Economic Evaluation of Routing Strategies for Hazardous Road Shipments

F. FRANK SACCOMANNO and A. Y.-W. CHAN

ABSTRACT

Potential risks from hazardous materials spills can be reduced by restricting shipments to designated safe routes. Several criteria can be used for designating safe truck routes with widely varying results. Three distinctive routing strategies for the road transportation of hazardous materials are discussed: minimum risk, minimum accident likelihood, and minimum truck operating costs. Each routing strategy is applied to the Toronto road network, on the basis of 1981 truck accident profiles. Recommended safe routes are analyzed for cost-effectiveness for a wide range of environmental conditions. Two important aspects emerge from this cost-effectiveness analysis: (a) the minimum risk routing strategy produces net economic gains in the form of enhanced safety, and (b) significant trade-offs occur between truck operating costs and safety benefits. These trade-offs are of fundamental concern to the implementation of this type of safety enhancement strategy for the transportation of hazardous materials.

The transportation of hazardous materials on congested urban roads is becoming an important concern. Several strategies for reducing the incidence of accidental spills have been considered. One such strategy is to restrict hazardous movements in urban areas to designated routes, where the potential risks are perceived to be less severe.

Ashton (1) Nemmers and Williams (2), House (3), and Wright and Glickman (4) provide an extensive review of current experience with safe routing strategies in North America and Europe. In general, recent practice has been to direct hazardous shipments to designated corridors, where land development is less intensive, and historical accident rates are less pronounced. The underlying basis of this approach is to project past accident trends into the future with a minimum assessment of the contextual factors that affect accident occurrence at specific locations in the road network at different points in time. A static assessment of past accident experience, however, may fail to effectively identify those routes that are safe under a wide range of random environmental conditions.

Three basic concerns that have not been fully addressed in the literature are examined in this paper:

1. Evaluation of alternative control strategies for restricting hazardous material traffic to specific routes. Three strategies will be assessed: minimum objective risk exposure, minimum accident likelihood, and minimum truck operating cost. Each control strategy reflects a different view of the underlying safety principle associated with this type of traffic.
2. Evaluation of the sensitivity of each designated route in the network to changes in random environmental influences.
3. Assessment of the incidence of costs and benefits associated with each control strategy for various environmental influences.

In the interest of implementation, an economic evaluation of alternative routing strategies for hazardous materials must address the incidence of costs and benefits to society in general and to the trucking industry in particular. Minimum risk routes may involve more circuitous travel patterns and, consequently, increased truck operating costs. These trade-offs are understandably of critical importance to the trucking industry and must be resolved if this type of safety enhancement program is to become more practicable.

METHODOLOGY FOR DESIGNATING SAFE TRUCK ROUTES

The three criteria under study are based on a minimization of truck operating costs, accident likelihood, and risk exposure.

Minimizing Truck Operating Costs

These costs include only time and out-of-pocket expenses borne directly by the truck operator. Accident costs occur too infrequently and too randomly to be perceived in normal route choice decisions; consequently, these costs have not been included in estimating direct operating expenses. Furthermore, although a significant portion of accident costs are borne directly by those individuals involved in the accident, the full allocation of these costs is distorted by legal and insurance settlements. A large component of the damage from specific accidents may be shared by the trucking industry as a whole through universal insurance premium increases. As a result, it is unlikely that these damages are perceived or incorporated into normal route choice decisions.

A routing strategy that is based on minimum truck operating costs is essentially an unregulated approach. Where route restrictions are not in effect, operators will likely select those routes that yield lower time and out-of-pocket expenses. Because safer routes may involve more circuitous travel paths, a control strategy that is based solely on minimizing operating costs serves as a reference for comparing the cost-effectiveness of these alternative safety strategies.

Minimizing Accident Likelihood

This routing strategy incorporates the relative frequency of truck accidents on select road links directly into the decision framework. Safety is essentially enhanced by restricting hazardous movements to routes where the potential for accident occurrence is reduced.

Because the frequency of accidents at specific locations in the road network varies from time to time depending on random environmental influences, a minimum accident likelihood strategy must be effective over a wide range of conditions. Two types of random environmental influences are considered in this paper: deterministic and stochastic. For each accident profile, deterministic influences can be controlled through specific planning and design options. Stochastic influences, however, although predictable to a degree, remain essentially unalterable in nature.

Deterministic influences are reflected in road design characteristics where these characteristics are expected to in some way affect general accident rates. For illustrative purposes, six homogeneous road classes have been selected to represent deterministic influences on truck accident rates:

- Expressways--design speed ≥ 100 km/hr,
- Expressways--design speed < 100 km/hr,
- Arterials and collectors--design speed > 50 km/hr,
- Arterials and collectors--design speed ≤ 50 km/hr,
- Major intersections, and
- Expressway ramps.

Similarly, four factors are used to represent stochastic influences at specific locations of the road network:

- Pavement surface condition--wet,
- Pavement surface condition--dry,
- Visibility--unrestricted, and
- Visibility--restricted.

In general, accident response to both deterministic and stochastic influences is expected to be random in nature, and can therefore be expressed in probabilistic terms.

In this paper, two assumptions are made concerning the interrelationships of constituent environmental factors. First, the occurrence of stochastic influences is assumed to be independent of the previous incidence of deterministic influences. For commercial traffic in urban areas, the choice of road type is not likely to be affected by random factors such as pavement surface and visibility. As noted by Saccomanno and Chan (5), observed truck movements in Toronto in 1981 substantiate this assertion. The second assumption concerns the probability of encountering certain road types along a given route. Because constituent links of a specific type are either present or absent for a given route, link probabilities of truck accident occurrence can be expressed as

$$\begin{aligned} P[A \cap E_d(i) \cap E_s(j)] &= P[A|E_d(i) \cap E_s(j)]\ P[E_d(i)|E_s(j)]\ P[E_s(j)] \\ &= P[A|E_d(i) \cap E_s(j)]\ P[E_s(j)] \end{aligned} \tag{1}$$

where

$P[A|E_d(i) \cap E_s(j)]$ = conditional probability of truck accidents given the previous joint occurrence of deterministic and stochastic factors $E_d(i)$ and $E_s(j)$, respectively;
$P[E_d(i)|E_s(j)]$ = conditional probability that factor $E_d(i)$ takes place given the previous occurrence of factor $E_s(j)$;
$P[E_s(j)]$ = probability for occurrence of stochastic factor $E_s(j)$; and
$P[A \cap E_d(i) \cap E_s(j)]$ = joint probability of a truck accident for a specific set of environmental influences.

Equation 1 is simply the truck accident rate for a specific combination of environmental influences, and can be rewritten as

$$P[A \cap E_d(i) \cap E_s(j)] = P[E_s(j)]\ (NA/TTV\text{-}km) \Big|_{\substack{E_d(i) \\ E_s(j)}} \tag{2}$$

where NA is the number of truck accidents for a given set of environmental conditions, and TTV-km is the total truck vehicle-kilometers for this same set of conditions. The distance factor in Equation 2 is used to standardize accident rates for a unit interval of roadway. Route probabilities for a single truck movement can be obtained by multiplying this standardized accident probability by the link distance and summing the result over all constituent links of the truck route.

Minimizing Objective Risk Exposure

Objective risk exposure for each link in the road network is defined simply as the product of accident likelihood and consequent damages from each material spill. Both accident liklihood and consequent damages are assumed to be affected by random environmental influences. As a result, estimates of risk exposure along specific links of the road network must account for variations induced by changes in these influences.

A number of studies have assessed the consequent damages to population and property from exposure to various hazardous materials spills (6-9). In general, these studies have recognized that certain environmental conditions present in each accident profile can affect the containment of damages to varying degrees. Again, the central concern in this literature is to suggest a context for each accident profile that relates directly to consequent damages.

Consequent damages are confined in this paper to three types of impact: (a) toxic--airborne dispersion of contaminants, (b) fire--ignition of flammable vapor cloud, and (c) explosion--blast effect of unconfined vapor cloud. As noted by Cairns (10), a realistic damage spectrum can be considerably more extensive than is implied by these three damage features. Individual damages may be augmented dramatically by process interdependencies. For example, Rose (11) has noted that an explosion can be followed by either a shock wave, a fireball, or fragmentation of material, each with a distinctive set of ramifications. The intricacies of the damage process are clearly outside the scope of this study, and have not been incorporated directly into the framework.

Three types of damages are assumed to result from the consequent impacts of hazardous materials spills:

1. Damages to individuals directly involved in each accident [this includes drivers and passengers of all vehicles (trucks and otherwise) involved];
2. Damages to individuals not directly involved in the accident but who reside in proximity to the spill site; and
3. General property damages that result directly or indirectly from a spill (this includes vehicles and other properties).

The damages associated with each spill are multiplied by the probability of accident occurrence to give an estimate of risk exposure along each link of the road network. The expression used in this study is of the following form:

$$R_i(k) = \sum_j P_{ij} \cdot D(k) \tag{3}$$

where

$R_i(k)$ = objective risk on a unit interval of class i road;
P_{ij} = joint probability of accident occurrence on road class i for stochastic event j from Equation 2...$P[A \cap E_d(i) \cap E_s(j)]$; and
$D(k)$ = likely damage associated with link k of the road network.

The minimum risk route is obtained by summing the link risk from Equation 3 over all constituent links (including intersections) for each route. Risk exposure for each route can be expressed either for a given set of stochastic environmental conditions or, if the probability of occurrence for these conditions is known, risk can be estimated for all possible stochastic conditions over a given interval. The latter is accomplished by summing link accident probabilities from Equation 3 over all events j.

ESTIMATING THE COSTS OF RISK EXPOSURE

Before evaluating the economic effectiveness of alternative routing strategies, it is desirable to express the potential damage associated with accidental spills in terms of actual costs. For the three types of impact under consideration, road link damages can be obtained from the expression

$$D(k) = \alpha^T C^T(k) + \alpha^F C^F(k) + \alpha^E C^E(k) \tag{4}$$

where

$D(k)$ = aggregate damage costs for road link k ($);
$C^T(k)$, $C^F(k)$, and $C^E(k)$ = costs for toxic, fire, and explosion damages, respectively; and
α^T, α^F, and α^E = proportion of hazardous materials spills that result in toxic, fire, and explosion effects, respectively.

An assessment of historical accident records that involve hazardous materials provides a basic estimate of the proportion of spills in which toxic, fire, and explosion effects take place. Table 1 is a summary of the types of damage associated with various hazardous materials spills in the United States from 1973 through 1979 as documented by FHWA (6). On average, toxic, fire, and explosion effects have occurred in 0.032, 0.019, and 0.065 percent of all reported spills, respectively. Because information on prevailing environmental conditions at each spill site is not available, it is not possible to adjust these values by random environmental influences.

TABLE 1 Types of Road Accidents Involving Hazardous Materials in United States, 1973-1979 *(6)*

Material	Fire	Explosion	Toxic	Spill without Damages
Gasoline	34	11	0	49
Flammable liquids	13	5	0	28
Flammable compressed gas	4	13	12	12
Nonflammable compressed gas	0	0	0	8
Oxidizing materials	0	1	0	3
Poison, class A	1	0	1	1
Poison, class B	2	0	0	3
Explosives, class A	1	3	0	1
Expolsives, class C	1	2	0	1
Combustibles	3	2	0	5
Corrosive materials	4	1	0	10
Radioactive materials	0	0	0	2
Total	63	38	13	109

Damages that result from toxic, fire, and explosion effects can be expressed in terms of specific impacts on population and property. For toxic effects, for example, the expression is of the following form:

$$C^T(k) = (\gamma^T_{ft} C^f + \gamma^T_{it} C^i) + (\gamma_{fp} C^f + \gamma_{ip} C^i)\, A^T(k)\, p(k) + \overline{PD}^T \tag{5}$$

where

$C^T(k)$ = total cost of damage on link k from toxic impact;
γ^T_{ft}, γ^T_{it} = the proportion of fatalities and injuries to individuals directly involved in each accident where toxic impact is realized;
γ^T_{fp}, γ^T_{ip} = the proportion of fatalities and injuries to population in proximity to each spill site, where toxic impact is realized;
C_i, C^f = average real cost value of injuries and fatalities, respectively;
$A^T(k)$ = impact area for toxic damages on road link k;
$p(k)$ = population density associated with link k; and
$\overline{PD}^T$ = average damages to property where toxic impact is realized (vehicles, buildings, etc.).

Similar expressions can be obtained for fire and explosion effects.

Analysis of 140 accident profiles from FHWA records from 1973 through 1979 provides an estimate of the proportion of accidental spills that result in fatalities, injuries, and property damage. These records are used to calibrate the parameters in Equation 5. Given the accidental release of hazardous material, the additional consequences following each spill are assumed to be similar for both the U.S. and Canada.

The average costs, associated with fatalities and injuries, are based on data obtained from the National Safety Council (NSC) (12) and the National Highway Traffic Safety Administration (NHTSA) (13), U.S. Department of Transportation. These costs, expressed in 1981 Canadian dollars, are as follows. (Note: "NA" means not applicable, and 1981 Canadian dollars can be converted to 1981 U.S. dollars by multiplying by 0.72.)

	NHTSA (1981 $ Canada)	NSC (1981 $ Canada)
Fatal	617,190	230,520
Critical injury	413,156	NA
Severe injury	17,376	9,085
Moderate injury	9,349	NA
Minor injury	4,707	NA

Cost differences between the two agencies are essentially a result of different reporting procedures. The NSC records include only direct costs of fatalities and injuries whereas the NHTSA records also include indirect social costs. In general, two assumptions tend to cause distortions in these damage estimates: (a) that relocation costs have been ignored, and (b) that only major spills were reported.

The costs of relocating victims of an accidental hazardous materials spill can be significant. In many accidents, this cost component tends to dominate the damage spectrum, particularly where actual fatalities and injuries are few, but the potential risk is perceived to be severe. Relocation costs are assumed in this paper to be proportional to population levels within designated impact zones for each road link. The absence of a clear estimate of relocation costs, however, necessitates the production, by using Equation 5, of a new cost estimate that will underestimate the real damage associated with each accidental spill. In this way, the inclusion of only major spills in the data base can be compensated for, so as to yield a more realistic cost estimate.

A zone of impact can be obtained for each link in the road network by assuming a continuum of possible spill sites along its length, and a circular range of impact for each spill. The assumption of a circular range of impact may not reflect a realistic dispersal of toxic contaminants. As noted by Schulze (14), plume dispersion arcs of 20 to 40 degrees have been observed, depending on wind speed and direction. The circular dispersion formula in this study is a center line of plume estimate, with the wind blowing from all directions. As such, the impact zone estimated for each road link tends to overestimate the area that is likely to be affected in a real spill situation. The area of impact for each link depends on the nature of damage from a potential spill. As an example, for toxic damage, the zone that is likely to be affected can be obtained from the expression

$$f_k^T(w) = \begin{cases} 2w\ell_w + \pi^2 & \text{for each link} \\ \pi w^2 & \text{for each intersection} \end{cases} \qquad (6)$$

where

$f_k^T(w)$ = impact area for toxic effects on road section k,
ℓ_k = link distance (km), and
w = range (m).

Similar expressions can be established for fire and explosion effects. Several empirical relationships have been used in this study to estimate the expected range of toxic, fire, and explosion impacts along each link of the road network. These expressions are a function of material properties and environmental conditions. For example, fire can be expressed by using the amount of hydrocarbons in the spill material; explosion can be expressed by using the amount of trinitrotoluene (TNT) equivalent in the material; and toxic dispersal can be expressed by using wind direction, wind speed, and atmospheric stability. The structure of these relationships is discussed in detail by Schulze (14).

Exposure to each potential spill varies with distance from the accident site. More distant points are not contained within the range of potential damage for the same duration time as nearby points. In this paper, the range w in Equation 6 is multiplied by a factor of $\pi/4$ to standardize the range for exposure variations with distance. Within this reduced range, all locations are assumed to be equally affected by hazardous materials spills.

SENSITIVITIES OF ALTERNATIVE ROUTING STRATEGIES FOR TORONTO

An aggregation of the Toronto road network is used to study the effects of alternative routing strategies for the transportation of hazardous materials. This network consists of 255 nodes and 457 links. Eleven origin-destination (OD) zones have been selected to represent areas where the production and use of hazardous materials is likely to be more pronounced. These OD zones are coincident with major concentrations of industrial activity and with principal entry or exit gates into the urban region.

A total of 1,084 heavy truck accident profiles were extracted from Metropolitan Toronto police records for 1981. These records provide an excellent description of the contextual framework in which each accident takes place. Annual network-wide heavy truck volumes were estimated from Metro cordon counts (15), supplemented by daily vehicle traffic counts on each section of the network. Population and employment densities associated with each road link are averages of nearby 1981 census district values.

Conditional accident probabilities for heavy truck movements, as estimated from Equation 2, are summarized in Table 2 for a range of environmental conditions. These values suggest that despite environmental changes, truck accident rates remain infrequent random events. When road class is considered, truck accidents are less likely to occur on expressways than on arterials over all pavement surface and visibility restrictions. This may reflect higher design standards on expressways, with emphasis on entry and exit controls, traffic stream separation, and less abrupt alignment changes. These standards are especially important for heavy trucks, where vehicle maneuverability is appreciably reduced relative to the automobile. On arterial roads, however, restrictions imposed by wet pavement can produce higher accident rates, especially where design speeds are also higher. More significantly, accident probabilities on expressway ramps are several times greater than probabilities on discrete 1-km segments

TABLE 2 Conditional Truck Accident Probabilities

	Probability ($X10^{-6}$)					
Conditions	A	B	C	D	E	F
Dry pavement						
Unrestricted visibility	3.715	2.744	0.876	1.478	2.215	0.830
Restricted visibility	3.957	1.779	1.672	2.519	5.218	0.935
Wet pavement						
Unrestricted visibility	1.816	1.895	0.956	1.728	2.580	0.878
Restricted visibility	0.957	1.737	0.531	2.740	8.279	0.593

Note: A = arterial/collectors with speed = 50 km/hr; B = arterial/collectors with speed > 50 km/hr; C = expressways with speed < 100 km/hr; D = expressways with speed = 100 km/hr; E = ramps; and F = major intersections.

of expressway links for the same set of environmental influences. Again, because ramps are associated with more abrupt changes in direction and speed, these results attest to the maneuverability problems associated with heavy trucks. It is interesting to note that no appreciable difference in accident rates is revealed between intersections and arterial links. (Link accidents are those that occur at minor intersections along each arterial link.) Apparently, maneuverability factors are not as critical on arterial roads, where speeds are lower and response times are less restrictive. It should be noted, however, that only major intersections have been identified in this study.

In the final analysis, however, it is not possible to speculate that all intersections are safer than arterial links solely on the basis of these results because accident rates for a selected number of major intersections tend to be lower than link accident rates.

Minimum path trees were obtained for each of the 11 zones in the road network, under the three control strategies that minimize risk, accident likelihood, and truck operating cost. For illustrative purposes, the minimum path trees for the downtown industrial zone have been included in this paper in Figures 1 and 2. Minimum paths for the downtown zone represent close, network-wide sensitivities to control strategies and environmental conditions. In general, the minimum path trees for all 11 zones indicate a high sensitivity not only to underlying routing strategy, but also for each strategy for which they represent significant variations for different combinations of environmental factors. As illustrated in Figures 1 and 2, when operating costs are minimized, arterial roads comprise a greater share of the minimum paths that connect the central zone to each of the 10 outer zones. For example, when risk is minimized, expressway use is increased commensurately especially for the more restrictive environmental conditions such as wet pavement and reduced visibility. In addition, when risk is minimized, road links in the central area are avoided for all environmental influences. This does not appear to be the case for the minimum accident likelihood or minimum operating cost strategies. Essentially, the risk measure appears to be sensitive to higher population and employment densities in the central area, where the potential damage from an accidental spill of hazardous materials is expected to be more pronounced.

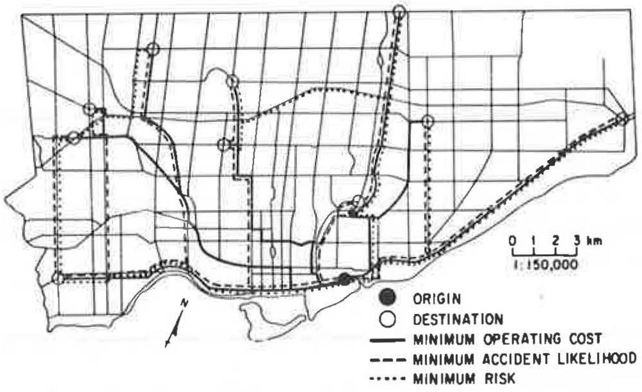

FIGURE 1 Minimum path trees for downtown zone under dry pavement and unrestricted visibility.

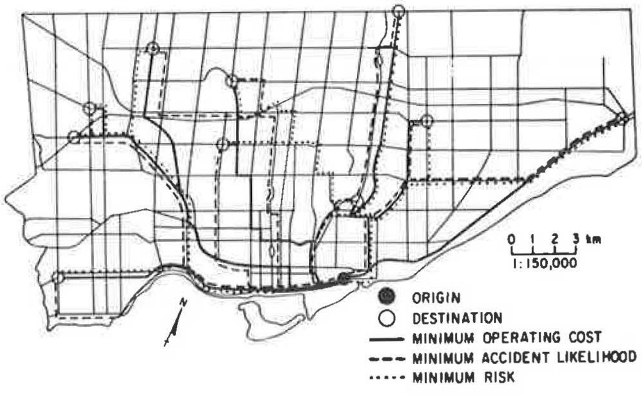

FIGURE 2 Minimum path trees for downtown zone under wet pavement and restricted visibility.

In this analysis, the Toronto road network is a simplified aggregation of reality in that minor streets and intersections have been ignored. A detailed road network with a more extensive array of links and nodes would very likely increase the choice options at each node and therefore accentuate the variations in route choice as suggested here.

EVALUATING COSTS AND BENEFITS

A true appreciation of the full incidence of costs and benefits associated with each routing strategy is not attainable without first determining the actual movements of hazardous materials over the network. Nevertheless, some insight into the relative cost-effective merits of alternative routing strategies is possible from the analysis of a single truck movement between all OD pairs in the network.

Several cost components are summarized in Table 3 for each of the three control routing strategies, and several combinations of environmental factors. All costs in this table are in terms of a single truck movement along the minimum paths joining all 11 OD zones in the Toronto road network. Total truck operating costs for constituent links are based on unit values from Table 4 for central and suburban locations where these costs are multiplied by the appropriate link distance. Expected accident costs in Table 3 are similarly obtained by multiplying estimates of direct unit damages to population and vehicles by the probability of accident occurrence associated with each constituent link of the desig-

TABLE 3 Summary of Cost Components for the Routing Strategies

	Cost Component (1981 $ Canada)		
	Minimum Operating Cost	Minimum Accident Likelihood	Minimum Risk
Dry pavement			
Unrestricted visibility			
Operating cost	1,746.17	1,939.48	2,049.35
Direct accident cost	67.96	57.50	63.70
Risk	990.23	706.47	603.58
Restricted visibility			
Operating cost	1,746.17	2,021.85	2,020.26
Direct accident cost	67.96	84.90	90.60
Risk	1,784.60	1,725.50	1,179.20
Wet pavement			
Unrestricted visibility			
Operating cost	1,746.17	1,814.73	1,919.56
Direct accident cost	67.96	67.23	71.94
Risk	811.01	772.30	647.58
Restricted visibility			
Operating cost	1,746.17	2,055.97	1,999.46
Direct accident cost	67.96	77.95	75.46
Risk	762.51	704.00	532.00

Note: To convert 1981 Canadian dollars to 1981 U.S. dollars, multiply by 0.72.

TABLE 4 Unit Truck Operating Costs *(16)*

Item	Cost (1980 $ Canada/km)
Central business district	
Crew	0.740
Fuel and oil	0.140
Tire wear	0.051
Maintenance	
Parts	0.060
Labor	0.046
Interest and depreciation	0.129
Fixed cost	0.059
Total	1.225
Other urban area	
Crew	0.446
Fuel and oil	0.101
Tire wear	0.042
Maintenance	
Parts	0.052
Labor	0.040
Interest and depreciation	0.129
Fixed cost	0.050
Total	0.860

Note: To convert 1980 Canadian dollars to 1980 U.S. dollars, multiply by 0.72.

nated minimum path. Costs that reflect risk exposure include indirect potential damages to adjacent population for each road link. Potential damages from accidental material spills are confined to toxic, fire, and explosion effects expressed in terms of fatalities, injuries, and property damages.

As expected, minimum operating cost routes produce aggregate truck operating costs that are significantly lower than either minimum risk or minimum accident likelihood options. This advantage for the minimum truck operating cost strategy is gained at the expense of higher risks. This trade-off between safety enhancement and increased truck operating costs occurs consistently for all environmental combinations without significant variations.

The inclusion of an accident cost component does not alter route patterns to any substantial degree. Accident costs are not significant in relation to either risk or truck operating costs and can thus be ignored. It is interesting to note that accident costs are not reduced for those routing strategies where safety is the primary concern. Expected accident costs are strongly influenced by exposure along selected routes, where exposure is a function of distance traveled. Because distance is minimized commensurately with a minimum truck operating cost strategy, accident costs also tend to be lower for these results.

The trade-offs between truck operating costs and risk are shown in Figures 3 and 4 for each routing strategy and two combinations of environmental influences. In general the minimum accident likelihood strategy is not cost-effective. With the exception of unrestricted environmental conditions (i.e., dry pavement and unrestricted visibility), minimum accident likelihood routes consistently yield both higher risk values and, in most cases, higher operating costs. Lower risk values associated with minimum risk routes, however, are sufficient to offset higher truck operating expenses relative to the minimum operating cost strategy. These minimum risk routes yield an average savings per vehicle-kilometer traveled of $0.22 per single truck movement.

An annual commercial traffic volume of 496.3 million vehicle-km was observed in Toronto in 1978 of which approximately 19 percent comprised some type of hazardous material (15). Restriction of this traffic to designated minimum risk routes can yield approximately $20.7 million in savings per year over the route option currently in effect that minimizes operating costs. Increased costs to the trucking industry, however, are approximately $11.8 million per year. Environmental conditions, as defined in this paper, do not generally appear to alter these cost trade-offs to any large extent.

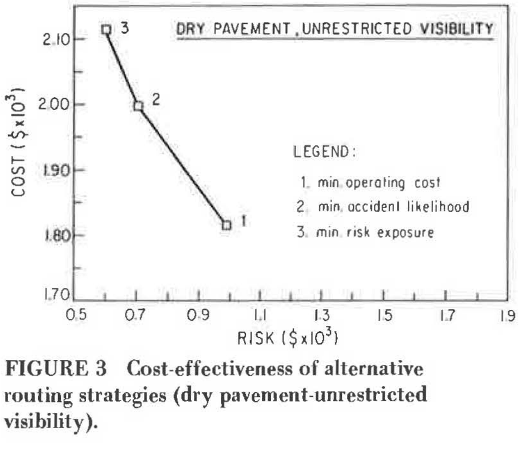

FIGURE 3 Cost-effectiveness of alternative routing strategies (dry pavement-unrestricted visibility).

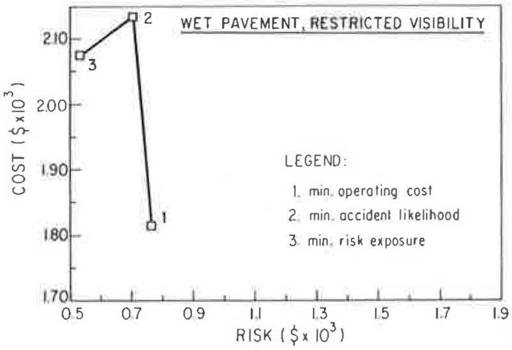

FIGURE 4 Cost-effectiveness of alternative routing strategies (wet pavement-restricted visibility).

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The safe transportation of hazardous materials in large urban areas can be enhanced through effective routing strategies. Distinctive route options are suggested for each of three strategies: minimum truck operating costs, minimum accident likelihood, and minimum objective risk exposure. Within each strategy, designated routes are observed to be highly sensitive to random environmental influences. These influences can vary over time and for different locations in the road network.

2. A minimum risk routing strategy can reduce potential damages associated with hazardous materials spills, and can produce net economic gains to society. Minimum risk routes are clearly the most cost-effective means of restricting hazardous shipments on the urban road network. The effectiveness of this strategy, however, must be viewed in relation to higher truck operating costs. In the interests of implementation, any safety enhancement program for the transportation of hazardous materials based on route choice must address the problem of higher operating costs as borne by the trucking industry.

3. A routing strategy that is based solely on minimum accident likelihood does not appear to be cost-effective. Not only are operating costs higher for this strategy relative to the minimum operating cost approach, but risk benefits are also lower. The introduction of direct accident costs into the analysis fails to alter any of these conclusions. Accident costs are not significant when compared with either truck operating expenses or risk exposure, and can be neglected without altering the results to any appreciable extent.

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