Emergency response planning for railroad accidents involving dangerous goods in Canada

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Abstract
In this paper, we propose a model for strategic and tactical emergency response to railroad accidents involving hazardous materials. We solve this model over the Canadian railroad network, and provide recommendations on where to locate response facilities and how they are going to respond to hazardous materials emergencies.

Keywords: Hazardous materials, Emergency Response, Railroad transportation

INTRODUCTION

Hazardous materials (hazmat) or dangerous goods (DG) are fundamental part of industrial societies. Locations where such materials are consumed are mostly different from their production sites, and they have to be transported possibly over long distances. Transport Canada classifies dangerous goods into 9 classes: explosives, gases, flammable liquids, flammable solids, oxidizing substances, poisonous and infectious substances, radioactive materials, corrosives, and miscellaneous substances such as dangerous wastes (Government of Canada 2014).

Being one of the safest modes, rail transportation is a growing mode for movement of hazardous materials in significant volumes (Verma et al. 2011), and a preferred mode over road for long-distance hazmat movements (Bagheri et al. 2014). According to Railway Association of Canada (2015), chemical and petroleum products, represent 12% of all rail traffic moved in Canada. Furthermore, analysis of the data provided by Statistics Canada shows that hazardous materials represent about 20% of the rail traffic in Canada. In terms of safety, statistics show a good record for rail; for instance, from 2000 till 2012 there have been only 3 deaths associated with rail accidents, as compared to 97 deaths associated with road accidents (Statistics Canada 2015). However, risk of low-probability, high-consequence events, such as those associated with multiple tank car derailment and significant hazmat release, still exists (Verma et al. 2011). The most well-known event of this type during the last few years is the Lac-Mégantic train disaster on July 6, 2013, with the death toll of 47 due to train crash and subsequent explosions. These sorts of risks can be managed and mitigated by means of preventive and/or protective measures to reduce probabilities and/or consequences of such events. In this paper, emergency response is considered as a protective measure to reduce accident harmful consequences imposed on people and the environment.

Gases, flammable liquids, and corrosives are the three classes that roughly account for 80% of hazmat railroad shipments with known DG class in Canada (Provencher 2008). Furthermore, according to Transport Canada (2013), they make up about 80% of hazmat emergencies in 2013. Thus, we study hazmat rail transport in Canadian context based on these three hazmat classes.

Fast response is crucial in keeping the accident damages relatively low. Although first responders are able to reduce damages associated with hazmat accidents, specialized response teams and equipment are required to effectively respond to such emergencies. For example, Railway Association of Canada (2015) has special response teams from railroad companies who work with chemical industry and local public security agencies to mitigate risks in case of emergencies. According to Transport Canada (2012), in hazardous materials accidents, first the material name or the associated identity number should be identified. Then, first responders are advised to call the emergency response telephone number, which is usually listed on the shipping papers.

A potential incident site can be covered if it can be reached from one of the emergency response stations within a specified time. This "critical" time might vary depending on the type of commodity or accident. Since resources are limited, a network is often partially covered; we need to prioritize sites that are more important. Berman et al. (2007) consider the population exposure as the measure of transport risk in the road transportation domain and suggest that links with higher risk should be prioritized. They do this prioritization through assigning higher weights to those arcs with higher number of people within a threshold distance of a road link multiplied by the number of hazmat trucks shipped across that link. Depending on the way one defines risk, demand links would be prioritized and parts of the network would be covered.

In this paper, we are interested in locating facilities with adequate specialized equipment packages so that hazmat rail transport emergencies can be responded efficiently and effectively. Therefore, in the strategic level, we deal with facility location, and in the tactical level, we deal with resource allocation. In the following section, we briefly review the related literature. In the subsequent sections, we state the problem, propose our mathematical model, and provide computational results from the model application to a simplified Canadian railroad network.

LITERATURE REVIEW

Here, we deal with facility location and resource allocation in the strategic and tactical levels, respectively. Toregas et al. (1971) propose a set covering problem to locate emergency service facilities. This view is based on the idea that each potential demand point in the area of interest must be reached from its allocated emergency response facility within a specified time in case of emergency. Given a specified coverage distance, set covering problem minimizes the number of facilities or an equivalent budget required to cover every demand over the network. On the other hand, maximal covering location problem (Church and Velle, 1974) aims at covering as many demand points as possible within a predetermined critical distance or time given a finite budget or a finite number of facilities.

As stated by Berman et al. (2007), in transportation of hazardous materials, emergency response should cover a set of arcs that makes the transport network rather than a set of points. They introduce a mixed-integer nonlinear formulation for the maximal arc-covering problem, which involves locating a finite number of facilities so as to maximize the total weighted arc length covered.

Verma et al. (2013) study the problem of location and capability of oil-spill response facilities for the south coast of Newfoundland. They define the south coast of Newfoundland as the area of interest, and divide it into five zones, where each zone is a likely location for oil spill, profile of which can be determined by oil type, weather conditions, and volume spilled. Emergency response to such spill is required within a predetermined critical time in order to be able to effectively mitigate the associated environmental risks. The authors define the problem using a two-stage stochastic programming model, where facility location and equipment acquisition decisions are made in the first stage, and equipment dispatching decisions are made in the second stage.

MATHEMATICAL MODEL

Specialized response teams and equipment are required to effectively respond to hazardous materials emergencies before the consequences escalate and result in substantial damages. We propose an optimization program which deals with both strategic and tactical aspects of emergency response to hazardous materials accidents on railroads. More specifically, we try to answer these questions: where to locate emergency response facilities; what types of equipment to stockpile at each facility; and how they are going to be assigned and dispatched in response to hazmat accidents. In such a problem, some factors or parameters are deterministic and some are stochastic. For example, fixed costs related to construction of emergency response facilities as well as estimates of scenario-specific release volumes and associated damages are deterministic factors. On the other hand, exact location, volume and type of hazmat release are stochastic factors.

For a given commodity type and location, we ignore the influence of weather conditions and define the profile of a hazmat accident only based on the volume of hazmat involved in the accident. Because of the uncertain nature of location, commodity, and profile of accidents, we use two-stage stochastic programming with recourse. Such technique is cited as a general-purpose technique to deal with uncertainty in model parameters. In our model, first stage is related to strategic decisions i.e. facility location and equipment acquisition, and the second stage is related to tactical/operational ones i.e. dispatching decisions. The two stages can be combined into a single optimization problem. We use the following notations:

I: set of candidate facility sites, indexed by i;
A: set of arcs or links in the railroad network, indexed by a;
E: set of equipment packages, indexed by e;
P: set of possible hazmat accident profiles, indexed by p;
M: set of hazmat commodities (gases, flammable liquids, and corrosives), indexed by m;
F_i: fixed cost to open an emergency response facility at site i;
B_i^{em}: buying or acquisition cost of an equipment package type e at site i, suitable to respond to accidents involving commodity type m;
v_{ap}^{m}: volume of hazmat involved in an accident with commodity type m and profile p along arc a;
C^{em}: containment capacity of an equipment package type e in response to hazmat release of commodity type m;
t_{ia}: average travel time for an equipment package to reach from site i to arc a;
T_p^m: critical time to respond to a hazmat accident involving commodity type m with profile p;

$I_{ap}^{m} = \{\mathrm{i} \in \mathrm{I} | t_{ia} < T_{p}^{m}\}$: set of facilities which are able to cover arc a in response to accidents with commodity type m and profile p;
A_{ip}^{m}: set of arcs which can be covered by facility at i in response to accidents with commodity type m and profile p;
EC_{ap}^{m}: environment and population exposure costs resulting from not responding to an accident with commodity type m and profile p along arc a;
OC_{ap}^{em}: cost to operate one unit of equipment package type e for an accident with commodity type m and profile p along arc a;
TC_{ia}^{em}: transport cost to move one unit of equipment package type e from site i to arc a, to respond to accident with commodity type m;
K_i: capacity of facility i in terms of the number of equipment packages;
l_a: length of arc a;
α^m: minimum percentage of required network coverage for accidents involving hazmat commodity m;
f_{ap}^{m}: probability of occurring an accident involving commodity type m with profile p along a;
Y_i= 1 if facility at site i is open, and 0 otherwise;
U_i^{em}: number of equipment packages type e stockpiled at i, suitable to respond to accidents with commodity type m;
N_{iap}^{em}: number of equipment packages type e dispatched from site i to arc a, to respond to a hazmat accident with commodity m and profile p;
Z_{ap}^{m}= 1 if accident with commodity m and profile p along arc a is covered, and 0 otherwise.

The mathematical formulation of our problem is given as follows:

$$\begin{aligned} Minimize \quad & \sum_{i\in I} F_i Y_i + \sum_{i\in I}\sum_{e\in E}\sum_{m\in M} B_i^{em} U_i^{em} \\ & + \sum_{a\in A}\sum_{m\in M}\sum_{p\in P} f_{ap}^{m}\left[EC_{ap}^{m}\left(1 - Z_{ap}^{m}\right) + \sum_{i\in I}\sum_{e\in E}\left(TC_{ia}^{em} + OC_{ap}^{em}\right) N_{iap}^{em}\right] \end{aligned} \tag{1}$$

$$Subject\ to \qquad K_i Y_i - U_i^{em} \geq 0 \qquad \forall i \in I, \forall e \in E, \forall m \in M \tag{2}$$

$$\max_{a\in A_{ip}^{m}} N_{iap}^{em} \leq U_i^{em} \qquad \forall i \in I, \forall e \in E, \forall m \in M, \forall p \in P \tag{3}$$

$$\sum_{i\in I_{ap}^{m}}\sum_{e\in E} C^{em} N_{iap}^{em} \geq v_{ap}^{m} Z_{ap}^{m} \qquad \forall a \in A, \forall m \in M, \forall p \in P \tag{4}$$

$$\sum_{p\in P}\sum_{a\in A} l_a v_{ap}^{m} Z_{ap}^{m} \geq \alpha^m \sum_{p\in P}\sum_{a\in A} l_a v_{ap}^{m} \qquad \forall m \in M \tag{5}$$

$$Y_i \in \{0,1\} \qquad \forall i \in I \tag{6}$$

$$U_i^{em} \geq 0 \ \ integer \qquad \forall i \in I, \forall e \in E, \forall m \in M \tag{7}$$

$$N_{iap}^{em} \geq 0 \quad integer \qquad \forall i \in I, \forall e \in E, \forall a \in A, \forall m \in M, \forall p \in P \tag{8}$$

$$Z_{ap}^{m} \in \{0,1\} \qquad \forall a \in A, \forall m \in M, \forall p \in P \tag{9}$$

This optimization problem minimizes the total costs including those related to strategic facility location and equipment acquisition decisions as well as those related to tactical dispatching decisions.

Constraint set (2) ensures that equipment acquisition is done only in open facilities, and also the number of equipment in open facility i does not exceed the available capacity K_i in that facility. Constraint set (3) ensures that the maximum number of equipment packages of a specific type dispatched from a facility to any covered location with any accident profile, does not exceed the required equipment of the same type and commodity in the facility.

Constraint set (4) ensures that the capacity dispatched to a covered link with given covered commodity type and accident profile is at least equal to the commodity volume involved in the accident. Constraint (5), a policy constraint, ensures at least a predetermined level of volume-weighted response coverage on the entire network for each hazmat commodity type transported over the railroad. All other constraints are related to the decision variables.

As we observe, our optimization model is a nonlinear integer programming problem and can be solved by commercial solvers for not very large systems. However, collecting realistic parameters and then solving the problem over a realistic network are challenging tasks. Regarding the network, we are going to consider the railroad network in Canada. Regarding the parameters, we are going to estimate their values based on public sources and scientific papers.

ASSUMPTIONS AND PROBLEM INSTANCE

In general, one may consider many factors such as weather conditions to determine the hazmat accident profile. However, for simplification, we assume that the hazmat accident profile is mainly determined by the volume involved in the accident. Therefore, for instance exposure cost EC_{ap}^{m} can be interpreted as a commodity-specific measure of risk which puts a higher weight on accidents involving a larger amount of hazmat.

In each open facility, there are different types of equipment to respond to hazmat accidents of different commodity types. Simplifying further, we assume that equipment packages which are suitable to respond to a given commodity type are different only in size; therefore, for example whether conditions would not affect the type of equipment which is going to be used.

Regarding the coverage area -reachable within a critical time-, we assume that in the preprocessing stage, we identify those arcs over the network, which can be completely covered by any of the potential response facilities. In contrast to the model by Berman et al. (2007), in which fractional coverage of arcs is possible, we assume that in our case, an arc (link) is either completely covered, or otherwise counted as uncovered. So, if only parts of a given link are covered, the link is not counted as covered.

The following map shows the railroad network in Canada. Different colors represent various population densities across the country. We will use population density information later in our analysis.

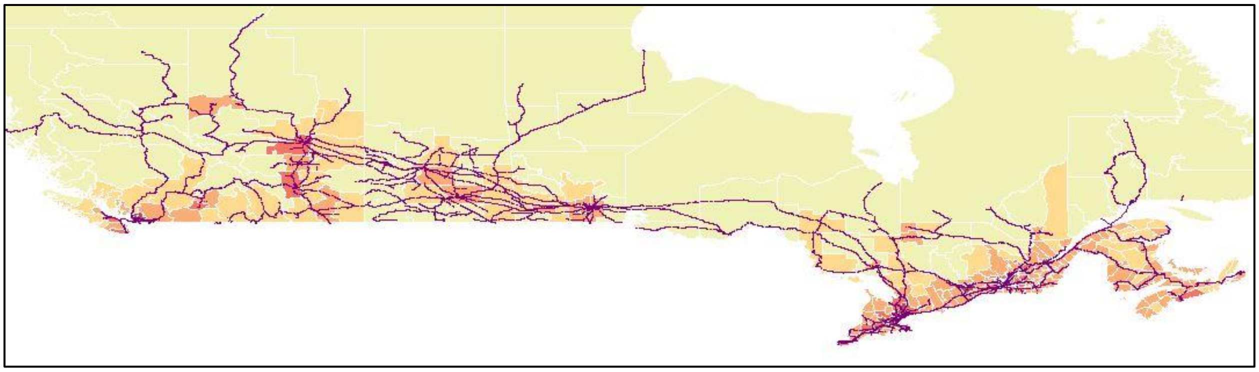

Figure 1 – Railroad network in Canada

The network consists of a large number of nodes and links. To define a problem instance, we need to estimate the following parameters.

- *Fixed costs to open emergency response facilities*: We assume that all nodes can be candidate locations for construction of the response facilities. According to RSMeans cost models, estimated construction cost of a 2-story fire station is somewhere between 1.6 and 2 million CAD across Canada (RSMeans 2015). Based on this estimate, we assume that the fixed cost to build a response facility, supposing that it is similar to a fire station in nature, is around 1.8 million CAD on average.
- *Acquisition costs of equipment packages*: We assume that the acquisition costs do not depend on the facility location. Furthermore, we assume that the commodity index can be neglected. However, they depend on the type of equipment in terms of size (containment capacity). We assume that for each hazmat class, there are equipment packages with two containment capacities. The replacement cost of a pumper engine is roughly 550,000 USD, which is approximately equivalent to 775,000 CAD (Dover Fire Department 2015). We use this number as an estimate for the smaller equipment with containment capacity of 100 tonnes; the containment capacity of larger equipment is assumed to be 200 tonnes, and its replacement cost is assumed to be 1,300,000 CAD. To estimate the latter cost, we used the idea of nonlinear extrapolation by Verma et al. (2013).
- *Probabilities of occurring hazmat accidents*: According to Verma (2011), railroad incident probabilities are of the order 10^{-6}; we use this as a proxy for accident probability along any given rail link. Also, according to Federal Railroad Administration (2015), 1219 railroad accidents happened in the United States in 2014, 180 of which involved cars carrying hazmat that were damaged; therefore, we assume that approximately 15% of the accidents involve damaged railcars which carry hazmat. We use the following conditional probability formula to calculate probability of occurring hazmat accidents along railroad:

$$P(Hazmat\ Accident) = P(Hazmat\ Accident \mid Accident) \times P(Accident) \quad (10)$$

  Thus, the probability of occurring hazmat accidents with damaged railcars is of order 10^{-7}. We will solve our model assuming three values (10^{-7}, 5×10^{-7}, and 9×10^{-7}) for probabilities which we assume are not dependent on hazmat commodity and profile due to simplification. However, we choose the right value on a provincial basis according to the number of emergencies in 2013 as reported by Transport Canada (2015). As a result, rail links located in Ontario and Quebec have the higher hazmat accident probability, i.e. 9×10^{-7}, those located in British Columbia, Alberta, Manitoba and Saskatchewan have the medium probability, and those located in other provinces or territories have the lower probability.

- *Environment and population exposure costs resulting from not responding to accidents*: It is a challenging task to estimate such costs since they include both direct and indirect costs each of which involves considerable complexities to calculate. Therefore, for each commodity and profile, we consider several scenarios and solve the problem in a way to meet effective response for each one of them. Regarding the location or arc index, a magnifying factor is applied to estimate exposure costs in more populated areas.

  Exposure costs depend on hazmat commodity type. Studying how different hazardous materials classes affect exposure costs is out of scope of this paper. Therefore, in order to distinguish between three classes of hazmat, we assign approximate factors to them according to the their evacuation distance in case of fire, recommended in CANUTEC ERGO 2012 by Transport Canada (2012). Table 1 shows how these factors are assigned to the hazmat classes:

Table 1 – Factors assigned to hazmat classes

Hazmat class	**Significant commodity**	**Evacuation distance (meters)**	**Assigned factor**
Flammable liquids	Crude oil	800	1
Gases	Hydrocarbon gas	1600	2
Corrosives	Sulphuric acid	800	1

  To clarify further, we have chosen a significant commodity in each hazmat class as a representative of the class according to the rail traffic data available through Statistics Canada. Then, we have assigned factors to them based on the evacuation distance recommended by Transport Canada.

  Exposure costs also depend on accident profile. We assume a direct relationship between hazmat release volume and corresponding exposure costs. A DOT-111 tank car has a maximum capacity of 34,500 US gallons, which is equivalent to 110 tonnes of crude oil. We assume that there are two accident profiles; a less severe one is related to hazmat release equivalent to 10 tank car or 1100 tonnes, and a more severe one is related to hazmat release equivalent to 40 tank car or 4400 tonnes. We consider these two profiles for all three hazmat classes studied.

  Finally, exposure costs depend on the location of rail links. A magnifying factor of 2 is applied to exposure costs happening along rail links with population density greater than 250/km^2.

  Since Lac-Mégantic is considered as the deadliest rail accident in Canada during the last few decades, it can be taken as the worst case scenario for accidents involving flammable liquids class releasing large volumes which hence correspond to more severe profile. Settlement fund for victims of the Lac-Mégantic train derailment was $446 million CAD (CBC News 2015). The settlement fund can be interpreted as a part of total exposure cost. To emphasize and put a higher weight on the population exposure component compared to environment exposure component, we assume that the total exposure cost is $500 million. Given this base number, we then generate exposure costs for different commodities, profiles and locations according to the following table:

Table 2 – Estimated exposure costs

Hazmat class	Profile	Population density	Exposure costs (million CAD)
Flammable liquids	Less severe	Less than 250/km^2	$62.5
		More than 250/km^2	$125
	More severe	Less than 250/km^2	$250
		More than 250/km^2	**$500**
Gases	Less severe	Less than 250/km^2	$125
		More than 250/km^2	$250
	More severe	Less than 250/km^2	$500
		More than 250/km^2	$1000
Corrosives	Less severe	Less than 250/km^2	$62.5
		More than 250/km^2	$125
	More severe	Less than 250/km^2	$250
		More than 250/km^2	$500

- *Transport cost of equipment packages*: According to Davis et al. (2015), a less heavy fire engine has a typical gross weight between 26,000 and 33,000 lbs. and a typical fuel consumption equal to 18.2 gallons per thousand ton-miles. This is equivalent to fuel consumption between 55.7 liter per 100 km and 70.6 liter per 100 km. We take the average value of 63.15 Liters/100km as a proxy for fuel consumption rate of the smaller equipment package. Similarly, an average value of 62.05 Liters/100km is derived as a proxy for fuel consumption of the larger equipment package. For simplification and since the fuel consumption rates are quite close, we assume an average value of 62.6 Liters/100km for any equipment vehicle.
  We assume that the transportation costs are independent of the hazmat commodity type. Let's assume that the transportation cost is mainly due to fuel consumption; then such cost would depend on how far an equipment package should travel from its base facility to reach the accident scene. Let's take fuel price of $1 CAD per liter. We analyze travel distances in ArcGIS and calculate transportation costs for each facility-link pair.
- *Operating cost of equipment packages*: For the sake of simplicity, we assume that operating costs are independent of the type of hazmat commodity, accident profile, or accident location. They do depend however, on the equipment type in terms of size; we use daily operating costs of oil-spill equipment packages as estimated by Verma et al. (2013); this approximately results in an operating cost of $55,000 CAD for the equipment with smaller capacity, and an operating cost of $67,000 CAD for the equipment with larger capacity.
- *Capacities of response facilities*: We assume that each response facility has the capacity to accommodate up to 20 equipment packages.

- *Scenarios for hazmat volume involved in accidents*: Factors deemed important to estimate exposure costs are also important for generating railroad hazmat accident scenarios. We solve our problem given a number of scenarios. Generation of more scenarios is subject to availability of corresponding estimated parameters.

Finally, we assume that the minimum required coverage of the network for each hazmat class is equal to 80%. We assume that the abovementioned parameters form our “base case” problem.

COMPUTATIONAL RESULTS AND DISCUSSIONS

We create a simplified version of rail network in Canada with 22 nodes and 23 arcs, as numbered in Figure 2. Numbers along arcs in the following network specify lengths of the arcs. We assume a critical distance of 1000 km within which the critical time criteria is satisfied. This distance is used to identify potential facilities capable of covering completely a given rail link in the network. For the sake of simplicity, it is assumed that there is a shortest path form each facility to a rail link.

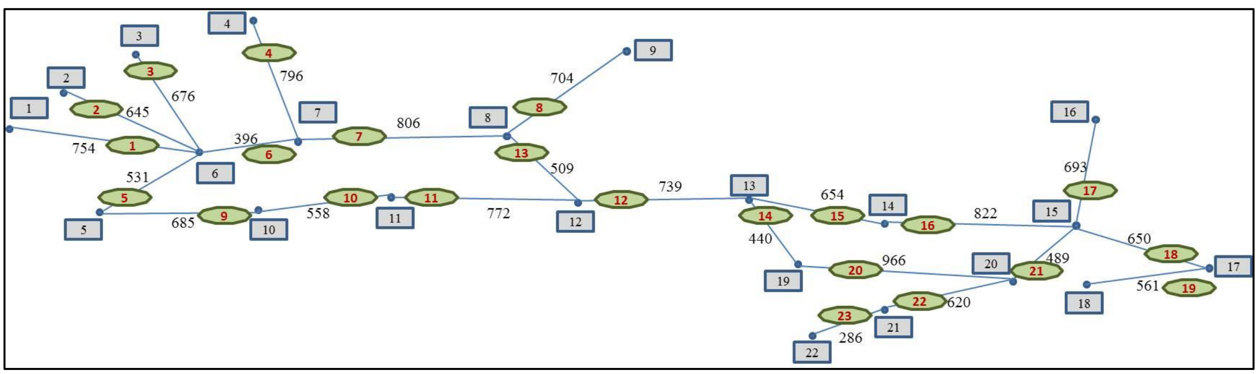

Figure 2 – Simplified railroad network in Canada

CPLEX 12.6.2 was used to solve the problem. Computational results suggest locating three emergency response facilities at nodes 6, 8, and 14. Furthermore, 4 equipment packages with smaller capacity of 100 tonnes and 20 equipment packages with larger capacity of 200 tonnes should be purchased at each facility. The solution also contains dispatching decisions for specific scenarios. Regarding coverage, only links 17, 18, and 19 are not covered according to the results. Total corresponding cost is equal to $267,301,453 CAD.

Table 3 shows results obtained in cases with slightly different parameter set. We observe that in all the cases, a response facility is required to be built at node 14 (near Caramat, Ontario), and in most of the cases the solution includes open facilities at nodes 6 and 8 as well.

In this paper, we studied the problem of emergency response planning for railroad transportation of hazardous materials in Canada. Our modeling approach takes in account some aspects of uncertainty involved in hazardous materials emergencies. Simplifying assumptions and parameter estimations make it possible to solve the model using an optimization software package. Modifying and solving this problem in other contexts as well as detailed scenario analyses are ideas for future research.

Table 3 – Solution results for problems with slightly modified parameter set compared to the base case

Parameter changed in base case	Facilities to open at nodes:	Total costs
$\alpha^m = 0.5$	7, 14	$178,205,060
$\alpha^m = 0.9$	6, 8, 14, 15, 20	$291,977,771
$F_i = 0.9\ millon\ CAD$	6, 7, 8, 14	$264,001,950
$F_i = 3.6\ millon\ CAD$	6, 8, 14	$272,701,453
Accident probabilities doubled	6, 8, 14	$267,302,906
Exposure costs doubled	6, 8, 14	$267,302,828

Bibliography

Bagheri, M., Verma, M., Verter, V., 2014. Transport Mode Selection for Toxic Gases: Rail or Road? Risk Anal. 34, 168–186.

Berman, O., Verter, V., Kara, B.Y., 2007. Designing emergency response networks for hazardous materials transportation. Comput. Oper. Res. 34, 1374–1388.

CBC News, 2015. Lac-Mégantic train disaster: U.S. judge approves settlement for victims. URL http://www.cbc.ca/news/canada/montreal/lac-megantic-settlement-united-states-1.3264325 (accessed January 10, 2016)

Church, R., Velle, C.R., 1974. The maximal covering location problem. Pap. Reg. Sci. 32, 101–118.

Davis, S., Diegel, S., Boundy, R., Moore, S., 2015. 2014 Vehicel Technologies Market Report.

Dover Fire Department, 2015. Frequently Asked Questions [WWW Document]. URL http://www.doverfire.org/faq.cfm (accessed January 10, 2016)

Federal Railroad Administration, 2015. Casualties by State/Railroad [WWW Document]. URL http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/Query/CasualitiesReport.aspx (accessed January 10, 2016)

Government of Canada, 2014. Consolidated Transportation of Dangerous Goods Regulations including Amendment SOR/2012-245.

Provencher, M., 2008. The movement and handling of dangerous goods in Canada for the year 2004. Transp. Danger. Goods Dir.

Railway Association of Canada, 2015. Ensuring the safe transportation of Essential Goods – RAC DG Team.

RSMeans, 2015. Square Foot Cost Estimates [WWW Document]. URL http://www.rsmeans.com/Square-Foot-Cost-Estimates/ (accessed January 10, 2016)

Statistics Canada, 2015. CANSIM- Transportation by Rail [WWW Document]. URL http://www5.statcan.gc.ca/cansim/a01?lang=eng (accessed January 10, 2016)

Toregas, C., Swain, R., ReVelle, C., Bergman, L., 1971. The location of emergency service facilities. Oper. Res. 19, 1363–1373.

Transport Canada, 2015. CANUTEC 2013 Annual Statistics [WWW Document]. URL https://www.tc.gc.ca/eng/canutec/stats-2013stat-1185.html (accessed January 10, 2016)

Transport Canada, 2012. 2012 Emergency Response Guidebook.

Verma, M., 2011. Railroad transportation of dangerous goods: A conditional exposure approach to minimize transport risk. Transp. Res. part C Emerg. Technol. 19, 790–802.

Verma, M., Gendreau, M., Laporte, G., 2013. Optimal location and capability of oil-spill response facilities for the south coast of Newfoundland. Omega 41, 856–867.

Verma, M., Verter, V., Gendreau, M., 2011. A Tactical Planning Model for Railroad Transportation of Dangerous Goods. Transp. Sci. 45, 163–174. doi:10.1287/trsc.1100.0339