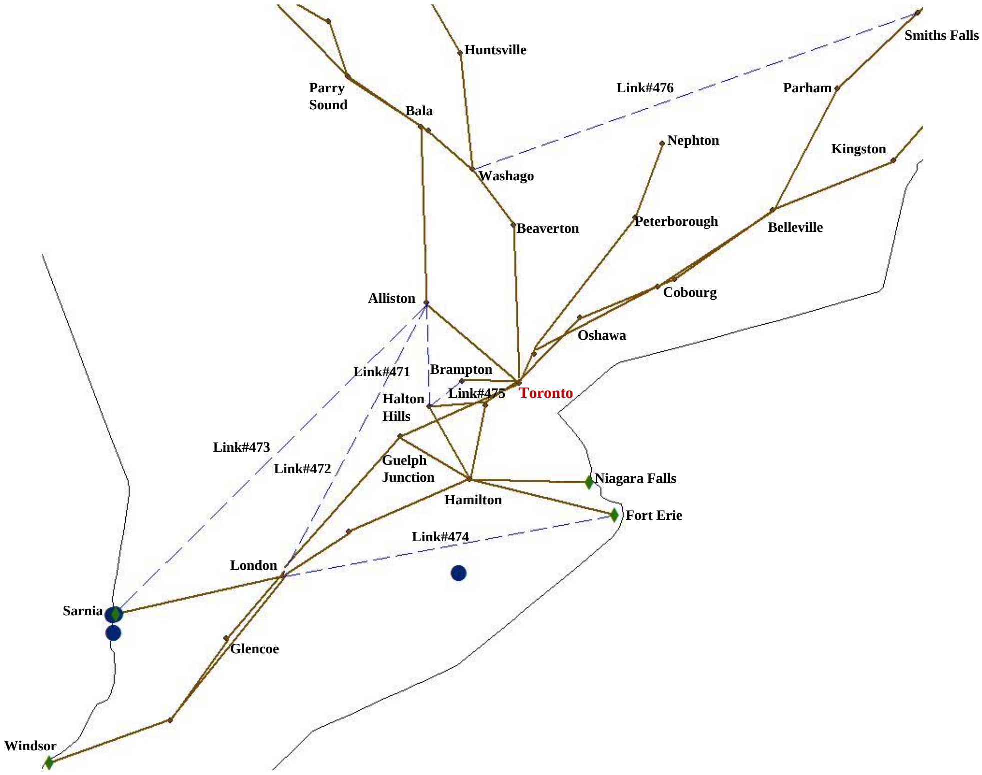


Fig. 5. Existing and proposed alternative rail-links around Toronto.

For a given hot-spot, alternative rail-links are selected taking into consideration the current volume and direction of traffic. We acknowledge the limitations associated with devising such alternatives, e.g. infrastructure design, engineering, etc. and focus on illustrating our methodology. A closer examination of the rail traffic through Toronto yard revealed that most of the class 3 traffic (mostly crude oil) is transiting it for either the refineries in Quebec to the east or the export terminals to the south-west. Hence, it can be argued that partially or completely bypassing the Toronto yard could likely mitigate hazmat risk. Consequently, we made use of ArcGIS to identify ten alternative rail-links, six of which are around Toronto and four around Montreal. For expositional reasons and to facilitate discussions to follow, we reproduce the mapped information from ArcGIS for Toronto and note that similar mapping was done for Montreal (not shown). Fig. 5 depicts the existing rail infrastructure around the city of Toronto, where the solid line represents the existing rail-links and the dashed line indicates the potential rail-link investment options. A total of six alternative rail-links have been identified, and they are: Alliston-Halton Hills (link#471); Alliston-London (link#472); Alliston-Sarnia (link#473); London-Fort Erie (link#474); Brampton-Halton Hills (link#475); and, Washago-Smith Falls (link#476). It should be evident from Fig. 5 that these links would take away traffic using Toronto as a transshipment point, hopefully providing less risky routes for those shipments. It is pertinent that we have simplified the representation of the alternative links as straight-lines without incorporating possible engineering design challenges, and have assumed that all the stakeholders are committed to risk reduction. A similar logic was applied to identify the location of four alternative links around the city of Montreal, and they are: Cornwall-Cantic (link#477); Les Coteaux-St Jean (#478); Cantic-Drummondville (link#479); and, Curry Hill-Joliette (link#480).

Then, **(P2)** was solved over the augmented network given each combination of two links (i.e. complete enumeration approach), followed by hazmat risk evaluation for each case in the post-processing stage. This way, we were able to capture the carrier's cost-minimising and the regulator's risk-minimising objectives, respectively. Table II provides a snapshot of the resulting solutions, and the setting when no infrastructure investment is made. The 1st column indicates the alternative links where investment was made, while the 2nd column denotes the routing cost on the augmented railroad network. The next two columns, respectively, depict the population exposure risk across the railroad network in Canada and at the top-ten high-risk links identified in Table I. Finally, for the given infrastructure investment decision, the last two columns indicate the percentage hazmat risk reduction. It is noteworthy that the top-ten high-risk links account for at least one-half of the hazmat risk in each setting, and around 57% across all of them. In other words, the remaining arcs are accounting for less than one-half of the risk across the Canadian railroad network, and thus the decision to focus only on the top-ten rail-links is not unreasonable.

Table II. Snapshot of the forty-five combinations and the current situation

Alternative Links	Routing Cost ($)	Population exposure risk		Risk reduction (%)	
		Network	Top-ten links	Network	Top-ten links
Current	12,211,674	5,541,025	3,050,757	Not applicable	
471-472	13,432,750	4,617,761	2,548,394	16.66	16.47
471-473	13,430,950	4,417,548	2,548,909	20.28	16.45
471-474	13,460,690	4,422,887	2,548,910	20.18	16.45
471-475	13,460,690	4,422,887	2,548,910	20.18	16.45
471-476	12,886,240	4,279,133	2,360,962	22.77	22.61
471-477	12,736,840	4,315,222	2,421,035	22.12	20.64
471-478	*12,718,260*	*4,115,167*	*2,319,929*	*25.73*	*23.96*
471-479	13,459,990	4,452,631	2,548,919	19.64	16.45
471-480	12,960,540	4,653,656	2,501,514	16.01	18.00
472-473	13,511,490	4,683,050	2,704,101	15.48	11.36
472-474	13,519,990	4,719,074	2,704,102	14.83	11.36
472-475	13,520,650	4,659,468	2,704,102	15.91	11.36
472-476	13,055,590	4,515,717	2,516,157	18.50	17.52
472-477	12,796,800	4,551,803	2,576,227	17.85	15.55
472-478	12,778,220	4,351,748	2,479,561	21.46	18.72
472-479	13,519,950	4,689,212	2,704,111	15.37	11.36
472-480	13,020,500	4,890,237	2,651,161	11.74	13.10
473-474	13,563,090	4,641,341	2,740,029	16.24	10.19
473-475	13,563,090	4,641,341	2,740,029	16.24	10.19
473-476	12,996,010	4,484,636	2,552,089	19.06	16.35
473-477	12,839,240	4,533,676	2,612,154	18.18	14.38
473-478	12,820,660	4,333,621	2,515,488	21.79	17.55
473-479	13,562,390	4,671,085	2,740,038	15.70	10.18
473-480	13,062,940	4,872,110	2,687,088	12.07	11.92
474-475	13,706,090	4,671,339	2,772,852	15.70	9.11
474-476	13,145,480	4,611,184	2,665,058	16.78	12.64
474-477	12,982,240	4,563,674	2,644,977	17.64	13.30
474-478	12,963,660	4,363,619	2,548,311	21.25	16.47
474-479	13,705,390	4,701,083	2,772,861	15.16	9.11
474-480	13,205,840	4,740,555	2,719,911	14.45	10.84
475-476	13,145,480	4,611,184	2,665,058	16.78	12.64
475-477	12,982,240	4,563,674	2,644,977	17.64	13.30
475-478	12,963,660	4,363,619	2,548,311	21.25	16.47
475-479	13,705,390	4,701,083	2,772,861	15.16	9.11
475-480	13,205,840	4,902,108	2,719,911	11.53	10.84
476-477	12,825,380	4,505,753	2,537,183	18.68	16.83
476-478	12,402,950	4,303,464	2,440,517	22.33	20.00
476-479	13,144,780	4,640,928	2,665,067	16.24	12.64
476-480	12,905,460	4,842,659	2,615,671	12.60	14.26
477-478	12,956,410	4,390,233	2,548,311	20.77	16.47
477-479	12,939,430	4,327,594	2,580,107	21.90	15.43
477-480	12,946,730	4,794,799	2,615,566	13.47	14.27
478-479	12,962,960	4,393,362	2,548,320	20.71	16.47
478-480	12,939,950	4,611,594	2,521,668	16.77	17.34
479-480	13,205,240	4,931,851	2,719,919	10.99	10.84

The optimum investment strategy calls for building the rail-link from Alliston to Halton Hills (link#471) near Toronto, and from Les Coteaux to St Jean (link#478) near Montreal. Doing so not only yields the maximum risk reduction in the network at 25.73%, it would also reduce the hazmat risk at the top-ten links by around 24%. Interestingly, the optimum investment strategy does not result in a prohibitively high routing cost, since the latter goes up by just 4.15% over the current routing cost.

Impact of the optimum investment strategy: Given the optimum investment strategy of constructing links 471 and 478, the risk ranking of the top-ten rail-links changes (Table III). Though five of the ten links are common (i.e., *italicised*) with the initial ranking, their attributes are different. For instance, hazmat risk around link#456 increased by 100K thereby making it the riskiest link in the augmented network. Of the five-links common to Tables I and III, hazmat risk has increased in two of them, decreased in one, and remained relatively constant in the remaining two that are around Montreal. Also, there are five new entrants to the list, one of which is connected to the populous west-coast city of Vancouver in the province of British Columbia (BC).

Table III. Top ten high-risk links following optimum investments in link#471 and link#478

Link		Province	Population Exposure Risk	Total hazmat traffic	Maximum hazmat railcars
Number	**Name**				
456	*Toronto-Scarborough*	ON	423,430	4,544	100
448	*Toronto-Alliston*		388,463	4,830	
236	*Montreal-Glen Robertson*	QC	387,203	182	23
226	*Toronto-Oshawa*	ON	229,149	31	7
469	Montreal-Saint Jean sur Ric	QC	189,809	3,706	100
459	Scarborough-Port Hope	ON	169,833	4,544	
255	*Montreal-Drummondville*	QC	162,111	2,941	
467	Saint Luc-Delson		124,799	363	21
37	Vancouver-Matsqui	BC	124,786	29	24
471	Alliston-Halton Hills	ON	120,346	2,943	100

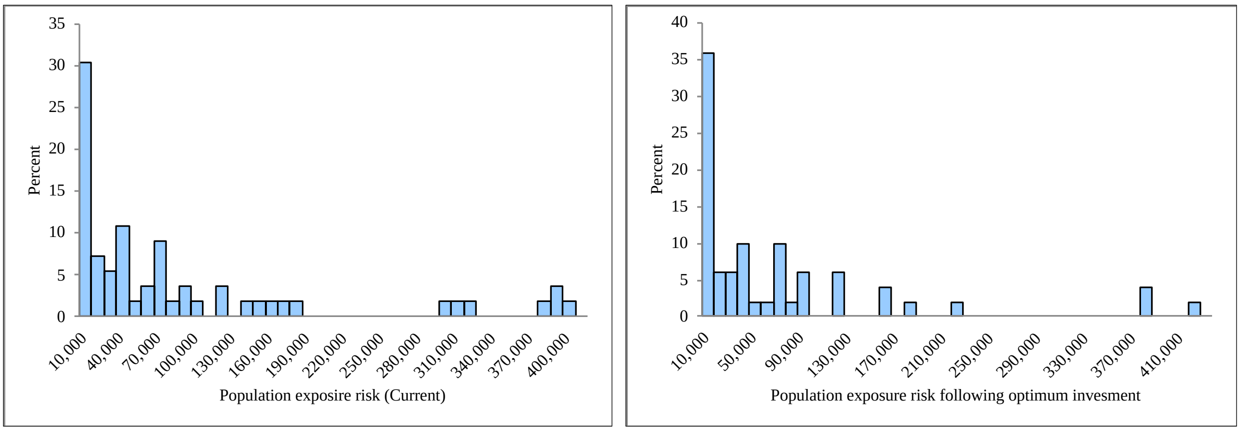
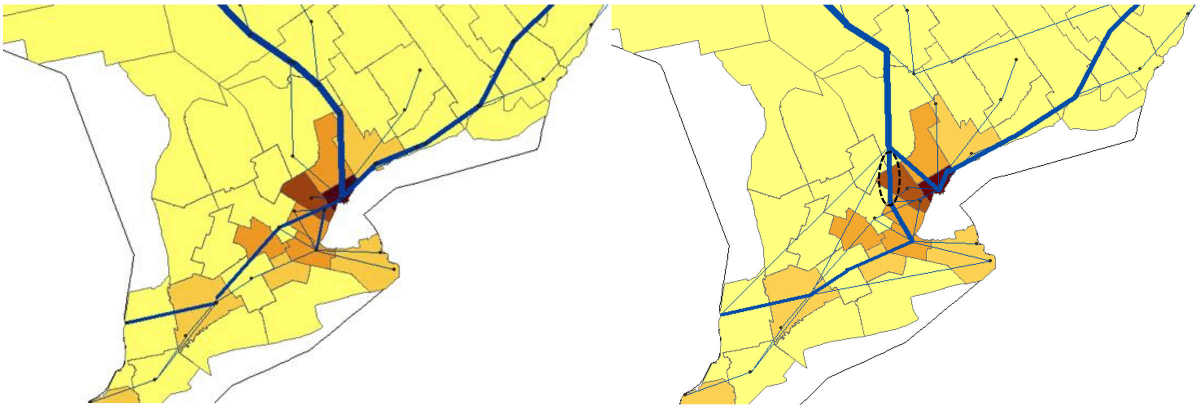


Fig. 6. Risk distribution Current v/s Post optimum investment.

The relevant experiments enable us to make three observations. *First*, if the total number of hazmat railcars is a surrogate measure for risk, then the new highest risk link does experience a dramatic increase in the number of hazmat railcars, i.e., from 84 to 4,544. It is important that, even against this sharp increase, the total number of hazmat railcars using the top-ten links has decreased by 5%, i.e., from 25,406 to 24,113. *Second*, if the maximum number of hazmat railcars in a train is used as the measure of population exposure risk, then for the five-common links, it has increased in two, decreased in one, and remained the same in two. This is because the chosen risk measure ignores the frequency of trains over the rail-links. *Third*, optimum investment not only resulted in six fewer links exposing more than 10K people (i.e., from 56 to 50), it also led to a risk redistribution with a reduced number of links exposed to higher values of hazmat risk (Fig. 6).

In closing, we make use of ArcGIS map depicting hazmat class 3 traffic around Toronto both before and after the optimum infrastructure investment decision (Fig. 7). It is clear that the introduction of the alternative link from Alliston to Halton Hills (link#471), which is circled in (b), is forcing a significant portion of the traffic coming from the western provinces away from the Toronto yard. It is evident from the thickness of the edges that most of the traffic destined for the export terminals or refineries to the south-west of Toronto are using the alternative rail-link, and even the east-bound shipments are using other available rail-links. It should be evident that the redistribution of population exposure hazmat risk behaves similarly following the optimum investment.



(a) Current state *(b) Augmented network*

Fig. 7. Redistribution of class 3 traffic around Toronto following the optimum investment.

C. Impact of increment in budget

In this subsection, we conduct an incremental analysis to estimate the impact of any increment in the infrastructure investment budget on hazmat risk reduction. This analysis builds on the optimum investment decision of Section IV.*B* and considers the impact of a unit increment at a time. For example, if one additional unit of budget is available, then one could construct three alternative rail-links but two of those links are given as a result of the optimum investment decision of the previous subsection. Thus, we conduct an incremental analysis by fixing the optimum decisions arrived at so far, and hence evaluate $\binom{8}{1} = 8$ candidate rail-links. However, given our focus on the ten initially proposed links, this would entail evaluating $\binom{8}{1} + \binom{7}{1} + \binom{6}{1} + \binom{5}{1} + \binom{4}{1} + \binom{3}{1} + \binom{2}{1} + \binom{1}{1} = 36$ problem instances. The last term implies that all ten-candidate rail-links are selected for infrastructure investment.

Fig. 8 depicts the reduction in network-wide hazmat risk as a result of the increment in infrastructure investment budget. As discussed in the previous subsection, the reduction is rather significant (i.e., 25.73%) when the budget is enough to construct two alternative rail-links. If additional budget were made available to build a 3rd alternative rail-link from Washago to Smith Falls (i.e., link#476), the network-wide hazmat risk could be further reduced by 2.6%, for an overall reduction of 28.33%. However, the availability of the 4th alternative rail-link from Alliston to Sarnia (i.e., link#473) brings about just a 0.09% reduction in hazmat risk, which does not improve for higher investment budget. In fact, the risk reduction does not change until the investment budget for seven rail-links, which perhaps indicates that none of the three subsequent investments happen on the links on the shortest routes for the railroad companies. In addition, network-wide risk reduction deteriorates beyond the 7th investment budget, in part because the augmented network might be presenting new shortest routes (from the carrier's perspective) that are not necessarily less risky than the alternative routes (from the regulator's perspective).

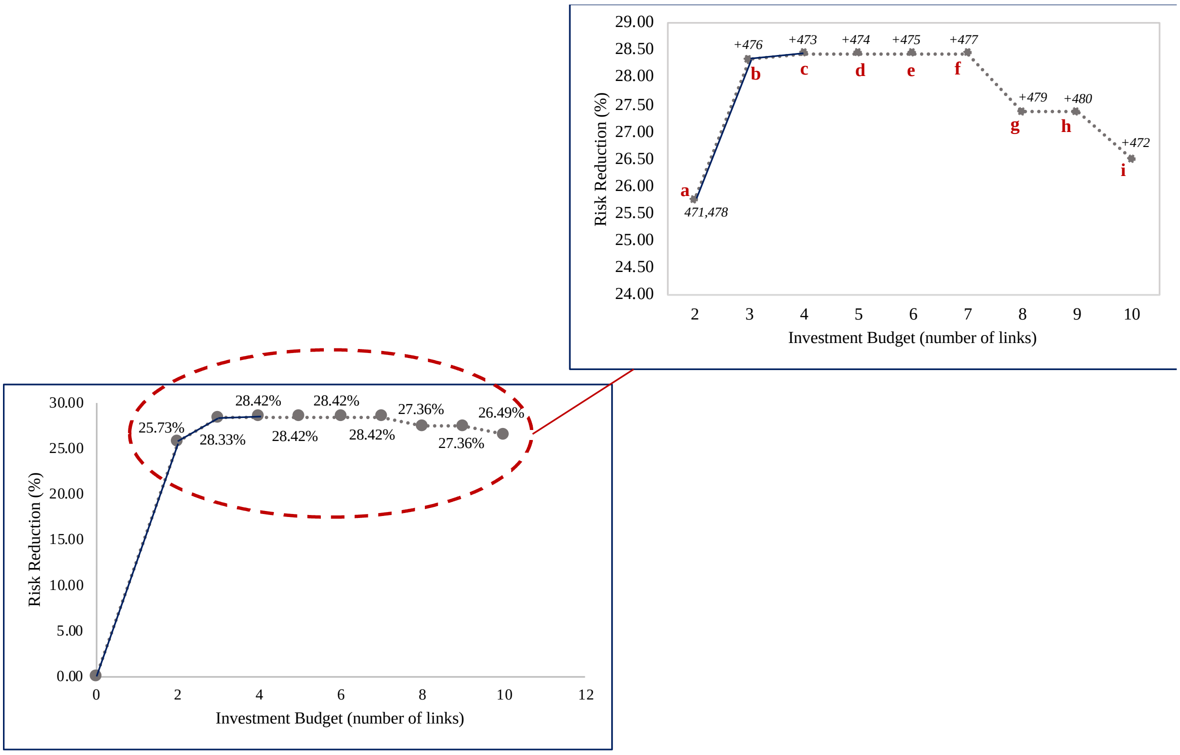


Fig. 8. Increment in investment budget v/s Network risk reduction.

To sum, for the illustrated example, it is possible to conclude that adding more than four alternative rail-links will not result in risk reduction and thus would constitute an injudicious use of scarce resources. Interestingly, the identities of the top-ten high-risk links do not change from Table III for subsequent investment budget increments of three and four, although their ranking in the same pool did. It is pertinent that hazmat risk reduction via the proposed methodology is a function of railroad network density and the population distribution, and hence expected to be different for a different setting.

V. Conclusion

In North America, a significant portion of hazmat shipments is moved via the railroad network. While railroad is one of the safest modes for hazmat transportation, the risk of catastrophic incidents does exist. In this paper, we make the first attempt to explore infrastructure investment as a potential tool to mitigate risk from rail hazmat shipments. The proposed methodology optimises the associated risk reduction benefits capturing the interactions among government authorities (regulators) and railroad companies (carriers), and has three steps: ascertain the hot-spots in the railroad network; identify alternative rail-links to add; and, determine the investment option that maximises network risk reduction.

The computational experiments conducted on the Canadian railroad network enabled us to conclude the following. *First*, hazmat risk reduction is possible by constructing alternative rail-links that could take traffic away from the network hot-spots. *Second*, the risk reduction curve exhibits non-linearity, i.e., risk reduces at a decreasing rate, becomes stable and then starts increasing. *Third*, risk reduction is a function of the densities of the railroad network and the population centers. For the Canadian case, investing in building two alternative rail-links returns a significant risk reduction, and far less for the third link, and almost nothing for the 4^{th}.

The proposed methodology was useful in identifying the best infrastructure investment strategy for the given budget given the interaction between the regulators and the railroad operators. Given the exploratory nature of the study, some assumptions were made that could be relaxed.

We list a number of limitations that need to be recognised in this research. First, while transport infrastructure investment decisions may be analysed based on a variety of factors, such as infrastructure design, track geometry, security aspects, predicted usage and environmental impacts (Quadros & Nassi, 2015), this study was limited to optimizing the risk reduction benefit through alternative rail-links capable of taking hazmat traffic away from the network hot-spots. Second, our risk assessment is based on population exposure (a well-known risk measure in the hazmat transport literature) which does not capture all factors contributing to hazmat risk. Third, the application of our methodology to the Canadian railroad network entails devising alternative rail-links based on network hot-spots and hazmat traffic flow; coming up with these alternatives is obviously associated with certain assumptions/limitations.

The abovementioned limitations can be seen as opportunities to be addressed in future studies. Other possible future research directions could consider the extension of this study to other regions of the world or incorporate risk equity considerations.

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APPENDIX A

A bilevel setting can be considered where the regulator is the leader, i.e., makes decision on risk-reducing infrastructure investment (and other regulations), and the carrier is the follower, i.e., makes routing decisions that minimise system-wide transportation cost in the augmented and regulated network. The regulator can anticipate the carrier's routing behavior in the presence of alternative links to maximise risk reduction. i.e., minimise risk. The corresponding bilevel framework is shown below:

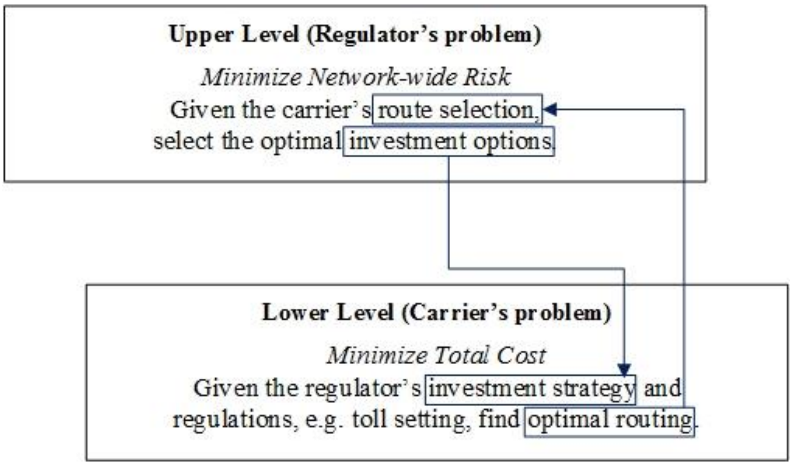

Fig. A1. Bilevel framework where regulator and carrier make decisions.

APPENDIX B

We first indicate the constituent elements, and then develop the mathematical model for the minimum cost multi-commodity flow problem **(P1)**.

Sets and indices

M:	Set of hazmat classes, indexed by *m*;
I:	Set of origin yards, indexed by *i*;
J:	Set of destination yards, indexed by *j*;
L:	Set of train services in the network, indexed by *l*;
P_{ij}:	Set of paths connecting yards *i* and *j*, indexed by *p*;
P_l:	Set of paths using train service *l*;
$(r, s) \in A$:	Set rail-links (arcs) in the network;

Decision Variables

X_{ij}^{pm}:	Number of railcars with hazmat class *m* using path *p* to travel from origin yard *i* to destination yard *j*;
N_l:	Number of trains of type *l* needed in the network;
Q_{rs}^{m}:	Number of railcars with hazmat class *m* moving over rail-link *(r, s)*;

Parameters

C_{ij}^{pm}:	Cost of transporting one railcar with hazmat class *m* on path *p* to travel from origin yard *i* to destination yard *j*
C_l:	Fixed cost to operate train service of type *l*;
U_l:	Capacity of train service of type *l*;
D_{ij}^{m}:	Number of railcars of hazmat class *m* demanded at yard *j* from yard *i*;
δ_{rs}^{p}:	Incidence vector that equals 1 if rail-link *(r, s)* is on path *p*, 0 otherwise.

(P1)

$Minimize$

$$\sum_{m\in M}\sum_{i\in I}\sum_{j\in J}\sum_{p\in P_{ij}} C_{ij}^{pm}\, X_{ij}^{pm} + \sum_{l\in L} C_l\, N_l \qquad (1)$$

$Subject\ to$:

$$\sum_{p\in P_{ij}} X_{ij}^{pm} = D_{ij}^{m} \qquad \forall i\in I, \forall j\in J, \forall m\in M \qquad (2)$$

$$\sum_{m\in M}\sum_{i\in I}\sum_{j\in J}\sum_{p\in P_{ij}} X_{ij}^{pm} \le U_l N_l \qquad \forall l\in L \qquad (3)$$

$$Q_{rs}^{m} = \sum_{i\in I}\sum_{j\in J}\sum_{p\in P_{ij}} \delta_{rs}^{p} X_{ij}^{pm} \qquad \forall (r,s)\in A, \forall m\in M \qquad (4)$$

$$X_{ij}^{pm} \ge 0\ integer \qquad \forall i\in I, \forall j\in J, \forall m\in M, \forall p\in P \qquad (5)$$

$$N_l \ge 0\ integer \qquad \forall l\in L \qquad (6)$$

$$Q_{rs}^{m} \ge 0\ integer \qquad \forall (r,s)\in A, \forall m\in M \qquad (7)$$

(P1) is a tactical planning model appropriate to determine the routes for rail shipments, where (1) computes the variable cost of routing railcars and the fixed cost to provide different types of train services. Equation set (2) ensures demand fulfillment, whereas (3) states that the number of trains of different types is determined by the total number of railcars using that specific train service. Constraint set (4) enables determining the arcs that are a part of different paths, and in turn facilitates estimating hazmat risk on different rail-links. Finally, (5) to (7) indicate sign and integrality restrictions on the variables.