

Interactive Selection of Minimum-Risk Routes for Dangerous Goods Shipments

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An interactive model for routing shipments of dangerous goods through an urban road network is presented and demonstrated. The model computes minimum-risk routes based on each shipment's origin and destination, and graphically illustrates the selected paths. Alternative approximations for estimating risk are considered. The consequences of these differences are compared against routings based on objective risk exposure. Objective risk exposure is predicted by using observed accident rates, a fault-tree analysis for estimating damage potential, and various damage propagation relationships. The resultant risk estimates in this model are responsive to various environmental conditions, material properties, and location-specific parameters. An application of the model to the routing of chlorine shipments within the metropolitan Toronto road network is presented. The application illustrates the sensitivity of minimum-risk routes to a range of external contextual variables and relationships. Route patterns appear to be strongly influenced by the nature of the risk measures applied to candidate links and nodes.

In recent years the risks associated with the shipping of dangerous goods have received increasing attention from the government, the public, and the industries involved. These concerns have prompted several jurisdictions to consider a range of strategies for controlling dangerous goods shipments within large urban areas. In general, the intent of these strategies is to minimize potential damage to nearby population and properties from accidental spills of dangerous goods.

BACKGROUND

Current strategies for restricting dangerous goods shipments along an extensive road network are based essentially on two measures of potential damage (1–3):

1. Truck accident rates or
2. Objective risk exposure.

Although the former only considers the probability of occurrence of dangerous goods incidents, the latter also attempts to incorporate directly some measure of their consequent damages.

In most cases damages are estimated by multiplying the accident rate by the number of people (or properties) affected

along each affected route within the network. However, frequently there is no provision for the variability in spill probabilities for different accident conditions. Similarly, estimates of the impact area associated with materials spills may fail to account for variabilities in environment and material properties. This variability is a significant factor, because the results of a given accident may range from a virtually negligible impact to a major disaster.

A model is presented that integrates the consideration of the foregoing variabilities into the process of selecting minimum-risk routes. Variations in risk exposure for different links and nodes of the network are estimated through a fault-tree framework, a family of damage propagation relationships, and truck accident statistics. These estimates are employed to compute minimum-risk routes for specific types of dangerous goods shipments.

The objectives of the paper are threefold:

1. To present the basic features of an interactive model for dangerous goods routing,
2. To demonstrate the feasibility and use of the model for a typical application, and
3. To illustrate the route pattern sensitivity in terms of alternative routing strategies or contextual factors, or both.

MODELING APPROACH

The modeling approach estimates risk exposure for each link in terms of four components:

- Accident rates per movement
- Probabilities of spill damage occurrence per accident
- Spill impact area
- Population exposed within impact area

Accident rates reflect the likelihood that a given shipment will be involved in an accident on each link and node in the network. For each accident, the fault-tree analysis estimates the probability of spill damage occurrence. Finally, for each potential such occurrence, the impact propagation models estimate the impact area involved and the number of people exposed. Details of each stage of this process will be provided.

Accident Rates

The accident rate component of the risk exposure is separated into two subcomponents. On roadways, it is expressed as the number of truck accidents per truck vehicle kilometer on each

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discrete 0.5-km section. For intersections, the accident rate is expressed on the basis of per-truck movement for all constituent approaches.

Two contextual factors were found to significantly influence truck accident rates, namely, geometric design and weather. The specific categories considered are summarized in Table 1. For each category, a separate "conditional probability" is estimated based on observed accident profiles for 1,400 truck accidents in Toronto during 1981 (4). These conditional probabilities are applied to all network links and nodes with similar contextual restrictions.

TABLE 1 CONDITIONAL TRUCK ACCIDENT RATES PER TRUCK KILOMETER (4)

	Dry Pavement		Wet Pavement	
	Unrestricted Visibility	Restricted Visibility	Unrestricted Visibility	Restricted Visibility
Arterials and collectors				
50 km/hr	3.72	3.96	1.82	0.96
> 50 km/hr	2.74	1.78	1.89	1.74
Expressways				
< 100 km/hr	0.88	1.67	0.96	0.53
100 km/hr	1.48	2.52	1.73	2.74
Junctions				
Ramps	2.22	5.22	2.58	8.28
Major intersections	0.83	0.94	0.88	0.59

NOTE: Accident rates are expressed in accidents per million vehicle kilometers.

Probability of Spill Damage Occurrence

Several methods are available for estimating the probabilities associated with system failures. A fault-tree analysis was selected for this study because it permits the contextual relationships associated with the handling and transportation of dangerous goods to be internalized (5-7).

In general, a fault tree represents a deductive failure mechanism. An undesirable state is specified, and the system is analyzed in terms of the inherent environmental and operational characteristics that influence the failure likelihood (6). The ultimate objective of the analysis is to estimate the probability of occurrence of a system failure subject to a sequence of preconditioning or prior events. In each case, the logical cause-and-effect relationships between lower- and higher-order occurrences in the failure sequence are represented by using logic gates.

The general fault-tree approach was adapted to the dangerous goods routing problem by specifying four distinctive failure mechanisms related to spill damage occurrence:

1. Airborne release of toxic vapor outside containment,
2. Explosion of unstable liquid or solid,
3. Explosion of confined or unconfined vapor cloud, and
4. Flash fire accompanying the spill of a flammable liquid.

As an example, a simplified representation of the fault tree for item 1 is shown in Figures 1-3. In Figure 1 two conditions need to be satisfied to permit a toxic vapor release:

1. A vapor plume must be present outside containment, and
2. The material released must be toxic.

Vapor is present outside containment if there is a direct vapor release from the tanker or if the material is spilled in the form of a liquid or solid solution with subsequent evaporation. Breach of containment (direct vapor release from the tanker) is broken down further into causes, for example, because of load-induced failure in the container or heat-induced internal pressure build-up (Figures 2 and 3, respectively).

The material is considered to be toxic if it is toxic in transport or if the material becomes toxic in reaction because of the presence of a catalyst.

Spill Impact Area

For each spill, the consequent damages are estimated in terms of several impact propagation relationships. These relationships estimate the magnitude of the affected area as a function of release rate, duration of release, wind speed, material toxicity, and concentration. An estimate of the number of people exposed is derived by multiplying this estimated impact area by the relevant population density.

The population density employed within the model is a weighted sum of the residential and employment population in an area for a complete 24-hr day. These population estimates are highly correlated with property distribution, so that separate data for property distribution and damage are not explicitly included.

Consequent damages are expressed only in terms of immediate impacts to nearby population. Immediacy here refers to damages that are sustained during the duration of the spill before any recontainment or cleanup action. Essentially, in this aspect the long-term effects of dangerous goods spills, such as any carcinogenic effects, are ignored. Exposure to long-term effects is frequently correlated with immediate population impacts.

The size of any impact area is determined from physical relationships associated with each spill. Four types of impact-range relationships are considered:

1. Dispersal of toxic airborne contaminants,
2. Fireball from ignition of vapor cloud,
3. Blast effect of vapor cloud explosion, and
4. Ignition of flammable liquid.

These damage relationships are as follows:

Dispersal of toxic airborne contaminants (8, pp. 10-13):

$$r = \left(\frac{W * e * Kt}{3.14 * u * p * a} \right)^{1/b}$$

where

- W = weight per unit volume (g/m^3),
 e = volume of material released (m^3/sec),
 Kt = duration factor (dimensionless),
 u = wind speed (m/sec),
 p = ppm equivalent (g/m^3), and
 a, b = coefficients dependent on air stability.

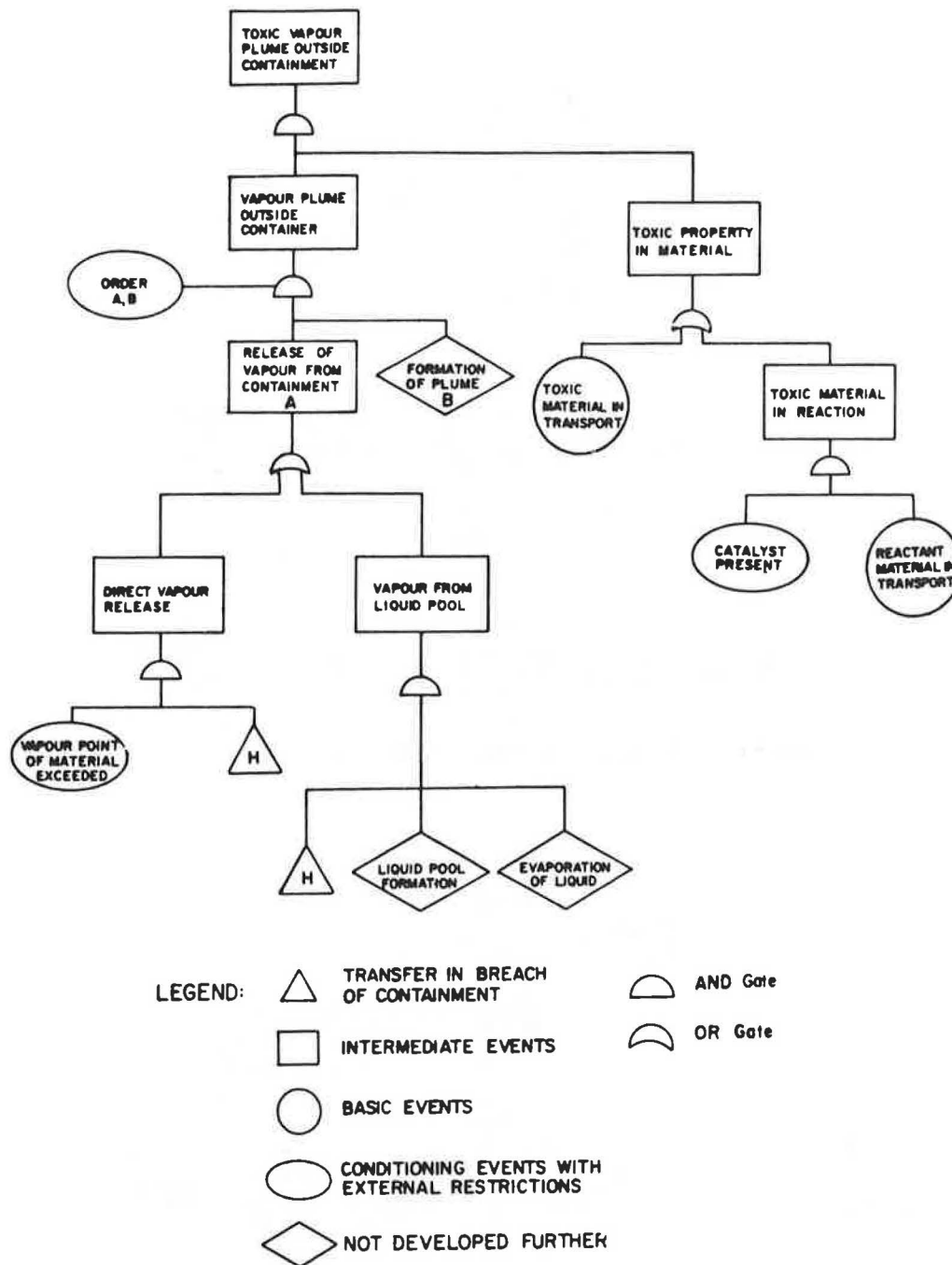


FIGURE 1 Fault tree for airborne release of a toxic vapor.

Fireball from ignition of vapor cloud (9, pp. 5–11):

$$r = 27.5 (M)^{1/3}$$

where r is the range of the fireball (m) and M is the mass of hydrocarbon in the material (tonnes).

Blast effect of vapor cloud explosion:

$$r = R(B) (M)^{1/3}$$

where

r = range of blast impact zone (m),
 M = mass of TNT equivalent of material (kg), and
 $R(B)$ = distance factor for specified damage class (for example, Class B damage: $R = 7.0$).

Ignition of flammable liquid:

$$r = f(R)$$

where r is the range of the flash fire and R is the radius of the pool of contaminated area.

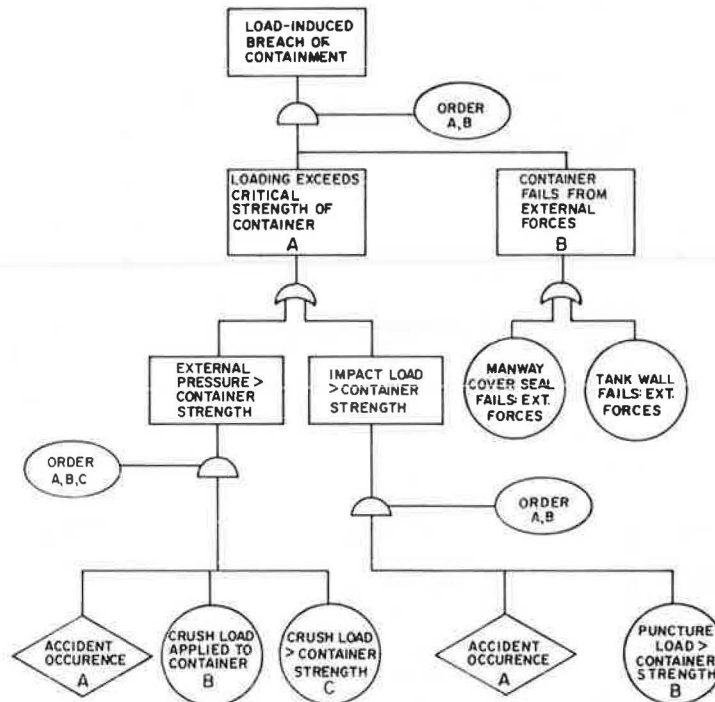


FIGURE 2 Load-induced breach of containment.

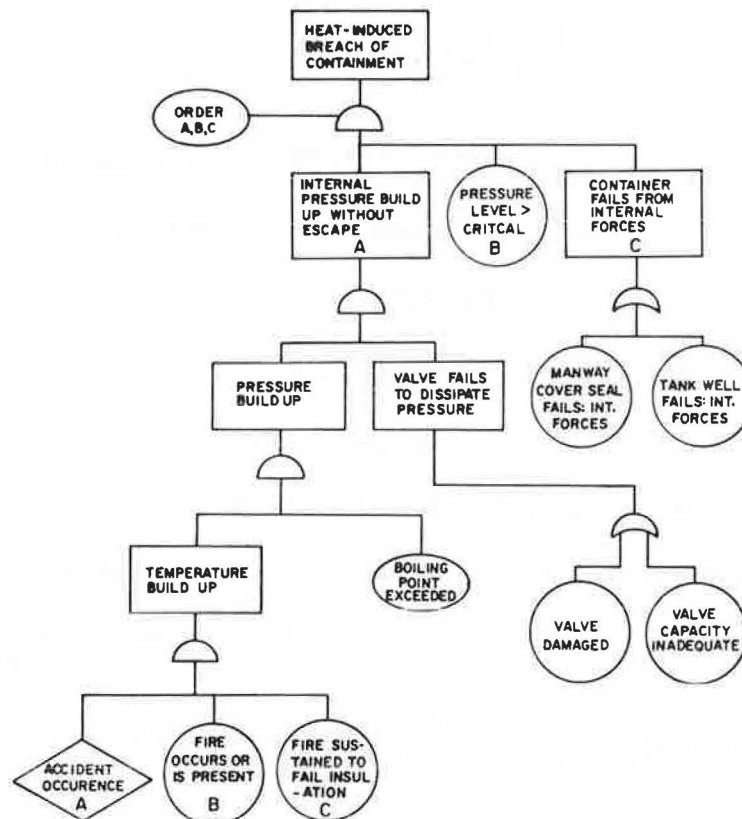


FIGURE 3 Heat-induced breach of containment.

Population Exposed Within Impact Area

The number of people affected by each dangerous goods spill is obtained from the cumulative effects of all relevant damage modes within a designated impact area.

For each road section k (link and intersection) the number of persons exposed to damage mode m is estimated as the following product:

Persons

$$\begin{aligned} \text{exposed} = & (\text{link accident rate} + \text{intersection accident rate}) \\ & * (\text{release/fire/explosion probability per} \\ & \text{accident}) \\ & * (\text{impact area for damage mode } m) \\ & * (\text{population density along road section } k) \end{aligned}$$

The model emphasizes the derivation of dangerous goods routes based on the foregoing estimate of objective risk exposure. However, from an operational standpoint, accident rates and spill damage potential may also be considered as simpler surrogates for objective risk exposure. The model can employ these partial indexes for suggesting dangerous goods routes and allows them to be compared with the more comprehensive risk estimate, as calculated earlier. In addition, routes based on minimum truck operating costs may also be generated.

The various options for computing alternative routings permit a true evaluation of the cost-effectiveness of minimum-risk routes. Comparisons against minimum-operating-cost routes indicate the trade-offs between the benefits to society and the costs to the trucking industry. Similarly, comparisons against simpler risk surrogates indicate the relative merits of using more sophisticated risk measures.

Model Implementation

The procedure is implemented in terms of an interactive program for a microcomputer. The model logic is coded in compiled BASIC to illustrate the approach and demonstrate the sensitivity of routes to different contextual factors. The core program structure consists of four distinct phases, as shown in Figure 4. In addition, a set of graphical routines is available to plot the routes being selected for any number of origin-destination (O/D) pairs in the network. The program phases are described in the following paragraphs.

Specification of Routing Strategy

In the initial phase, the user selects the routing strategy to be considered from the four alternatives:

- Minimum truck operating cost
- Minimum truck accident rate
- Minimum spill damage potential
- Minimum objective risk exposure

Specification of Contextual Factors

In the next phase a range of specification factors is determined for each routing strategy, for example:

- Accident environment
- Material properties
- Spill relationships
- Containment factors
- Location characteristics

From these contextual factors, impedance measures per individual link movement are calculated for each link and node in the network.

Route Estimation

In the third phase the minimum-path tree for a specified origin node is calculated. This optimization finds routes that minimize the cumulative link impedances between a given origin and all destinations. Given a destination, the desirable minimum path can be selected.

Evaluation

In the final phase, a specific route is evaluated and the cumulative route impedance for all strategies is computed subject to the underlying contextual factors. At this stage the selected route can be stored for plotting and a feedback loop can be entered. The latter permits a variety of model parameters to be reselected, so that sensitivity analyses are possible. All route files are stored as external permanent files for later reference.

MODEL APPLICATION

The model was validated on the basis of an application to the metropolitan Toronto road network. Details are provided in the following paragraphs.

Background

Metropolitan Toronto has a total population of nearly 2.5 million. An abstraction of the Toronto road network used in this analysis is shown in Figure 5. The abstracted network involves the use of 255 nodes and 457 links, reflecting the network's major traffic arteries, which also serve the bulk of the truck movements within the area.

The primary objectives of model application are

1. To assess the sensitivity of route patterns to different routing strategies for a given set of contextual factors, and
2. To assess the sensitivity of route patterns to different contextual factors for a given routing strategy and material.

The first objective attempts to capture the differences in routes that arise when different strategies are used. The second objective addresses the extent to which different environmental conditions affect the resultant route patterns.

Chlorine was selected for testing the algorithm subject to certain contextual restrictions. In addition, the analysis was concentrated on trips starting from the downtown area (Node 66) and proceeding to four external areas (Nodes 8, 142, 200, and 253), as shown in Figure 5. The contextual restrictions used were

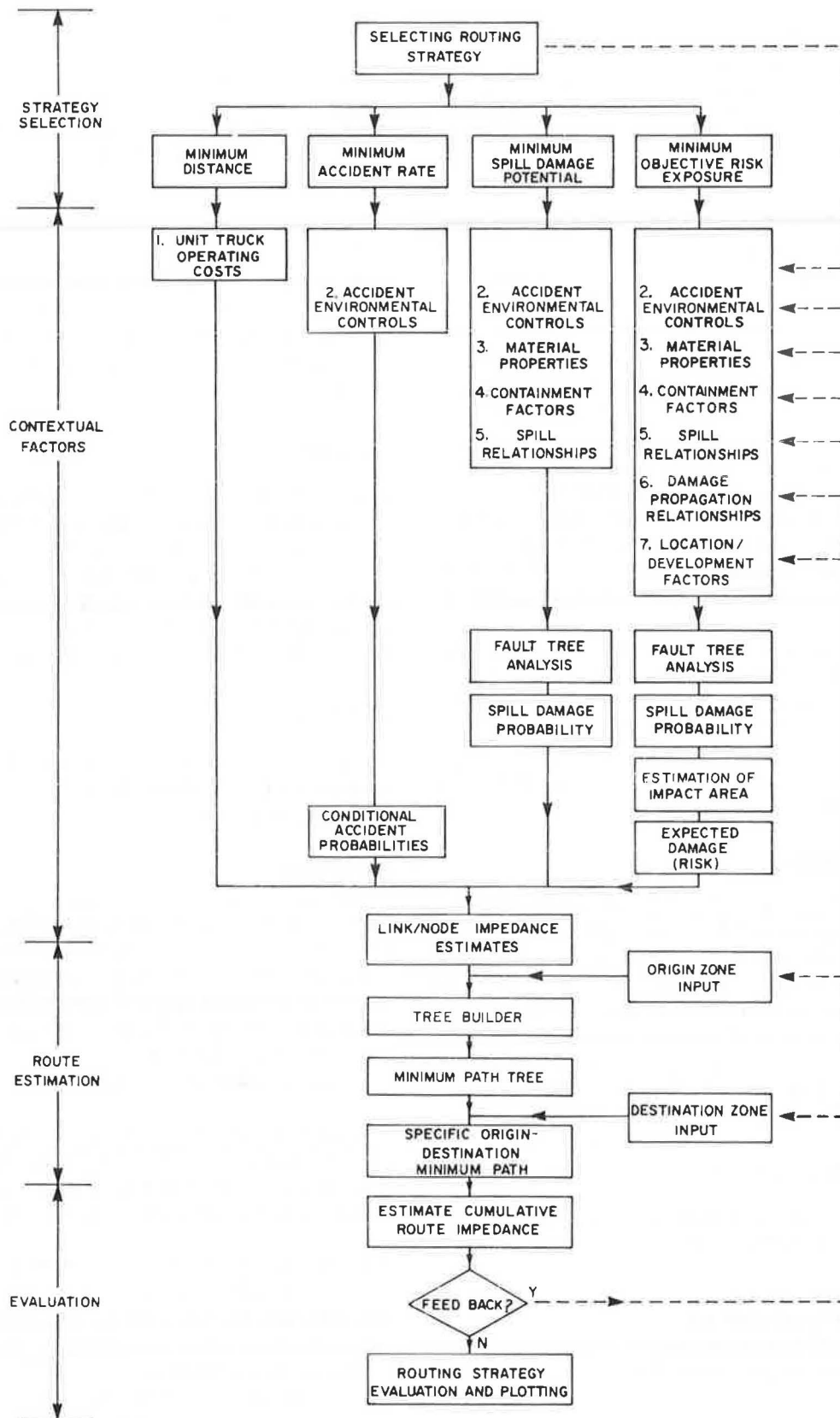


FIGURE 4 Program structure of routing-model implementation.

1. Density of chlorine at standard temperature and pressure (STP) = 320 g/m³,
2. Critical toxic concentration 60 min from spill = 20 ppm,
3. Spill rate for spill damage occurrence = 0.5 m³/sec,
4. Volume in container at STP = 320 m³,
5. Prevailing wind speed at spill site = 0.50 m/sec (negligible wind), and
6. Atmospheric conditions = unstable.

Results

Table 2 gives the results of the model application for four representative O/D pairs in the Toronto network. For each pair the relevant routing criterion impedance measure and the corresponding trip distance are listed.

A graphical comparison between the results for the four alternative routing strategies is provided in Figure 6. Similarly, Figure 7 provides a comparison of the routes that were selected for each combination of the two different types of environmental conditions that were assessed for each routing strategy. The significance of both these comparisons is discussed next.

DISCUSSION OF MODEL APPLICATION

A comparison of routings between alternative strategies and different environmental conditions reveals a number of interesting findings.

Alternative Routing Strategies

Figure 6 shows the sensitivity of routes to the use of different routing strategies. This sensitivity, however, is not ubiquitous

TABLE 2 SUMMARY OF ROUTING CRITERIA FOR EACH O/D PAIR

a. Minimum Truck Operating Costs								
Conditions	Destination 008		Destination 142		Destination 200		Destination 253	
	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.
All		16.3		18.1		19.9		23.4

b. Minimum Truck Accident Rate								
Conditions	Destination 008		Destination 142		Destination 200		Destination 253	
	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.
U - D	44.8	18.6	74.3	27.2	56.0	19.9	85.0	27.3
U - W	61.7	18.9	72.2	19.5	62.0	20.5	85.1	27.3
R - D	41.8	18.7	49.9	18.1	47.2	20.6	62.8	23.4
R - W	42.6	17.1	36.5	26.0	32.6	20.9	60.4	28.0

c. Minimum Spill Damage Potential								
Conditions	Destination 008		Destination 142		Destination 200		Destination 253	
	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.
U - D	1.1	18.6	1.8	27.2	1.4	19.9	2.1	27.3
U - W	1.5	18.9	1.9	19.5	1.5	20.5	2.1	27.3
R - D	1.0	18.7	1.2	18.1	1.2	20.6	1.6	23.4
R - W	1.0	17.1	0.9	26.0	0.8	20.9	1.5	28.0

d. Minimum Objective Risk Exposure								
Conditions	Destination 008		Destination 142		Destination 200		Destination 253	
	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.	Imp.	Dist.
U - D	356.0	23.4	433.0	29.5	370.0	22.1	451.0	34.6
U - W	1386.0	23.5	1358.0	32.3	1091.0	21.4	1304.0	37.3
R - D	4264.0	19.6	4526.0	22.4	3982.0	21.4	4663.0	25.0
R - W	703.0	17.1	591.0	26.0	693.0	25.0	906.0	40.8

Notes:

Conditions: Visibility (U = Unrestricted, R = Restricted)

Pavement (D = Dry , W = Wet)

Impedance : Expressed as E-06: b. number of accidents

c. number of releases

d. number of people affected

Distance : Expressed in kilometers

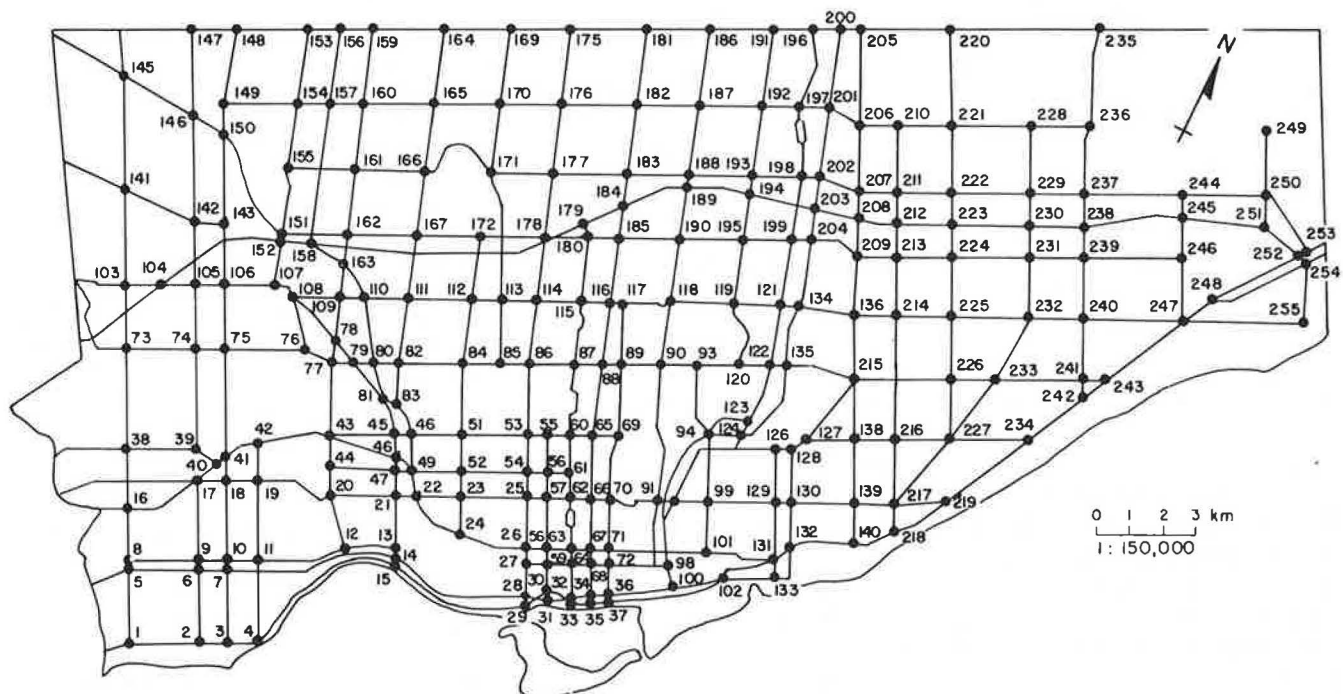


FIGURE 5 Abstracted Toronto link-node road network.

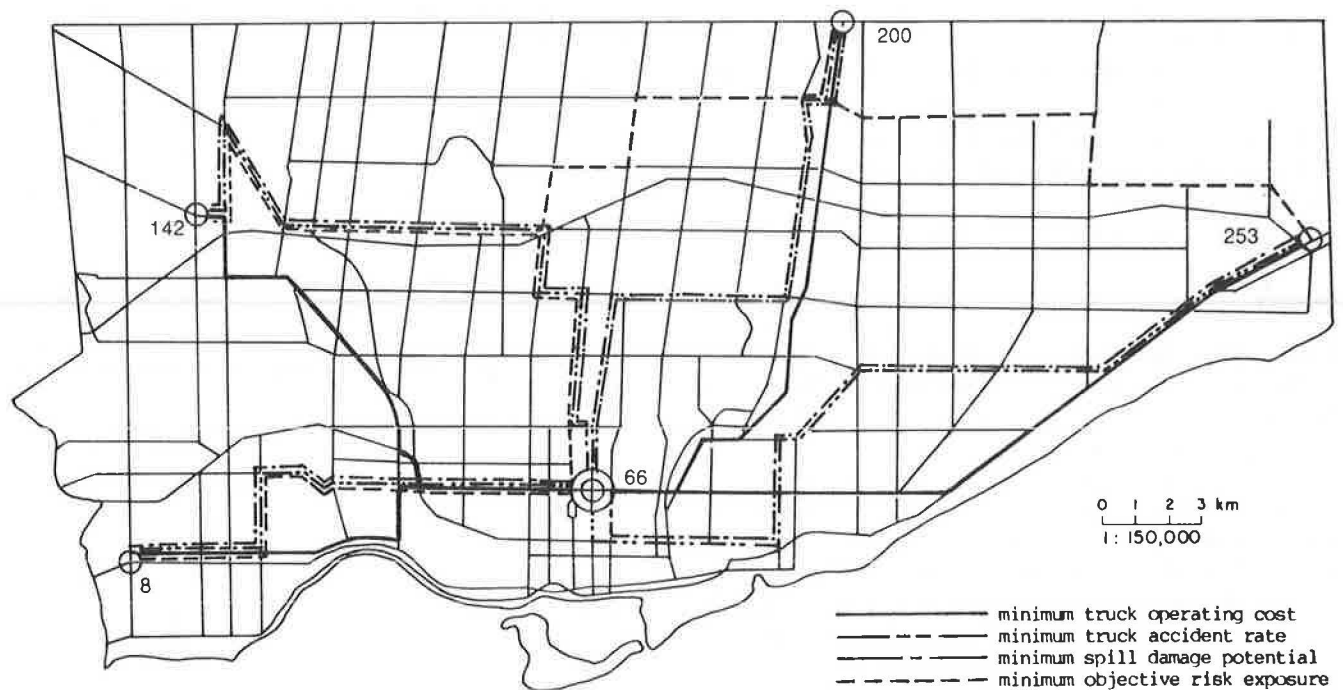


FIGURE 6 Alternative routing strategies for sample O/D pairs.

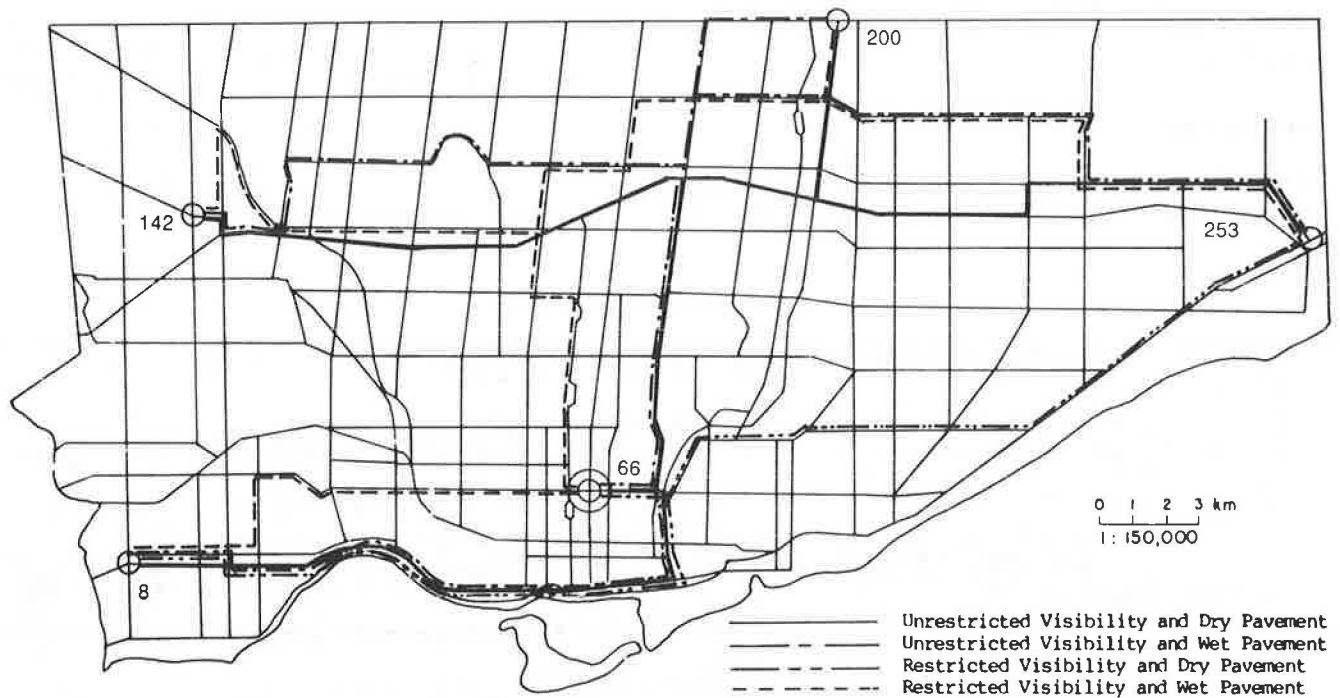


FIGURE 7 Minimum-risk routes for alternative weather conditions.

for all O/D pairs in the network. For example, O/D pair 66–8 suggests the same route regardless of the underlying strategy. This is expected, given the lack of alternative routes. O/D pair 66–253, on the other hand, suggests a range of routes unique to each routing strategy. Other O/D pairs in the network yield route options that are moderately sensitive to these strategies.

For the contextual restrictions used in the analysis, both the accident rate and the spill damage potential strategies yield essentially the same route pattern. This indicates that enhancements to the accident rate measure, by means of supplementary

fault-tree analyses, have not affected the resultant route options to an appreciable extent. This implies that from a routing standpoint, the two measures yield essentially the same patterns regardless of context.

Different Environmental Conditions

Figure 7 shows the differences in route patterns for the minimum-risk strategy under two different meteorological conditions (favorable and adverse). Although in some cases routes

appear to be highly sensitive to these conditions, again the extent of sensitivity is not ubiquitous for all O/D pairs in the network. For example, O/D pair 66-200 indicates negligible change for the two environmental extremes, whereas routes for O/D pairs 66-142, 66-200, and 66-253 are significantly affected.

The cumulative route impedances in Table 2 indicate that risk levels may be higher under favorable weather conditions than under adverse weather conditions. This apparent contradiction may be due to lower observed truck accident rates in Toronto for adverse weather conditions on certain classes of roads, which may indicate that, all factors assumed constant, truck drivers are much more careful during adverse weather. This aspect was observed to be true in the case of the 1981 truck accident statistics used in this application. Furthermore, during adverse versus favorable weather, the differences in dispersal conditions result in a more confined critical concentration isoline for the spill area. Adverse weather causes a greater dispersal of contaminants and a further dilution of the material in the plume. Consequently, damages under adverse conditions are correspondingly reduced.

Cumulative Truck Accident and Damage Rates

The probability of dangerous goods incidents appears to be relatively low on a per-shipment basis, regardless of whether accident rate or spill damage potential is considered. The low values obtained in this study may suggest that the possibility of negative impacts on population from dangerous goods shipments is too rare to warrant any remedial action. Although this argument has been made in the past to justify lack of action, it may lack validity when total shipments are considered for an entire network and for an extended period of time.

Saccomanno and Chan (4) indicated that the restriction of dangerous goods movements to designated risk routes can yield approximately \$20.7 million in savings in risk costs over the route option that strictly minimizes operating cost. This would result in an increased operating cost to the trucking industry of approximately \$11.8 million per year.

CONCLUSIONS

The safety of transporting dangerous goods in large urban areas can be enhanced through the application of effective strategies. The methodology and model presented in this paper have provided a basis for evaluating and comparing such strategies.

The application of the model also demonstrated that routing patterns may be sensitive to the specific strategy that is selected and, within each specific strategy, to varying environmental

conditions. To the extent that these latter conditions vary over time and space, safe routes must be viewed in dynamic terms. In general terms, this analysis has demonstrated the value of developing a systematic framework for risk assessment that is sensitive to these dynamics.

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