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مخطط عمل لنقل طلبات المواد الخطرة
مخطط عمل لطلبات نقل البضائع الخطرة في نظام إسناد المسارات لمنطقة معينة : فان كوفر (كندا)

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الخلاصة

تقدم هذه الورقة إطار عمل لتكامل الظروف المناخية الحالية مع أنظمة المعلومات الجغرافية (GIS) وذلك لتطوير وسائل نقل المواد الخطرة. يركز إطار العمل على تقليل نسبة المخاطر المرتبطة بنقل المواد الخطرة عن طريق اختيار المسارات الأنسب . إن اختيار طرق نقل المواد الخطرة يعتمد على عدد من القرارات التي تتطلب اعتبارات متعددة وأحياناً متعارضة. لذلك فإن إطار العمل يحوي عدد من المسارات المختلفة بناء على: الأمان والفعالية والسلامة والتكلفة. ثم تطبيق إطار العمل على نطاق كبير ضمن شبكة النقل في مدينة فان كوفر الكبرى. تم تمثيل إطار العمل المكاني في نظام المعلومات الجغرافية (GIS) مع نموذج الانتشار السحابى (Plume) وفق الزمن الحقيقي لنمذجة انتشار مادة كميائية معينة تحت الظروف المناخية المحلية. أظهرت النتائج أن مقارنة المسارات المختلفة بينت أفضل مسار يمكن اختياره.قام الباحثون بمقارنة المسارات وفق تعليمات الاستجابة للطوارئ (ERG) للتنبؤ بإمكانية العزل الوقائي وفق نموذج الانتشار السحابى. أظهرت نتائج المقارنة أن تطبيق سيناريو الاستجابة للطوارئ (ERG) لحالة انسكاب صغيرة يجعل أصحاب القرار في إحتمالية من تعريض عدد كبير من الأفراد لتأثيرات صحية خطيرة. وفي المقابل إذا طبق نظام (ERG) في حالة انسكاب كبير فإن كثير من الأفراد الذين ليسوا في خطر سيتم إخلاؤهم من غير ضرورة. مما يتسبب في تكاليف إخلاء غير ضرورية بالإضافة لإضاعة وقت وجهد كادر الطوارئ. تظهر الدراسة أن هذه المسائل يمكن معالجتها بطريقة أفضل باستخدام نموذج انتشار لفلترة المناطق المتضررة بإضافة معلومات خاصة بنوع المادة المنقولة.

A framework for an on-demand dangerous goods routing support system for the metro Vancouver area

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ABSTRACT

This paper proposes a framework that integrates existing climate conditions with a Geographical Information System (GIS) to develop an on-demand dangerous goods (DG) routing support system. The framework focuses on mitigating the risks associated with DG transportation via route selection. Evidently, DG routing involves a number of decisions that require the consideration of multiple and sometimes conflicting risks. As a result, the framework includes a number of different routing criteria pertaining to safety, efficiency, security, and cost. The framework was applied to a large-scale transportation network representing the Metro Vancouver area. The network was represented spatially in a GIS database along with a real-time dispersion plume model to simulate a specific chemical release under local weather conditions. The results show that different routing criteria lead to different optimal route choices. The authors also compared route selection based on the Emergency Response Guidebook (ERG) for protection and isolation actions with route selection based on dispersion models. The comparison results show that, when employing the ERG in a small spill scenario, decision-makers are at risk of exposing a large number of individuals to severe health effects. Vice versa, if the ERG was to be followed in a large spill scenario, many individuals who are not at risk would be unnecessarily evacuated. This translates into increased evacuation costs, and wastes the time and effort of emergency personnel. The study shows that these issues are properly addressed if a dispersion model is used to refine the estimation of the impact zone by including measures that are specific to the shipment.

Keywords: Consequence; dangerous goods; dispersion model; probability; risk; routing.

INTRODUCTION

Each day, particular products and materials specially defined as Dangerous goods (DG) are shipped from one point to another within Canada. These products include explosives, gases, flammable liquids and solids, oxidizing substances, poisonous and infectious substances, corrosive substances, and hazardous waste. As such, these products and materials require special precautions to ensure their safe transportation.

In an effort to minimize the risks and potential consequences of DG incidents, many government agencies have enacted not only statutes and regulations that apply to all stages of DG movement and inspection, but also enforcement programs to ensure compliance. These rules and regulations include setting design standards for DG vehicles, designating specific roads for DG transport, and banning the import and (or) export of certain DG.

However, there are a limited number of regulations on the routing process, which significantly impacts the potential risks of an incident. In some cases, DG routing is the sole responsibility of DG couriers. To DG couriers, taking the shortest route between a given origin and destination may be the most appealing route choice. However, the shortest distance should not be the only routing criteria. Certain routes may incur low accident rates, but run through heavily populated areas, while other routes may not run through heavily populated areas, but are much longer, and other routes yet may use major freeways, thus minimizing the transport time. Hence, it is important to acknowledge that decisions regarding DG transportation are often intricate and sometimes conflicting. Costs, probability, consequences, and public concerns are all important issues that must be taken into consideration.

Recognizing the increase in risks and dangers to the public and environment due to the increase in global trade and long-distance DG transport, the British Columbia (BC) Ministry of Transportation is researching the development of a real-time interactive decision-support system (DSS) to provide optimal routing for truck drivers travelling within BC. This study was conducted to develop an initial prototype of such a system.

The study developed a framework for an on-demand DG routing support system that uses local climate conditions to assess the risks of alternative routes in the Metro Vancouver area. The framework considers a number of routing criteria pertaining to safety, efficiency, security, and cost. The objective of this study is to examine the tradeoffs between the different routing criteria. There are a number of methods to combine the different routing criteria into one meaningful measure. However, the means by which these measures can be combined is left to the policy and (or) decision-makers who are responsible for making such a judgment; some will favor the use of weights, while others will favor "normalizing" risks and costs into dollar amounts.

Moreover, the proposed framework uses a dispersion model to effectively incorporate climate conditions, release quantities, DG type, and topography into modeling the DG release, explosion, or dispersion. This method refines the determination of the impact zone, allowing for a more accurate representation of a specific chemical release. This approach is different from traditional routing methods that are based on a long-term static strategic route planning method. The proposed framework assumes that trips will most likely be equal to or less than 1 hour long. As a result, local climate conditions are to remain unchanged along the route. Because the climate forecast remained stable in the short term, there was no need to simulate all possible climatic scenarios. To facilitate a large-scale implementation in the Metro Vancouver area, the above information was integrated into a Geographical Information System (GIS) database.

LITERATURE REVIEW

The main objective of DG routing is to determine the optimal travel path(s) on a network, subject to certain routing criteria. The objective, which can be either a single criterion or multiple criteria, is typically based on risk, equity, and cost considerations. The choice of the objective criteria highly influences the best route selection. Current literature includes different modeling techniques to aid in DG routing between a given origin and destination. The techniques differ in the type of criteria being examined and the methods by which these criteria are combined. The most common criterion considered in the literature to route DG is risk minimization.

Researchers have generally agreed that, in the context of DG, the term "risk" has to do with the probability and consequence of an undesirable event. Although some authors define risk as only one of these terms (either probability or consequence), it is more common to define risk as the product of both the probability and the consequence of the undesirable event (***1,2***). The probability component is related to accident likelihood and the release probability. Undesirable events include spills, fires, and explosions in the case of flammable liquids, or a toxic cloud or plumes in the case of pressure-liquefied gasses. The ensuing consequences include fatalities, injuries, property damage, losses in property values, and environmental damage. This is known as the "expected consequence" or the "traditional risk," primarily because it is defined as such in the U.S. Department of Transportation (DOT) 1989 (***3***) guidelines for DG transportation. Such risk-based models are probabilistic in nature and use conditional probabilities of accidents and the magnitude of their consequences as the two main parameters. In general, these risk-based models differ in (a) how the two parameters are combined to provide a risk estimate; (b) the types and levels of detail and quality of the data acquired; and (c) the methods of obtaining or estimating data and model parameters.

To develop probabilities, some models use fault-tree analyses, whereas others use average accident rates by mode and vehicle. To determine the magnitude of consequences, atmospheric dispersion models and simulations are used to determine spill behavior and, thus the population exposure. Additional details on the quantification and assessment of risk and the estimation of release rates are given in several references (***4-11***).

Several risk definitions and models have been proposed and examined in the literature (***2,12***). Alternative risk models that include either incident probability or population exposure (or both) - to quantify risk were explored. The general consensus is that risk minimization is a bi-criterion optimization problem; one of minimizing incident probability and population exposure.

DG routing involves a number of decisions that require the consideration of multiple and sometimes conflicting objectives. Risk minimization seems to be the most common criterion examined in the literature. However, other factors, such as travel time, distance, emergency responsiveness, and delay, are also important. According to Leonelli *et al*. (***13***), if risk minimization is the sole criterion for DG routing, then the routes selected are likely to be more than twice as long as the fastest alternative and, in most cases, their feasibility comes into question for financial reasons. In the literature, the models are classified according to the number of criteria included in the analysis along with the method by which such criteria are combined to determine the best paths between origins and destinations.

The Single Optimization Criterion (SOC) is a widely used approach to combine several criteria into a single score or value (***14-17***). The new score and (or) value is often taken to be a linear function of different attributes, such as population exposure, distance, time, and accident probability. With a single link score and (or) value, a simple solution method (e.g., Dijkstra's shortest path algorithm) is used to connect the origin-destination pair. By varying the weights of the attributes, different routes can be generated. The process of varying the weights indicates the sensitivity that the criteria have on route selection. Leonelli *et al*. criticized the weighting approach, since the routing problem becomes one of fixing the values of the weight factors or the thresholds. In fact, their calculations have shown that different weights (or different threshold values) can produce different optimal routes. As such, the determination of the optimal path becomes strongly dependent on the decision-maker, who has to adjust the value of the weights and thresholds (18). However, this problem could be adequately addressed by having an expert panel suggest the weight and (or) threshold values or through the use of a weighting system (such as an analytical hierarchy process or a genetic algorithm).

An alternative approach that has recently gained attention is the Multiple Objective Criteria (MOC). This approach simultaneously minimizes a number of criteria for route selection purposes (***19-21***). Minimizing travel time and the total population at risk is an application of the MOC routing method. MOC routing models can be used to study tradeoffs between conflicting routing objectives. Using an MOC approach for DG transportation decisions usually means that it is not possible to identify a single best route, but rather the goal is to identify a set of "non-dominated" or "Pareto-optimal" routes so that the tradeoffs between different objectives can be represented explicitly. However, researchers have argued that many routes can exist within the solution set. As a result, the number of "non-dominated" paths can become very large in networks, thus rendering the approach impractical (***22***). Alternatively, the Constrained Shortest Path approach is used to minimize one attribute, while limiting the sum of other attributes (***22,23***).

PROPOSED DANGEROUS GOODS FRAMEWORK

Figure 1 shows a diagram representing the conceptual framework. The framework contains two major components: a dispersion model and a GIS database. The dispersion model uses site data, chemical, atmosphere, and source information to generate a plume footprint. Afterwards, the footprint and a number of datasets are integrated together in a GIS environment to perform the analysis. The GIS environment provides the ability to create interactive queries (user-created searches), analyze spatial information, edit data, create maps, and present the results of all of these operations by integrating common database operations with visualization and geographic analysis capabilities. A set of DG routing criteria pertaining to safety, efficiency, security, and cost was formulated from the available datasets.

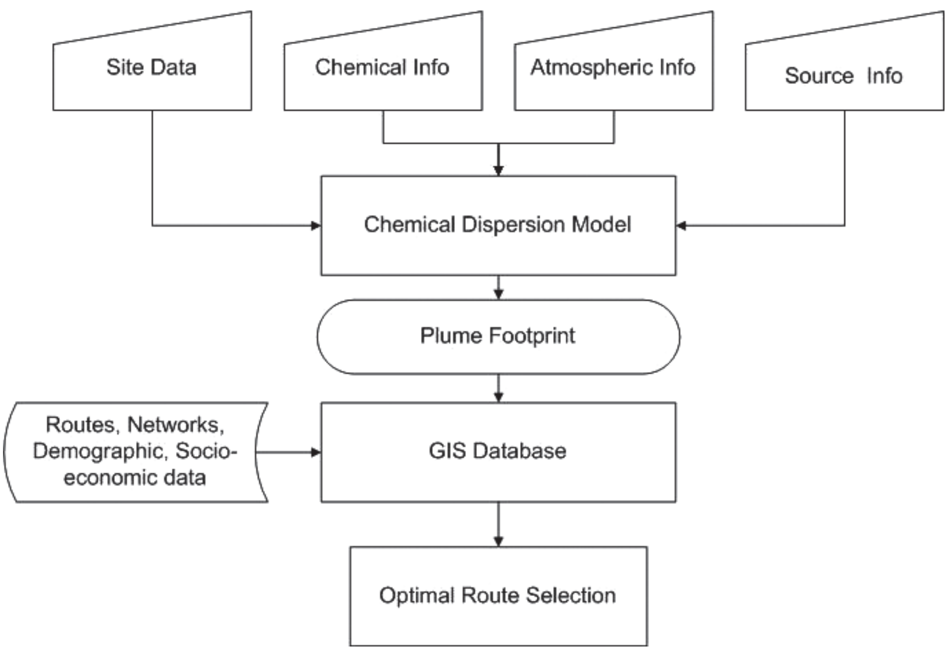

Fig. 1. DG routing support conceptual framework

In addition, this study investigated the effect of varying the time of day on the route selection. This was accomplished by studying population distribution during the day and evening. It could also be argued that traffic flow also varies by time of day; however, volume data by time was unavailable.

This paper presents the developed on-demand routing support system based on a particular DG type and local weather conditions. The results from the dispersion model were compared to the results computed using the Emergency Response Guidebook (ERG) procedures for protection and isolation actions (***26***). However, it is prudent to note that the ERG method conservatively represents the spill impact because, in a routing decision, it is not known in advance how much will be spilled and under what climatic conditions the spill will disperse.

To demonstrate the proposed approach, a hypothetical scenario involving the transport and subsequent release of chlorine was investigated. Chlorine is a nonflammable gas in liquid state. However, like oxygen, it is capable of supporting the combustion of certain substances. Many organic chemicals react readily with chlorine, and, in some cases, with explosive violence. A scenario was developed where it was assumed that a truck carrying three 150-pound liquid chlorine cylinders was routed through the Langley area. The scenario was developed assuming a worst case approach where the contents of all cylinders were released due to the occurrence of an incident. Figure 2 depicts the study area and the three possible routes, which pass through almost the same number of intersections, but have variable lengths. There are no tunnels, bridges or HOV lanes present along the three routes. Route 1 (R1) is a major highway in the lower mainland region. The highway is known as Highway (1) and begins at the Horseshoe Bay ferry terminal in West Vancouver and continues for 170 (km). Route 2 (R2) traces part of the Fraser highway and passes through Langley's town centre. Route 3 (R3) passes through a mixture of local arterials in the city of Langley.

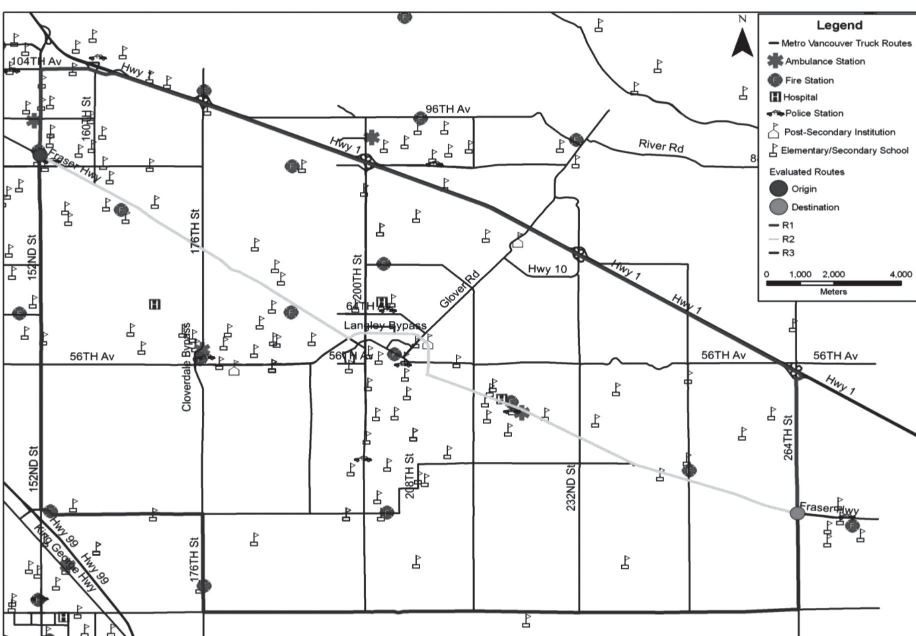

Fig. 2. Study area and evaluated routes

Routing criteria

For a given network, assume that there are a number of alternative routes connecting a pair of origin and destination (O-D) and that a DG shipment will traverse the O-D pair. Four of the most commonly applied routing criteria in the literature include (1) efficiency, (2) incident probability, (3) incident consequence, and (4) traditional societal risk.

Efficiency involves the minimization of travel distance, time, and cost, which are formulated as follows,

$$TD_r = \sum_{i=1}^{m} L_i \tag{1}$$

$$TT_r = \sum_{i=1}^{m} L_i / S_i \tag{2}$$

$$TC_r = \left(\sum_{i=1}^{m} L_i / S_i\right) \times OC \tag{3}$$

Where,

TD_r	Travel distance for route *r*
TT_r	Travel time for route *r*
TC_r	Travel cost for route *r*
L_i	Length of route segment *i* (km)
S_i	Speed of route segment *i* (km/hr)
OC	Operating cost ($/hr)
m	Number of segments in route *r*

The operating costs were determined based on the courier's value of time, as proposed by Waters *et al*. (***24***) and were assumed fixed regardless of shipment type, size, or time of day. After conversion from US to Canadian dollars, the operating cost was estimated at CAD$55 per hour.

The probability of an incident is a function of truck accident rates, the probability of a release given an accident, and segment length. Due to the lack of information on truck accident rates for the province, an accident prediction model (APM) was used to predict the expected number of accidents for the Metro Vancouver area based on traffic exposure and geometric characteristics. Using the predicted number of accidents, traffic volumes, and segment length, an accident rate (AR) was developed for each of the road segments in the network. Shortreed *et al*. (***25***) suggested a 5% conditional probability for the occurrence of an incident given a traffic accident involving a DG truck. The work by Shortreed *et al*. represents the most recent attempt to quantify the conditional probabilities of a release in Canada. This value was adopted throughout this study and is assumed to be fixed and independent of road conditions or truck tanker specifications. The probability of an incident occurring during transportation on route (r) is,

$$IP_r = \sum_{i=1}^{m} AR_i \times L_i \times 0.05 \tag{4}$$

Where,

IP_r	Incident probability for route *r*
AR_i	Accident rate (accidents/km) for route segment *i*

The consequences of a DG release were assumed to be proportional to the number of individuals within a release impact zone along the route. Regardless of the method used to determine the impact zone, the following equation was used to determine the consequences due to the occurrence of an incident during DG transportation:

$$IC_r = IZ_{POPr} \tag{5}$$

Where,

IC_r	Incident consequence around route *r*
IZ_{POPr}	Population exposure within the impact zone generated by using a dispersion model or ERG around route *r*

In the context of DG routing, the ultimate objective is to rank and select routing options that reduce the risk to the population and (or) environment. This is accomplished by recognizing that risk is a function of both incident probability and consequence. The formulation of the risk on a particular route is given by,

$$TR_r = IP_r \times IC_r \tag{6}$$

Where,

TR^r	Traditional risk on route r.

Chemical dispersion model

The exposed population is a key factor in determining the consequence of a DG release. By overlaying the census information with the impact zone, the number of individuals that might be exposed to a release was estimated. There are different methods to create the impact zones. The first method uses the ERG (***26***) evacuation distances for a large quantity of explosives as well as isolation and protection action distances for small and large spills. The impact distance serves as the radius that defines the impact zone.

An alternative method to estimate the impact zone is to use a dispersion model to effectively incorporate local climate conditions, release quantities, DG type, and topography into modeling the DG release, explosion, or dispersion. This method refines the determination of the impact zone and allows for a more accurate representation of a specific chemical release. The Areal Locations of Hazardous Atmospheres (ALOHA) dispersion model is typically used to simulate the movement and dispersion of hazardous chemical gases. ALOHA estimates pollutant concentrations downwind from the source of a release, while accounting for both the toxicological and physical characteristics of the released material. The dispersion model requires four inputs: (1) site-specific data, (2) local atmospheric conditions (i.e., wind speed, wind direction, ground roughness, cloud cover, air temperature, stability class, inversion heights, and humidity), (3) type of hazardous material released, and (4) data relating to the source strength of the chemical.

This level of detail is lost when an impact zone is based on isolation and protection action distances (as per the ERG). These distances are based on modeling spills assuming one set of topography conditions and quantities released. Furthermore, the ERG does not indicate what constitutes a small or a large spill and it is up to the user to determine the spill category. There are two benefits of using a dispersion plume model: (1) the model refines the impact zone estimation, as it is based on a number of key inputs, including information about the actual DG shipment, and (2) the generated impact zone includes both the dispersion size and concentration within each level.

The generated impact zone represents the extent of the chemical dispersion and is assumed to be of the same concentration (the "Immediately Dangerous to Life and Health" (IDHL) concentration), with its shape representing the spread of the released gas cloud to the level of concern. A typical footprint diagram contains four shaded areas representing three ground level concentrations and a 95% confidence interval. The innermost area of the footprint is the region predicted to have ground level concentrations above the limit that is specified during the model run. The outer lines drawn on either side of the footprint reflect uncertainty in the wind direction and are computed based on a 95% confidence factor. Figure 3 shows the generated chlorine footprint using ALOHA at the three concentration levels as well as at the 95% confidence interval.

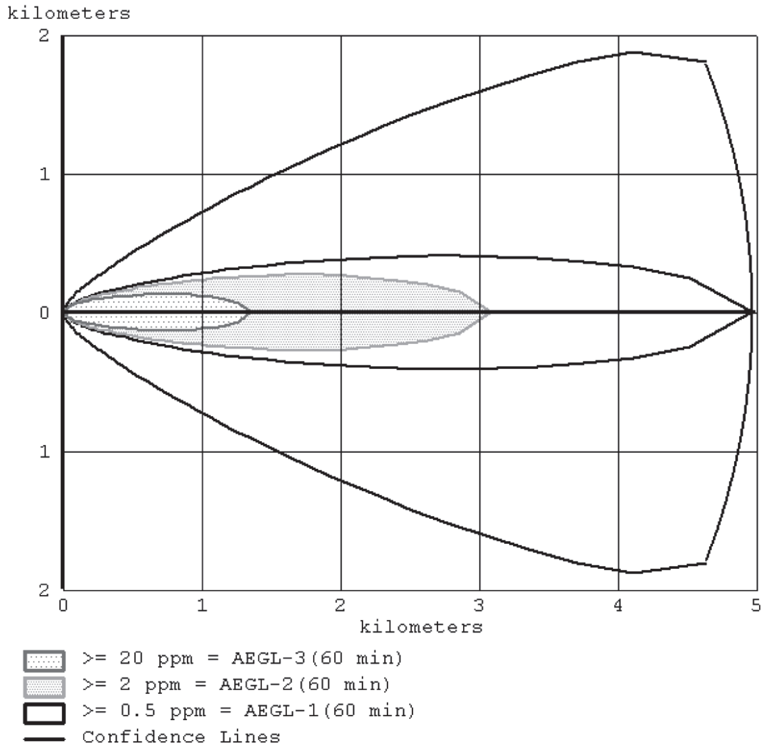

Fig. 3. ALOHA-generated plume footprint for chlorine.

Geographical information system (GIS) database

DG routing analyses should adequately integrate the road network with its surroundings, since risk levels strongly depend on the characteristics of the region traversed by the shipments. As a result, several researchers used GIS to aid DG route planning. Existing literature shows that the use of GIS in DG routing dates back to the early 1990s. Researchers have argued that GIS development could provide means to concurrently analyze network topology and spatial features (***18,27-29***). GIS provides useful techniques for data storage, data manipulation, and map display solutions. Moreover, GIS provides an ideal environment for the design and management of DG routes, because of its ability to integrate multi-theme and multi-source data into an operational information system.

This study made use of a number of available datasets from the province of BC. Road segment data for Vancouver, BC was obtained from the GIS Innovations dataset, titled Digital Road Atlas. This dataset includes all of the official, designated truck routes primarily used for DG transportation. Spatial data, including a set of EMME/2 traffic volumes (from TransLink) and the Metro Vancouver truck routes, was combined to calculate accident rates. Three types of datasets were used to describe the population distributions in the GIS database. The first dataset contained information relating to the location of regional town centres (RTC). The second and third datasets contained evening and day population census information. The calculation of daytime exposure was more complicated, as the GIS data inventory did not include any daytime population spatial dataset. The only data file that could be used for analysis was a table containing 2008 daytime population attribute data obtained from MapInfo. Using GIS capabilities, the evening and daytime populations were matched. RTCs, evening, and day population census data was incorporated as a second layer in the GIS environment.

An additional layer encompassed locations of emergency-response and special facilities. Special facilities most vulnerable to the impacts of DG incidents were identified as schools and hospitals. If an incident occurs, it is critical to know the number and proximity of these special facilities. The location of emergency-response facilities, such as ambulance, fire, and police stations, was necessary to determine the nearest immediate responder to commence evacuation procedures, provide on-site traffic management, and instigate incident mitigation measures. The relevant information about these facilities was obtained from a GIS Innovations dataset, called Places.

To determine the number of affected individuals, the footprint co-ordinates (impact zone) were transferred from ALOHA into the GIS database using a special import tool. The mapped output includes a layer for each level of concern specified in the analysis. To determine the impact zone along an entire route, a composite plume was generated by creating multiple footprints every 100 metres (m) and combining them into an impact zone, as shown in Figure 4.

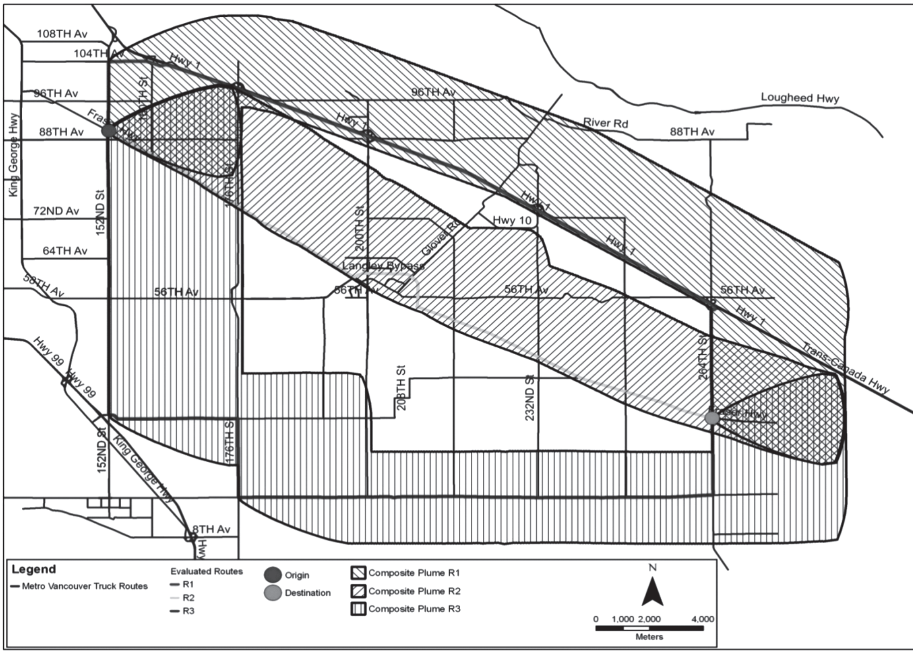

Fig. 4. GIS-generated impact zones for all three routes

Using the ERG method for small or large chlorine spills, the impact distance was used to determine the impact zone. In this case, the impact distance serves as the radius that defines the impact zone. It is possible to consider the DG shipment over a road segment as the movement of a danger circle along that road segment. These movements carve out a band on both sides of the road segment, thereby defining the possible impact region. This process was conducted using GIS, where a buffer zone was generated on both sides of the three proposed routes based on ERG's action distance. In both cases, the analytical capability of the GIS software was used to enumerate the affected population as well as the emergency-response and special facilities alongside each route.

RESULTS

Table 1 indicates that R1 minimized travel time and consequently transport cost. On the other hand, R2 minimized travel distance and accident probability. R3 had the highest accident probability, travel distance, travel time, and transport costs.

Table 1. Risk measures and percentage increase from the base value.

Description	Routes		
	R1	**R2**	**R3**
Accident Probability	0.000410 (4%)	***0.000395 (base)***	0.000588 (49%)
Travel Distance (km)	33 (22%)	***27 (base)***	41 (52%)
Travel Time (min)	***23 (base)***	25 (9%)	41 (78%)
Travel Cost ($)	***21 (base)***	23 (9%)	38 (78%)

Table 2 reveals that R2 minimized population exposure at the three concentration levels during the evening. However, during the day, R3 minimized the number of overall evacuees as well as population exposure at the highest concentration zone.

Table 2. Exposed populations by time of day.

Description		Routes		
		R1	**R2**	**R3**
Evening Exposed Population	**20 (ppm)**	41,163	***36,230***	41,289
	2 (ppm)	19,932	***16,206***	21,085
	0.5 (ppm)	9,503	***4,538***	14,339
	Evacuated	92,870	***80,942***	90,315
Day Exposed Population	**20 (ppm)**	63,584	63,581	***47,608***
	2 (ppm)	19,861	9,768	13,194
	0.5 (ppm)	6,421	2,756	15,622
	Evacuated	104,841	104,632	***85,866***

Table 3 shows that R2 had the highest number of emergency-response facilities at 20 parts per million (ppm). This is very important, since exposure to chlorine at this concentration level is expected to have a very severe impact on human health. Furthermore, R2 and R3 passed by the least number of schools and hospitals within the highest concentration zone. As the concentration level dropped to 0.5 (ppm), R2 still had the least number of such sensitive facilities. On the other hand, R3 exposed 30 special facilities to probable danger. Should an incident occur during the transportation process, this route places some school-aged children and potential ill individuals at risk of being exposed to harmful materials.

Table 3. Number of special and emergency facilities alongside each route.

Impact Zone	Concentration Level/ Spill Size	Facility Type	No. of facilities on each route		
			R1	R2	R3
Plume Dispersion	20 ppm	Sensitive	*11*	***9***	***9***
		Emergency	*1*	***3***	*2*
	2 ppm	Sensitive	*20*	*21*	***18***
		Emergency	*4*	***5***	***5***
	0.5 ppm	Sensitive	*25*	***24***	*30*
		Emergency	*5*	*7*	*8*
ERG Isolation & Protection	Small	Sensitive	*3*	***0***	*3*
		Emergency	*1*	*1*	***2***
	Large	Sensitive	*15*	*20*	***12***
		Emergency	*3*	***8***	*4*

Table 4 summarizes population exposure numbers, if ERG isolation and protection action distances are used to determine the impact zone. For small spills, R1 minimized the evening population exposure, while R3 minimized the day exposure. For large spills, R3 minimized population exposure during the evening and the day. Examining Table III reveals that all of the routes had a limited number of emergency-response facilities within the generated buffer zones for small spills. For large spills, R3 had the least number of sensitive facilities, while R2 had the largest number of emergency-response facilities.

Table 4. Population exposure based on ERG isolation and protection requirements.

Spill Size	Time of day	No. exposed individuals Isolation Requirements			No. exposed individuals Protection Requirements		
		R1	R2	R3	R1	R2	R3
Small	Evening	***17,342***	19,176	22,209	90,441	108,234	***58,389***
	Day	48,173	50,649	***35,634***	55,614	66,597	***39,341***
Large	Evening	52,950	63,550	***41,599***	306,131	244,921	***239,047***
	Day	70,146	79,911	***44,385***	137,635	168,123	***122,618***

Table 5 shows the results of the traditional or societal risk measure. Using a dispersion model, R2 minimized the risks for both the evening and the daytime.

Using the ERG method, all of the risks were minimized on R1, except for large spills occurring during the evening period.

Table 5. Traditional or societal risk results.

Impact Zone			Routes		
			R1	**R2**	**R3**
Plume Dispersion		**Evening**	67	***54***	98
		Day	80	***71***	95
ERG	**Small**	**Evening**	***44***	50	47
		Day	***43***	46	44
	Large	**Evening**	147	122	165
		Day	***85***	98	98

DISCUSSION

In Table 1, the percentage increase in the base values is reported for each criterion. The travel distance was increased by 22% and 52% for R1 and R3, respectively, over the base value (R2). The travel time and cost were both increased by 9% and 78% for R2 and R3, respectively, over the base values (R1). This indicates that R1 and R2 could be considered surrogate routes, as the results are not significantly different under the criteria. Similarly, the incident probability criterion shows no significant difference between R1 and R2. R3 is probably the worst choice, since it has the largest distance, longest time, and the highest cost and incident probability, while showing a significant increase in all criteria compared to the best alternative.

Route evaluation is generally time-of-day dependent, because many of the criteria for routing and risk assessment depend on traffic volumes and activity patterns that vary throughout the day. Residential neighborhoods are expected to be densely populated during the evening, whereas commercial and industrial areas are expected to be sparsely populated. Vice versa in the daytime, when commercial and industrial areas are expected to be occupied. To capture the difference in population distribution and to properly estimate the incident consequence, evening and daytime population distributions for the Metro Vancouver area were integrated with other spatially referenced data into the GIS database.

Table 6 compares and differentiates the findings for each routing component. The results indicate that R2 minimized travel distance, but not travel time. The difference in speed profiles is explained by the fact that R1 is a major highway that has a higher speed, whereas R2 passes through the city of Langley's town centre, where lower speeds are enforced. Recalling that transport cost is a function of travel time and operating costs, which were assumed constant, the travel time and transport cost criteria would identify the same route. As expected, the incident probability and travel distance criteria identified the same route, since both measures are based on road segment length.

Table 6. Summaries of the routing criteria results.

Description	Impact Zone	Time	Routes		
			R1	R2	R3
Travel Distance	N/A	All		√	
Travel Time	N/A	All	√		
Travel Cost	N/A	All	√		
Incident Probability	N/A	All		√	
Incident Consequence	Plume Dispersion	Evening		√	
		Day		√*	√
	ERG	Evening	√**		√
		Day			√
Traditional Risk	Plume Dispersion	Evening		√	
		Day		√	
	ERG	Evening	√	√***	
		Day	√		

*Based on concentration levels 2 (ppm) & 0.5 (ppm)
**Based on isolation requirements for small spills during the evening
***Based on large spills during the evening

Using the dispersion model to generate the impact zone, Table 6 reveals that R2 minimizes incident consequence during the evening and R3 does so during the day. This is a reasonable finding since route R2 passes through Langley's town centre, which is surrounded by a large number of commercial and industrial facilities that are occupied during the day and vacant during the evening. Conversely, the land use around R3 is mostly made up of residential areas that are densely populated during the evening and sparsely populated during the day. These findings are totally overlooked, if the isolation and protection distances are used to generate the impact zone. As a result of using a large radius, R3 is the preferred route, except for small evening spills, in which case R1 is favored.

To further investigate the differences between the two methods, the number of exposed individuals was compared. The ERG specifies isolation and protection distances in all directions for small and large spills. Individuals residing within the impact zone, generated using isolation distances, are considered to be under serious threat, while individuals within the protection zone need to be evacuated. The dispersion model generates a footprint with three shaded areas representing three ground level concentrations and a 95% confidence interval representing changes in wind direction. The innermost area of the footprint is the region with concentration levels exceeding tolerable limits, and is therefore comparable with the ERG isolation requirements. The 95% interval corresponds to the number of individuals that need to be evacuated and is comparable with the protection requirements. Tables 2 and 4 reveal that the two methods show notably different results.

For small spills, the ERG underestimated both the number of individuals that are under serious threat and the number of evacuees. For large spills, a considerable overestimation is observed regardless of the time of day. Such findings could have severe societal and economic impacts. If the current scenario was characterized as a small spill, then the decision-maker is at risk of exposing a large number of individuals to severe health effects, if proper isolation and evacuation procedures are not attempted. Also, in a large spill scenario, many individuals who are not at risk would be unnecessarily evacuated. This translates into increases in evacuation costs, and wastes the time and effort of emergency personnel. The use of a dispersion model refines the estimation of the impact zone by including measures that are specific to the shipment, such as type, discharge rate, release duration, IDHL level for toxic materials (or lower flammability levels for flammable materials), weather, and terrain conditions.

Finally, the results of the incident probability and consequences were sometimes conflicting, as seen in Table 6. R2 minimized the incident probability, while R2 and R3 minimized the incident consequence during the evening and the daytime, respectively. By combining the two criteria, the risk is minimized on R2 for the evening and daytime exposure.

CONCLUSIONS & FUTURE RESEARCH

This paper proposed a framework that integrates existing climate conditions with a Geographical Information System (GIS) to provide an on-demand dangerous goods (DG) routing support system. The framework focuses on mitigating the risks associated with DG transportation via route selection. The framework included a number of different routing criteria pertaining to safety, efficiency, security, and cost. The framework was applied to a large-scale transportation network representing the Metro Vancouver area. The network was represented spatially in a GIS database along with a real-time dispersion plume model to simulate a specific chemical release under local weather conditions. The results showed that different routing criteria leads to different choices of optimal routes. The study also compared route selection based on the Emergency Response Guidebook (ERG) protection and isolation actions with route selection based on dispersion models. The ERG assumes static plumes and does not account for chemical type, weather, terrain, and release rate, which are bound to change over time and space. The study developed a potential method to account for such changes by using a dispersion model to generate the impact zone providing valuable information related to both the size of the dispersion and the concentration within each level.

A major drawback in this approach is the underlying assumption that climatic conditions (air temperature, relative humidity, cloud cover, and wind speed and direction) remain constant. A different month of the year, or a change in wind speed or direction would generate a footprint from the same source with a different shape, size, and orientation. This limitation can be addressed by developing a composite plume model that takes into account general trends in wind direction as well as the overall climatic variability in the area.

Future research would include expanding the given data set to include more variables, such as the locations of farms, crops, watersheds, and other environmental locations, to determine the environmental effects. Moreover, the number of students enrolled in schools can be obtained to determine the exact number of evacuees; a similar process can be undertaken for hospitals. Additional research is warranted to estimate the probability of a release, given an accident. This probability could be developed as a function of DG type, roadway category, accident severity, and container characteristics. Furthermore, the computation of the incident probability could be expanded by using a safety performance function to tune the prediction to specific facilities depending on particular factors, such as roadway functional class, design speeds, geometrics, traffic volumes, truck percentages, etc.

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