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Foreword

Truck transportation is the subject of the first two papers in this volume. List and Turnquist describe a method for estimating multi-class truck trip matrices from partial and fragmentary observations. The method is linked to a geographic information system environment for data management and display of the results. A case study focused on the Bronx, New York, estimates trip matrices for vans and medium and heavy trucks.

The focus of the work reported by Fawaz and Garrison is a system-level approach to new combinations of trucks, highways, and operations that could achieve significant productivity gains. An example of grain transportation in rural areas is used to demonstrate a simulation model to assess benefits of new combinations. Institutional and operational changes required to implement new truck-highway combinations are discussed.

The next three papers address issues involved in the transportation of hazardous materials. In the first paper, Saccomanno and Cassidy present a discussion on the use of quantitative risk assessment in the transport of dangerous goods. The emphasis areas in this discussion include risk uncertainty, communication, and decision support. In the second paper, Leeming and Saccomanno describe the application of Transport RISKAT (Risk Assessment Tool) to a case study involving a road-rail alternative available to an industrial facility handling chlorine. The evaluation addresses the transfer of risk from one system to the other and the level of overall risks to the transportation networks. In the third paper, Kornhauser et al. review the road-rail alternative in shipping anhydrous ammonia using a distribution risk decision support tool. The authors identify the problems involved in evaluating hazardous materials transport, the attributes needed to conduct the evaluation, and how the results are used to select a specific mode and route.

The final paper presents a model to predict tow delays caused by the interruption of service at a single lock.

Estimating Truck Travel Patterns in Urban Areas

GEORGE F. LIST AND MARK A. TURNQUIST

A method for estimating multi-class truck trip matrices from partial and fragmentary observations is presented. Data sets of widely varying character are combined in an efficient and effective manner so that each piece of information plays a role in developing the estimated flows. The method is linked to a geographic information system environment for data management and display of the results. Its use is illustrated through a case study focusing on the Bronx in New York City. Trip matrices are estimated for three truck classes: vans and medium and heavy trucks. Future advances for the method are outlined.

Although trip matrix estimation has been an area of research for some time, interest has increased recently because of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and its renewed support for local planning activities. In the New York City area, for example, the New York Metropolitan Transportation Commission (NYMTC), the metropolitan planning organization, has embarked on an extensive effort to update its baseline origin-to-destination (OD) trip matrices (*1*).

It is also becoming more common to treat truck flows explicitly, instead of simply as percentages of estimated automobile flows. Planners have become concerned with the impacts of capital investments on truck flow patterns and want to take those effects into account when evaluating the benefits and costs of alternative capacity and mobility enhancement options.

However, the development of truck trip matrices, at least from currently available data, is a significant challenge. Different agencies often collect and keep various pieces of the data, the sampling bases are different (e.g., with certain truck classes, origins, or destinations being included or excluded), different definitions are used for the items being collected (e.g., heavy truck, medium truck), and different time frames are employed (e.g., different years, seasons, and starting and ending times during the day).

Thus, there is a need for a matrix estimation technique that is tolerant of wide variations in the input data and robust in its estimation of flows. The technique should also be able to sift through the existing data and determine not only the best current estimate of what the flows are, but also what additional data would have the greatest value in improving that estimate.

Such a method and its application to a case study in the Bronx in New York City are described in this paper. Additional details on the material presented, as well as a second complete case study, are contained in a larger report (*2*) from which this paper is drawn.

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REVIEW OF EXISTING FLOW ESTIMATION TECHNIQUES

One of the earliest efforts to formulate the problem of estimating an OD matrix that would produce an observed set of link flows was by Robillard (*3*). He proposed a nonlinear regression model but did not fully appreciate the degree to which the problem is underconstrained. A much more complete solution based on nonlinear programming was offered by Turnquist and Gur (*4*). This work also introduced the concept of a "target matrix" as a way of incorporating information other than link counts, but did not develop the idea fully.

Van Zuylen and Willumsen (*5*) adapted Wilson's idea (*6*) of "entropy maximization" to the problem as a way of differentiating among alternative OD matrices, each of which would produce the same set of link volumes. This work was followed by efforts by several other authors (*7–12*), resulting in a series of improvements to the basic ideas. The underlying theory was improved and greater recognition was given to important empirical problems like inconsistent or missing link data.

An alternative approach was also developed in the early 1980s, based on a more statistical view (*13–17*). This line of work views the problem as a constrained regression, in which parameters of an underlying model are to be estimated so as to yield the "best fit" to the set of observed data. Both ways of viewing the problem lead to some form of optimization formulation, and Brenninger-Gothe, et al. (*12*) have provided an excellent summary of the relationships among many of the models.

The approach presented here contains elements from several of these earlier efforts, but extends the general model formulation in some important respects. First, because of the interest in truck movements, it deals with multiple vehicle classes and data that include observations over different subsets of classes. Some of the previous authors have mentioned multiple-class problems briefly, but their main emphasis has been on passenger automobiles.

Second, the method provides control parameters sufficient to allow specification of both varying degrees of confidence in different observations as well as asymmetric error functions for overestimation and underestimation of observed values. This is similar in some respects to the previous work of Maher (*14*) and Brenninger-Gothe, et al. (*12*), but more extensive.

Third, the model that develops the estimates is designed to accept data in forms other than link counts. The objective is to be able to use all of the available data, in whatever form and from whatever source. This is a much broader objective than is present in the earlier efforts, and requires a more general formulation. The formulation is different from the specification of a "target matrix," which is embedded in most of the earlier efforts, because constraints on row-sums or column-sums, for example in the OD matrices to be estimated, can be specifically created.

DESCRIPTION OF THE METHOD

It is assumed that the analysis network consists of links joined at nodes, and that each link has at least three attributes: (*a*) a directional flag (i.e., $i \rightarrow j$, $j \rightarrow i$, or both); (*b*) a use label (which truck classes are allowed); and (*c*) a travel time (which may vary by time of day). Further, the underlying geography is presumably divisible into exhaustive, non-overlapping zones, such as zip codes or census tracts. Each zone must have a centroid where trips originate and terminate, and that centroid must either be an existing network node or a new node that is attached to one or more existing network nodes by centroid connectors.

A set of truck classes is assumed, based on the Federal Highway Administration truck classes ("*F*" classes) or some other suitable classification scheme. In the case study presented in this paper, a three-tier classification scheme is used: (*a*) commercial vans, (*b*) medium trucks (two-axle, six-tire and three-axle single unit), and (*c*) heavy trucks (trucks with four or more axles, and all tractor trailers).

Finally, a routing algorithm must be employed to develop link use coefficients for each OD pair (i.e., the proportion of a given OD flow that will appear on a given link). Dial's probabilistic path assignment algorithm (*18*) is used in the example presented later, but other algorithms could be used.

Types of Input Data

A set of postulates concerning input data augments the basic assumptions. The data are of three types:

1. Link volumes or classification counts;
2. Partial OD estimates for various zones, time periods, and truck classes; and
3. Originating/terminating data (e.g., the number of trucks within certain classes or sets of classes originating or terminating in a particular zone or entry node on the network's periphery).

Link Volume Data

The link volume (LV) data provide estimates of link flows for the network. For example, a classification count provides truck volumes by direction, vehicle type, and time of day for a given location. Turning counts and data from automatic counters provide similar information, especially if they classify vehicles (e.g., a video-based detection scheme).

The model constraints must relate the truck classifications in these volume counts to the classifications employed in the analysis. For example, assume that a count for link j includes both two-axle, six-tire trucks, and three-axle trucks in the same group, whereas on link, k, three-axle trucks are grouped together with four-or-more axle trucks. If these two counts are denoted as C_j and C_k respectively, and the model variables V_{2j} and V_{2k} refer to link flows of two-axle, six-tire trucks, V_{3j} and V_{3k} represent three-axle trucks, and V_{Hj} and V_{Hk} represent four-or-more axle trucks, then the following constraints capture the information contained in both counts:

$$V_{2j} + V_{3j} = C_j \qquad (1)$$

$$V_{3k} + V_{Hk} = C_k \qquad (2)$$

OD Data

OD data provide estimates of flow matrix entries. Typically, such data come from surveys of vehicles crossing a given link or passing through a network gateway. A survey conducted at an internal location generates observations for selected trip table cells, and an inbound survey provides estimates for one row ("from" entries), and an outbound survey the estimates for one column ("to" entries).

Constraints link these observations to trip matrix cells. For example, let Figure 1 depict a situation in which one zone structure (e.g., zones A, B and C) is used for modeling purposes and another (e.g., zones X and Y) was used for an OD survey. Constraints are needed that relate the observed trips (to and from zones X and Y) to those being modeled (i.e., zones A, B, and C). Specifically, if an observation exists (from a survey) of trips from X to j, denoted by T_{Xj}, a constraint can be created, as follows:

$$T_{Aj} + T_{Bj} + T_{Cj} \geq T_{Xj} \qquad (3)$$

Note that this constraint is written as a less-than-or-equal-to constraint because the aggregation of model zones A, B and C is larger than the survey zone X. Hence, the observation should be a lower bound on the total estimated trips from the three zones (A, B and C) to Zone j.

OT Data

Originating/terminating (OT) data provide observations of flows destined to or originating from some specific location in the network (i.e., row and column totals). A count of truck trips originating within a given zone or combination of zones represents a row total; an estimate of trucks outbound at a gateway node (e.g., at a bridge or toll plaza) is a column total.

As with the LV and OD data, constraints translate and relate the observation-related truck classes to those used in the model:

$$\sum_{k \in K_x} \sum_{d} v_{odk} \geq V_{ox} \qquad \forall\ o, x \qquad (4)$$

where

- V_{ox} = the observed volume in truck class cluster x originating at node (zone centriod or gateway node) o,
- K_x = the set of truck classes k contained in the observation, and
- v_{odk} = the variable for the number of trucks of type k going from origin o to destination d.

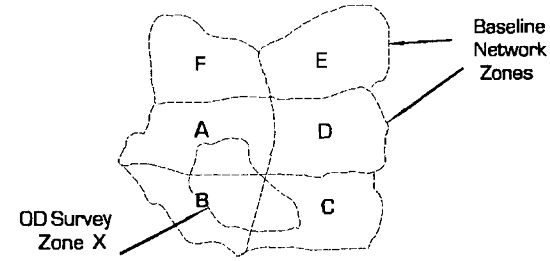

FIGURE 1 Zone mapping illustration.

Overall Model Description

In summary, estimation of the trip matrices is treated as a large-scale linear programming problem in which the objective is to minimize the weighted sum of all deviations from the observed values, given (*a*) the choice variable definitions provided by the user (i.e., truck classes and zone structure), (*b*) the network definition, and (*c*) the link use coefficients provided by the traffic assignment algorithm.

Mathematically, the model can be stated as follows:
Minimize

$$\sum_{k} [w_k^d (d_k^- + d_k^+) + w_k^e (e_k^- + e_k^+)] \tag{5}$$

Subject to

$$\sum_{m \in M_k} \alpha_{mk} x_m + e_k^- - e_k^+ + d_k^- - d_k^+ = b_k \quad \forall k \tag{6}$$

$$e_k^- \leq E_k^- \quad \forall k \tag{7}$$

$$e_k^+ \leq E_k^+ \quad \forall k \tag{8}$$

$$e_k^-, e_k^+, d_k^-, d_k^+ \geq 0 \quad \forall k \tag{9}$$

The b_k values are observations (LV, OD, OT) relevant to the problem under consideration. The weights w_k^d and w_k^e ($w_k^d > w_k^e$) are attached to "large" and "small" deviations, respectively, from the observed value, b_k. The magnitudes of "large" deviations (negative and positive) from b_k are denoted by d_k^- and d_k^+, with e_k^- and e_k^+ denoting the magnitudes of "small" deviations. E_k^- and E_k^+ are limits on the magnitude of deviations that may be considered "small." In addition to the b_k, the values of w_k^d, w_k^e E_k^- and E_k^+ are inputs to the model that characterize the penalty functions for observation *k*. The values of d_k^-, d_k^+, e_k^- and e_k^+ are model outputs that reflect the deviations to be minimized.

The major outputs of the model, besides the observation deviations, are the variables x_m, which represent the entries in the OD matrices for the truck classes considered. The subscript *m* is used to denote a "market"—a combination of an OD pair and truck class. Thus, vans from origin *A* to destination *B* constitute one market, three-axle trucks from *A* to *B* are a second, and vans from *C* to *D* are a third.

The values of α_{mk}, which measure the extent to which x_m contributes to creating b_k, are inputs to the model. These are specified in different ways for different types of observations, as described more fully in the next section. M_k is the set of markets that contribute to the generation of b_k.

Use of a piecewise-linear objective function has four major advantages. First, it allows greater sensitivity to large errors than to small ones, in the same way that would be accomplished by minimizing a squared-error function. However, by using a piecewise-linear function, the second advantage of being able to solve the model using commercial large-scale linear programming software can be achieved. Third, by varying the weights associated with different observations, differing degrees of confidence can be reflected among the various observations. Finally, by varying the weights (and limits) associated with positive or negative deviations from the observed (target) value, asymmetric error functions can be created for specific observations, reflecting the fact that it may be important for the model not to underestimate (or overestimate) certain values. The value of these features is best illustrated through a case study application.

CASE STUDY ANALYSIS

The case study focuses on the Bronx in New York City. The network used to conduct the analysis is shown in Figure 2. The Cross-Bronx Expressway (I-95), from the George Washington Bridge at the western side of the study area to the Bronx-Whitestone and Throg's Neck Bridges in the southeastern corner of the area, is a primary corridor for truck flows. The connection to the Bruckner Expressway (I-95 and I-278) at the eastern side of the study area forms a heavily used route to New England. It has been estimated, for example, that more than 13,000 trucks cross the George Washington Bridge eastbound on an average weekday (*19*). In addition, the Hunt's Point area (south of the interchange between the Bruckner Expressway and the Sheridan Expressway—I-895) is the location of the major fresh meat and produce wholesale markets for New York City, generating approximately 15,000 truck trips per day (*20*).

Three time periods and three truck classes are considered. The time periods are 6 to 10 a.m. (a.m. peak), 10 a.m. to 3 p.m. (midday), and 3 to 8 p.m. (p.m. peak). The truck classes are vans (light-duty trucks with two axles and four tires), medium trucks (two-axle, six-tire, and three-axle single unit trucks), and heavy trucks (those with four or more axles, and all tractor-trailer units). A total of nine OD matrices need to be estimated. These matrices are generated three at a time—a van, medium, and heavy matrix—for a given time period. This takes maximum advantage of the overlap among the data sources available without creating complexity (e.g., trying to take into account interplay among the time periods).

Zone and Network Definition

As shown in Figure 3, the study area has 20 internal zones based on zip codes. Ten Bronx zip codes in the northern part of the study area are collapsed into three zones because the land use in these areas is primarily residential or parkland. Also, all 11 of the zip codes in northern Manhattan are collapsed into two zones, one to the north of the George Washington Bridge and one to the south.

Seven external zones augment these internal ones, providing a way to represent flows to and from major traffic generators:

- 100: George Washington Bridge,
- 101: I-87 (New York State Thruway),
- 102: I-95 (New England Section of New York State Thruway),
- 103: Throg's Neck Bridge (I-295),
- 104: Bronx-Whitestone Bridge (I-678),
- 105: Triborough Bridge (I-278), and
- 106: Manhattan south of 110th Street.

Nodes in the original network data base are used as zone centroids. No special nodes are created, nor are centroid connectors designated.

Model Constraints

The model for this situation contains 180 realizations of Equation 6: 44 OD constraints, 52 OT constraints, and 84 LV constraints.

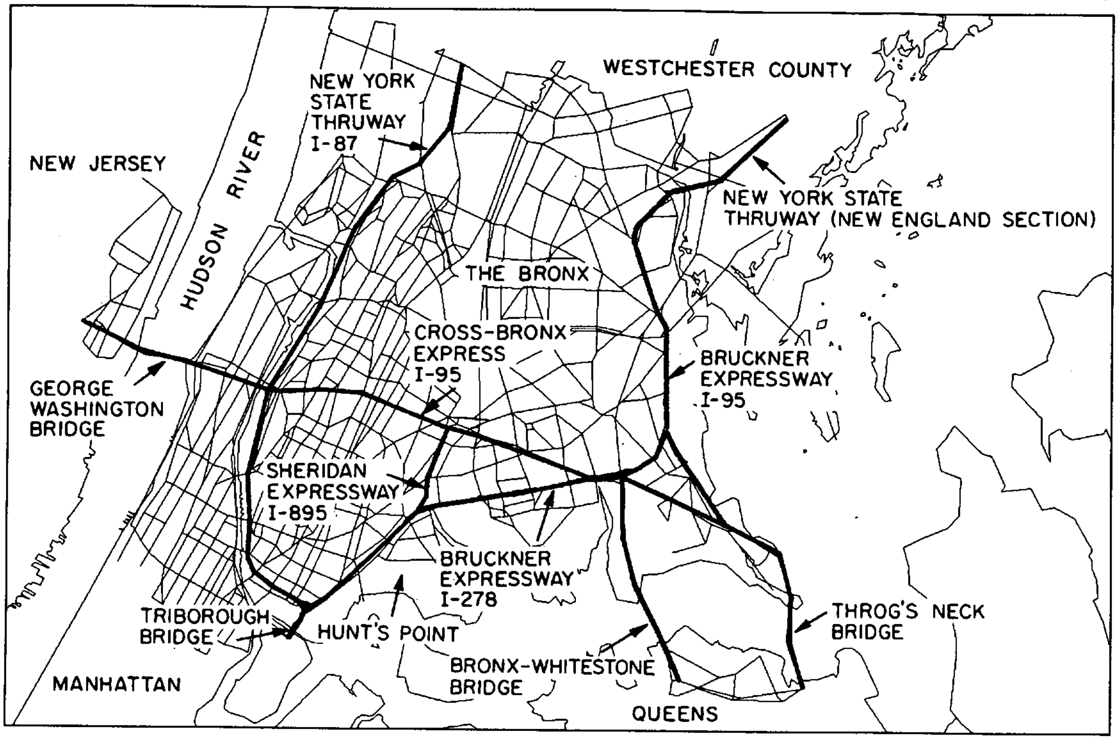

FIGURE 2 Case study network.

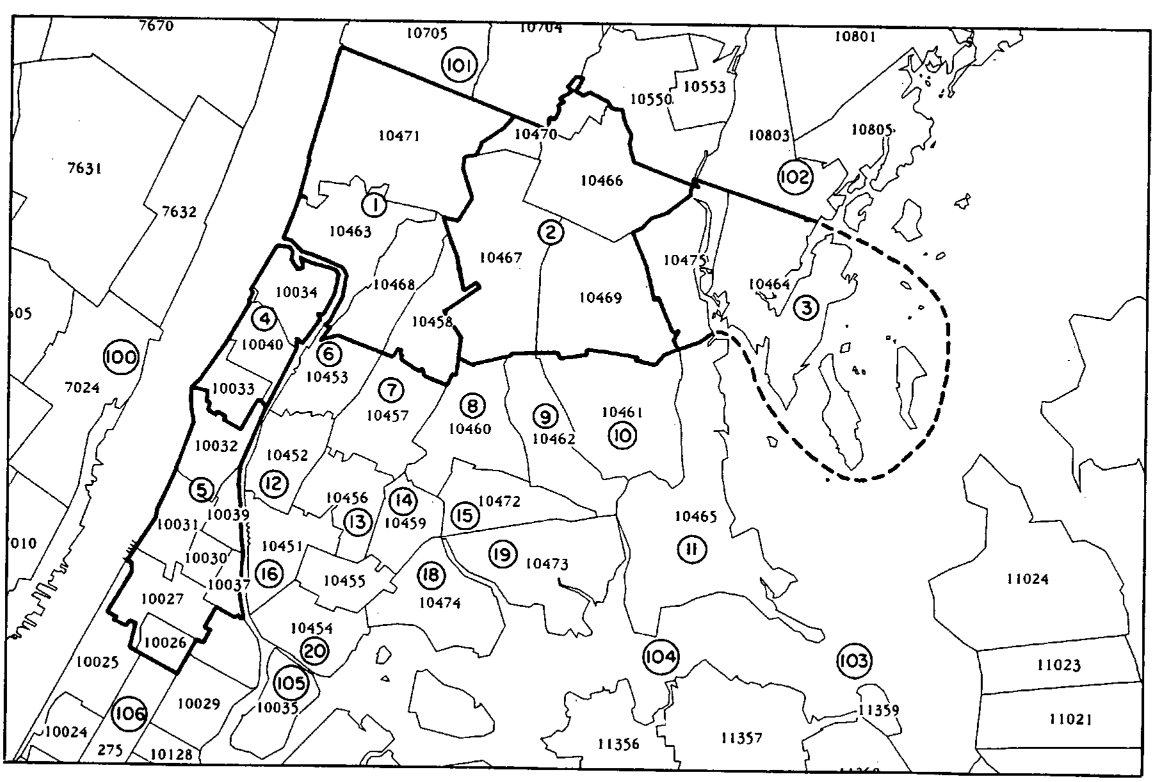

FIGURE 3 Bronx area zip codes and case study zones.

The following three subsections provide examples of how these constraints are developed.

OD Constraints

The 1991 Port Authority of New York and New Jersey (PANYNJ) Truck Commodity Survey and the 1988 Triborough Bridge and Tunnel Authority (TBTA) Truck Survey contain data about flows between a given bridge and a location within the study area. For example, the PANYNJ data capture eastbound flows crossing the George Washington Bridge and the TBTA surveys are for southbound trips at the Triborough, Whitestone, and Throg's Neck Bridges because that is the direction in which tolls are collected.

From these data, generation of the OD constraints is a four step process:

1. Establish the mapping between the survey's zones and those used in the case study. These are the "inclusion rules" discussed earlier pertaining to Equation 3;
2. Expand the survey responses to total truck flows based on counts of trucks by truck type for the same 15-min time periods for which the survey data were collected;
3. Combine the two-axle, six-tire, and three-axle volumes because these both fall into the medium category being used in the modeling effort.
4. Aggregate these observations (for both medium and heavy trucks; vans were not surveyed) into OD flow observations based on the "inclusion rules" from Step 1.

OT Constraints

From the TBTA toll data, the Hunt's Point Access Study, the Bronx Truck Route Study and toll data from the New York State Thruway Authority, it was possible to generate 48 OT constraints. The following example, using the Thruway Authority data, shows how these constraints were created.

For the New Rochelle toll plaza, the Thruway had eastbound volumes by truck class and hour. This information provides an estimate of truck trips "terminating at" or destined for Zone 102. To create an OT constraint from these data involves computing truck volumes by truck class (medium and heavy only, no vans) and time period (a.m., midday, and p.m.). The result is 60 total observations (3 time periods × 2 truck classes × 10 days).

Unlike most of the other data sources, for which only one observation is available, these data provide an explicit statistical rationale for specifying the E_k^+ and E_k^- values. Given the data in the following table, these can be set to the values of the standard deviations for the six observations.

	Medium Trucks		*Heavy Trucks*	
Time Period	*Mean*	*Std. Dev.*	*Mean*	*Std. Dev.*
6 a.m. to 10 a.m.	618	37	784	44
10 a.m. to 3 p.m.	852	52	1,118	81
3 p.m. to 8 p.m.	458	22	787	106

Thus, any model solution within one standard deviation of the observed sample mean will be considered "close," in the sense of having only a small deviation from the observed values.

Link Volume (LV) Constraints

Data from various data sources allowed development of 154 link volume constraints (*21–23*). For example, the Bruckner/Sheridan Interchange Study (*20*) provided data sufficient to generate 12 observations per time period. This data source can be used to illustrate how the LV constraints are developed, and how the link and node structure of the network model affects the way in which flow volumes must be specified.

The Bruckner/Sheridan Study provides four pieces of data for each location counted: total traffic in the a.m. peak hour, total traffic in the p.m. peak hour, annual average daily traffic (AADT) and total daily trucks, as shown in Figure 4. To estimate truck volumes for the 6 to 10 a.m. and 3 to 8 p.m. periods, the following steps are followed:

1. Expand the peak hour traffic volumes to full-period volumes using expansion factors developed by the Planning Division of the New York State Department of Transportation [Erlbaum, N. LDV and HDV Truck Percentages for Mobile 4.0. Internal memorandum, New York State Department of Transportation, Albany, Aug. 9, 1991];
2. Estimate peak period truck flows by vehicle class on the basis of classification counts collected at the same location in a separate study (*24*);
3. Estimate midday flows on the basis of AADT value and hourly distribution data from the Planning Division (*25*); and
4. Assign these volumes by truck class and time period to specific links at the interchange. The unusual part of this process is that the various ramp counts must be aggregated to form link counts for use with the network model. The total exiting and entering volume is assigned to just one link, the ramp link representing all of the exiting and entering movements in this section of the network.

Resolving Inconsistencies in the Data

Because several different sources have been used to generate the individual observations, consistency is a problem that must be faced. A good example of this involves the flows from the George Washington Bridge to the Throg's Neck Bridge (Zone 100 to Zone 103). The Port Authority Truck Commodity Survey (*19*) shows this flow as being 327 medium trucks and 481 heavy trucks during the a.m. peak, 220 and 381 during the midday, and 150 and 190 during the p.m. peak. However, the 1989 TBTA Truck Survey (*26*), which sampled trucks that were Queens bound at the Throg's Neck Bridge, showed only 180 medium and heavy trucks for this same flow in the a.m. peak, and 190 and 250, respectively, for the midday and p.m. peaks. The Port Authority-based values are between 1.3 and 4.5 times larger, with the largest difference in the a.m. peak. There are several possible reasons for this difference, including the following:

1. The expansion from survey proportions to total flow proportions is in error;
2. The translation of survey origins and destinations into zone definitions used in this analysis is incorrect;
3. The estimate of flow proportions by time of day in the TBTA data is in error;

4. The differences exist because the data were collected about two years apart;
5. The survey results are erroneous in one or both surveys; or
6. Some combination of these reasons.

The expansion from survey proportions to total flow estimates has been done differently for the two surveys. For the PANYNJ survey, both the raw survey responses and the toll booth counts of trucks by hour during the survey period are available. For the TBTA survey, the available data are total percentages of trucks by aggregated origin areas, and the aggregate estimate of truck flows by time of day. Thus, the expansion of the TBTA survey results is subject to much larger potential errors, particularly by time of day.

The specification of origin and destination areas in processing of the two surveys is also done differently. In the TBTA survey, it is assumed that the reported origin area "New Jersey" corresponds to the George Washington Bridge (Zone 100). In the Port Authority survey, the reported destination is a PANYNJ zone number, and several zones in eastern Queens, Nassau County, and Suffolk County have been aggregated into the analysis Zone 103.

The fact that the surveys are two years apart is also a potential source of significant variation in results. However, to minimize this likelihood, the TBTA survey data have been expanded using the May 1991 toll data. This should effectively remove the differences in time period as significant sources of error.

Although the differences in these observations are quite substantial, particularly in the a.m. peak period, a decision was made to use both observations with relatively loose "small deviation" limits indicating low confidence in the specific observations. The optimization model then balanced off the differences, together with all other observed values entered as data.

Results of Analysis

Nine OD matrices and associated sets of link flows are generated for the network. The flow pattern for all trucks in the p.m. peak period is shown in Figure 5. Note the large volumes on the major expressways and bridges: (*a*) across the George Washington Bridge, particularly in the westbound direction; (*b*) in both directions on I-87 running north into Westchester County; (*c*) on the Cross-Bronx Expressway and out to the northeast on the New England Section of the New York State Thruway; (*d*) on the Bruckner Expressway, particularly southbound toward the Triborough Bridge; and (*e*) across the Bronx-Whitestone and Throg's Neck Bridges in both directions.

There are also significant flows on some arterials, notably Westchester Avenue and White Plains Road, as well as in the southwestern section of the Bronx. The latter is a direct result of the land use data input to the model, which indicates a very high density of truck trip ends in that part of the analysis area.

The flows of heavy trucks are almost all on the expressway system, as illustrated in Figure 6. The largest volumes are on the George Washington Bridge, the Cross-Bronx Expressway, and the Bruckner Expressway. It is also true that heavy truck flows in the p.m. peak period are principally external-external, going from the George Washington Bridge to Connecticut. This flow pattern

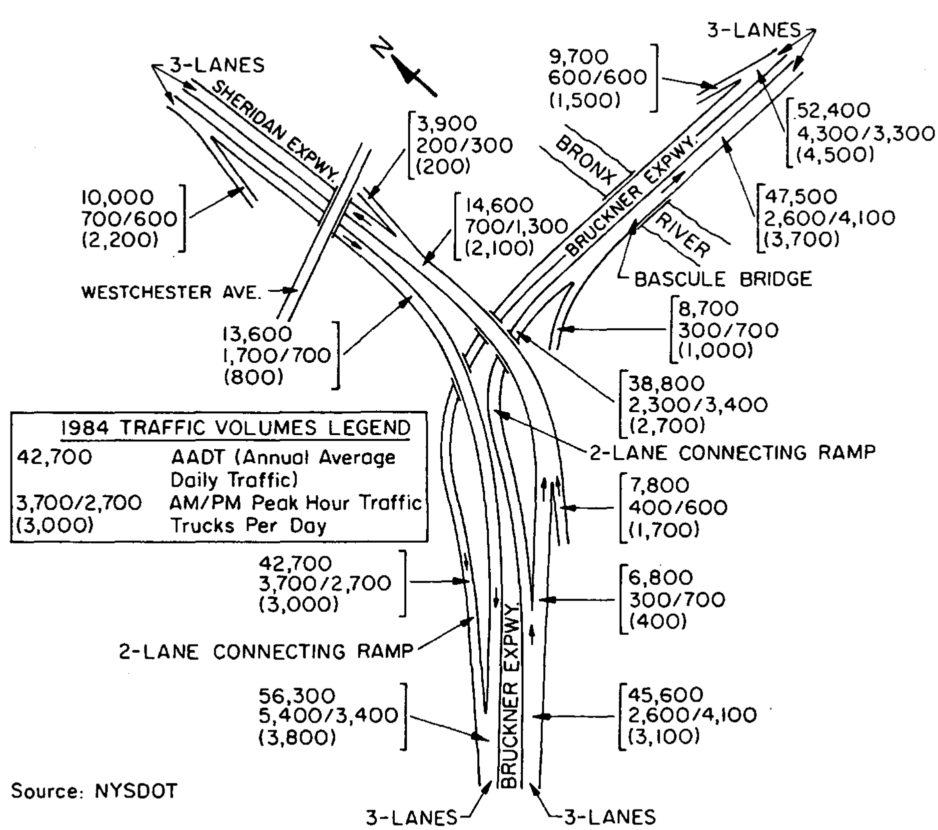

FIGURE 4 Bruckner/Sheridan Interchange.

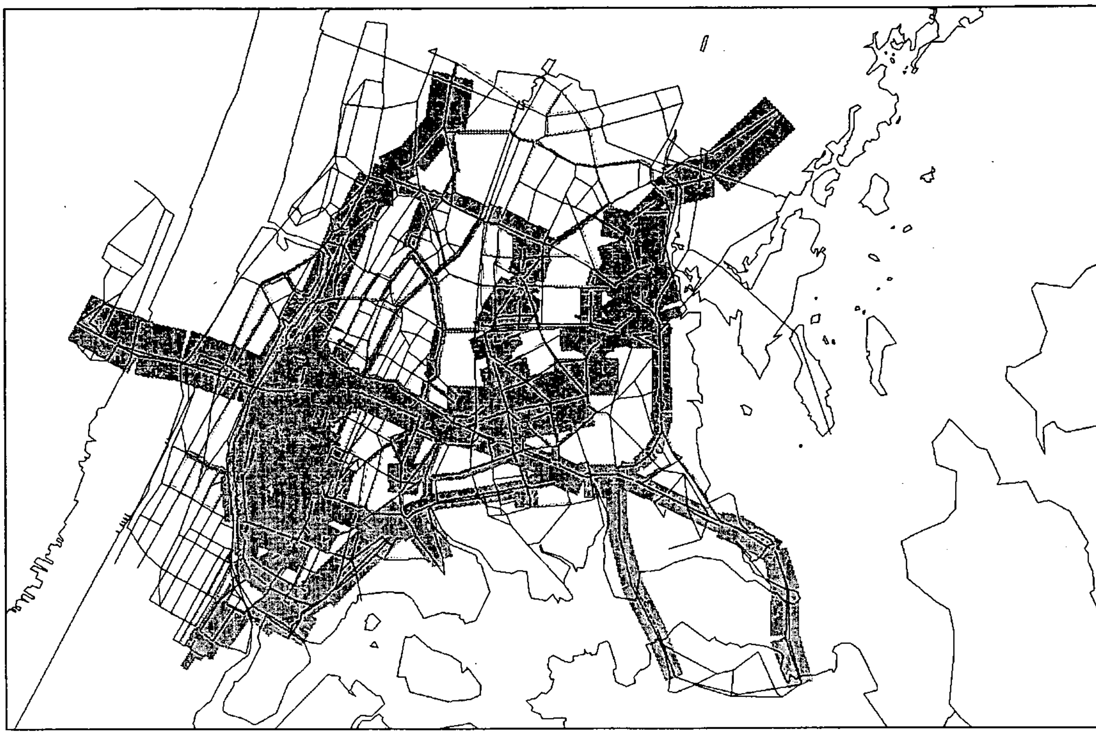

FIGURE 5 Total truck flows in p.m. peak (3 to 8 p.m.); maximum one-way flow is 4,000 trucks.

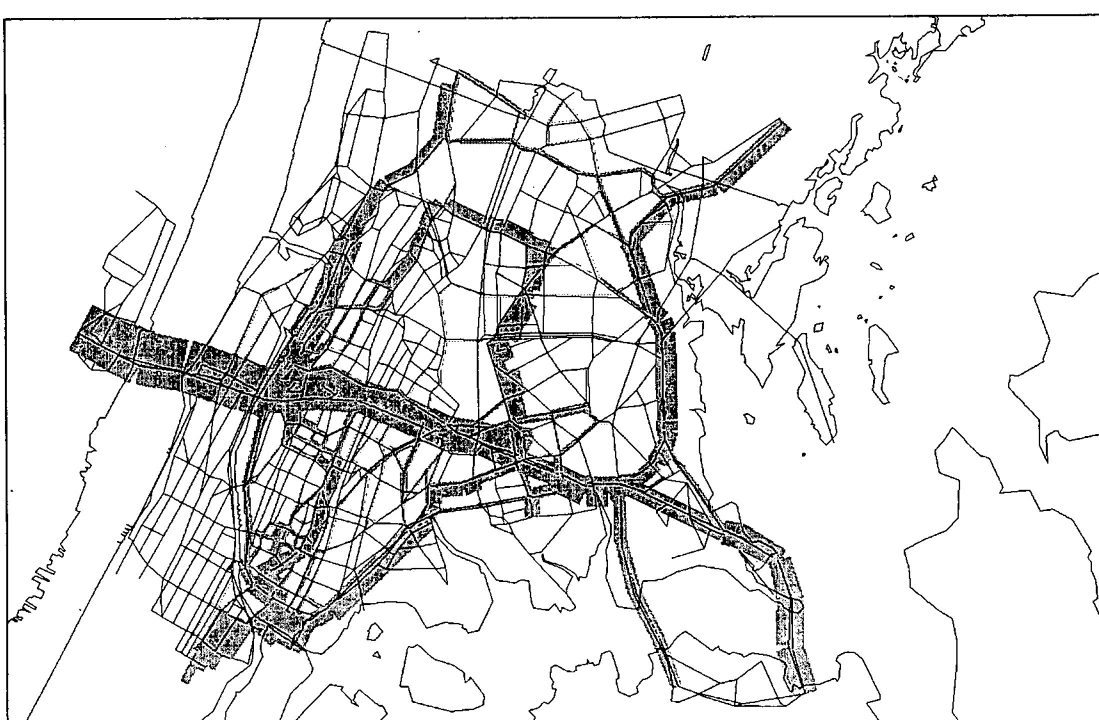

FIGURE 6 Heavy truck flows in p.m. peak (3 to 8 p.m.); maximum one-way flow is 2,000 trucks.

is quite evident in the input data from the PANYNJ Truck Commodity Survey gathered at the George Washington Bridge. Secondary flows of importance in the overhead heavy truck movements are (*a*) northbound traffic on I-87 into Westchester County and (*b*) southbound traffic across the Throg's Neck Bridge to Long Island.

These overhead (external zone to external zone) trips for the network are shown in a three-dimensional way in Figure 7. Note that the trip table is relatively sparse. This must be expected from an optimization that is based on linear programming. (The authors are currently exploring an additional step in the overall model that would produce more highly populated trip tables.) Note also that most of the volume is originating at Zone 100. This is a result of the OD constraints from the PANYNJ Truck Commodity Survey taken at the George Washington Bridge. These constraints force a large number of origins at Zone 100, and distribute the destinations roughly as they appear in the final solution. Because these constraints apply only to eastbound trips, there is little to force overhead trips in the westbound direction.

SUMMARY

Presented in this paper is a method for synthesizing truck flow patterns from partial and fragmentary observations. The method can estimate such matrices from data typically available: link volumes, classification counts, cordon counts of trucks entering and exiting the study area, and partial observations of the OD flows themselves. The method

- Makes maximum possible use of existing information,
- Works with many different types and combinations of data,
- Deals effectively and efficiently with new types of data and new forms of information,
- Generates multi-truck class OD flow matrices,
- Deals with multi-time period problems, and
- Accommodates network use restrictions (e.g., no trucks or heavy trucks) and changes in those restrictions.

As such, the tool has real and immediate practical value. As evidence of this, New York State Department of Transportation is currently developing a User's Manual that explains how the method should be applied and how the input data should be developed. In addition, NYMTC (*1*) in a recent project chose to use this method to update trip tables in the New York metropolitan area.

The tool also has potential applications beyond those illustrated in this paper. In the case study presented, trip matrices have been estimated for a set of truck classes, but redefinition of these classes to reflect commodity groups is conceptually straightforward. Redefinition of the network and zone scale used would also make this technique applicable to interregional freight flow estimation. In light of the changing freight flow patterns across the United States, and, for example, the potential implications of the North American Free Trade Agreement, such interregional use of this method might be quite beneficial.

Continuing research by the authors is focusing on extending the usefulness of the tool and finding improved ways to assess the benefits and costs of "goods mobility enhancements" in urban areas. These include dedicated-use lanes, new and improved freeway ramps, truck-only highways, and intelligent vehicle-highway systems–elated services for commercial operations. The process involved in assessing such changes clearly depends on a method

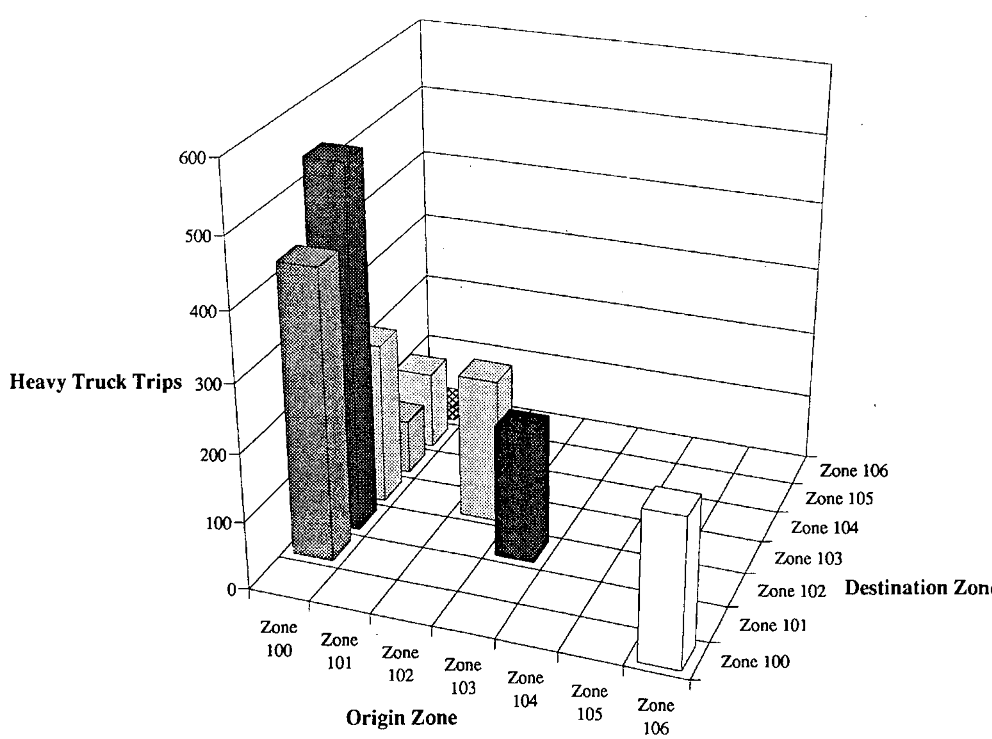

FIGURE 7 Overhead heavy truck trips in p.m. peak (3 to 8 p.m.).

by which trip matrices are estimated so that flow changes can be assessed in light of the network improvements being contemplated.

Flow changes on the highway network as a result of goods mobility enhancements will involve automobile as well as truck traffic. The nature of the truck flow changes is likely to be related to commodities being carried as well as to the physical characteristics of the trucks. Thus, there is need to extend the type of flow estimation model described in this paper to include commodity groups in the vehicle-class definition and to include interactions between the truck and automobile flows. These extensions are currently under way.

As the need to be more efficient in the use of existing capacity increases and the demand for real-time flow management grows, the value in having up-to-date and accurate information about network flow patterns will continue to increase. Eventually, the data collection and processing will become more automated and more accurate, so that less human intervention is necessary and more effective decisions can be made. This project is part of that evolutionary process and the tools and techniques developed help form the underpinnings for future, more comprehensive treatments of the problem.

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Truck and Highway Combinations for Increasing Trucking Productivity in Market Niches

YOUSSEF M. FAWAZ AND WILLIAM L. GARRISON

The focus of this work is at the system level instead of the component level of the autotruck highway system. New combinations of trucks, roads, and operations that could achieve sizeable productivity gains if introduced into the truck-highway system are explored. A simulation model to assess the benefits expected from new truck and road combinations is developed. Grain transportation in rural areas is chosen as a possible market niche. The results of the case-study analysis indicate that trucks of up to 200,000 lb gross vehicle weight operating on a network of low-maintenance roads present an opportunity for substantial productivity gains. The new combinations can offer services four to six times less costly than those of present day grain shipping. Institutional and operational changes necessary to the implementation of such truck-highway formats are discussed.

Trucking has become the principal mode of freight transportation as measured by expenditures, accounting for roughly 70 percent of the nation's freight bill (*1*). While truck transportation continues to grow in absolute terms (in terms of tonnage carried), by the early 1960s, trucks had captured about 90 percent of their present share of the freight transportation market. Market share subsequently has been relatively stable, fluctuating at around 25 percent for the ton-miles carried and between 35 and 39 percent for the total tonnage of freight carried.

Although there may be disagreement among researchers on measuring trucking productivity, indications are that productivity growth as traditionally measured is much slower today than it was between the 1930s and early 1970s. For example, the growth of output per employee dropped from 3.70 for the period 1948 to 1973 to −0.28 between 1973 and 1987 (*2*). However, the trucking organizations serving modern logistics systems have changed the characteristics of their services. These important changes are not reflected in traditional productivity measures.

One action to increase trucking productivity has been to allow larger and heavier vehicles to operate over certain highways. The effects of increases of truck size and weight limits have been unequal among those engaged in trucking, for truck operations take place in highly varied circumstances. Changes in weight and length limits are more important to some segments of the trucking industry than to others. Today, greater trailer lengths mainly benefit carriers and shippers of low-density cargoes, whereas carriers of high-density goods are constrained by weight limits. Furthermore, highway engineers are dissatisfied with current standards of truck size and weight limits because heavier traffic accounts for the larger fraction of road wear, increasing the pressure on an aging infrastructure.

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PERSPECTIVE

The damage caused by truck axles, requirements for pavement strength to handle weights, and road tax-cost relationships have undergone much study, mainly at the national aggregate and road test level. Part of this work has looked hard at larger and heavier trucks (*3*) and highway tax allocation (*4*). More recently, there has been interest in new truck designs (*5*). In nearly all cases, the present debates and investigations of heavier and larger trucks take as givens the previous evolution and current status of the truck-highway system (equipment, fixed facilities, taxation, institutions, etc.). Typically, most of these studies recommend further liberalization of truck size and weight limits (*4–10*). Recommendations are for small, marginal changes nationwide on specially designated networks.

The alternative is to seek changes, market niche by market niche. Put another way, the present thrust is for "one suit fits all" policies, and the alternative is to focus policies on specific markets and road infrastructure situations. For example, responding to the need to move heavy containers is being done to some extent in the vicinities of marine ports.

Why emphasize market niches? One reason is the cumulative experience of transportation and other technological systems as they traverse their life cycles. The trucking system, along with most other transportation activities, may be regarded as a mature activity, having grown along an S-curve and saturated its markets, hardening its predominant technological, institutional, and service formats along the way (*11*). In this mature stage, firms compete and seek productivity improvements by specializing products or services to market niches (*12,13*). There is much evidence of such behavior in the trucking industry (e.g., the growth of firms serving just-in-time and container collector and distributor markets). A second reason for considering market niches is that services in market niches may discover pathways for the evolution of important new services, pathways replicating the ways changes have occurred in the past (*14–16*).

The perspective of this work has now been stated. Concern is with advances in market niches that may open new development pathways. Designs are to have a system scope and use the building blocks at hand.

IDENTIFICATION OF TECHNOLOGICAL FORMATS AND POTENTIAL MARKET NICHES

There appear to be no significant technological barriers to designing and operating specialized trucks considerably larger than those permitted today on the Interstate system, as examples from logging areas and open pit mines indicate. There are also examples from other countries. In Canada, six provinces have a limit of 50,000 kg (110,000 lb), four have a limit of 56,750 kg (125,000 lb) or more, with a maximum of 63,500 kg (140,000 lb) in Ontario. Equally relevant to the discussion would be the Australian road-train experience, in which trucks of up to 136,000 kg (300,000 lb) gross vehicle weight (GVW) are allowed to operate on designated routes. Therefore, using current truck technology as a first building block of a new system would be a natural beginning. Other in-place building blocks include roads and operation protocols.

The technological format to be tested must be at first an effective substitute for an existing service, while at the same time presenting a potential for improved service, lowered costs, and productivity increases. That is, introduction should be incremental, but the new format should have the potential to provide great improvement over the previous system configuration. Short-term gains must be substantial, because only such payoffs would stimulate others to explore further or emulate the new technological format in other locations.

What about market niches? Potential niches include

- Areas that are currently experiencing problems either as a result of heavy truck traffic or inadequate service,
- Areas in which the changes in socioeconomic conditions have in turn generated changes in the demand for freight services, and
- Gaps in the existing system or some transportation functions that are not well performed.

Overall, the niche should allow degrees of freedom. Even if a trial design is quite successful, for example on cost-saving grounds, there would likely be a need for continued design changes. Further, however the design emerges, room is needed for continued growth and development. The notion is advanced that a successful design will open a pathway and continued progress will be achieved by learning, feedback, modifications, and so on.

ANALYSIS APPROACH

Given the scope of the present study, the models available in the literature that simulate vehicle operations, pavement, and bridge impacts are quite satisfactory for measuring the cost impacts of a wide range of truck and highway configurations. Models adapted from the literature for this study use a combination of theoretical concepts and empirically derived relationships to evaluate the impact of the various vehicle configuration alternatives. (Note that "using what is available" is consistent with the notion of using available building blocks.)

The conceptual model begins with an exogenously specified set of service requirements (Figure 1). Based on the volume and density characteristics of the goods to be transported, the model begins by specifying a vehicle configuration (number of trailers and axles) and computing the trailer length, tare weight, effective payload, and GVW for the particular truck configuration. Once the vehicle's physical characteristics are determined, the model computes the vehicle operating costs required to ship the volume of freight. Next, the model computes fixed facility requirements, including pavement maintenance, and geometric and bridge costs. Vehicle and road costs are added to determine the total cost. The model then allows for feedback between vehicle configurations and fixed facility requirements to evaluate the performance of particular truck-road configurations. The simulation is carried out again with a new higher or lower GVW until a minimum total cost is reached for the particular truck configuration. Similarly, the simulation is run again for the particular truck configuration with a different road configuration (such as that with existing pavement, thicker pavement, or gravel roads). Once a particular truck and road configuration reaches its minimum total cost, it is compared with present-day truck costs to estimate potential savings.

Vehicle Operating Cost Model

The vehicle operating cost (VOC) model begins by determining the horsepower requirements for a given speed and GVW by using the Davis equation. Once the horsepower is determined to be within the range of currently manufactured engines, the model checks for trailer and overall truck length. The length of trailers needed to carry the specific GVW is a function of the truck combination tare weight, effective (useful) trailer volume, and the density of the freight to be transported. Next, the number of vehicle trips required, cycle times, and labor costs are determined. The model then computes the remaining components of operating

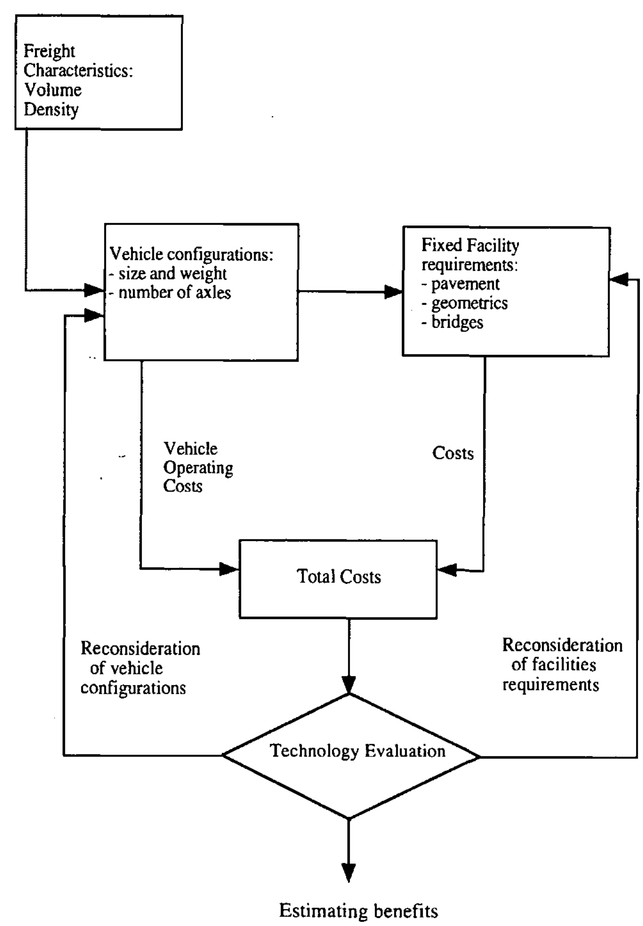


FIGURE 1 Conceptual model.

costs: tire, fuel, lubrication and maintenance, and depreciation. These cost relationships are taken from the Highway Research Board's (HRB's) *NCHRP Report 141* (*17*) and adjusted for inflation to reflect 1987 costs. However, extrapolating to heavy vehicles using the HRB estimating equation for maintenance costs resulted in overestimating heavy truck costs throughout the study. This, of course, means that the ratios of costs for heavy vehicles versus conventional vehicles are conservative throughout the study. Research is under way to improve the cost estimates.

Pavement Cost Model

Two approaches can be taken for estimating pavement costs resulting from changes in truck weights and configurations. One way would be to estimate the additional maintenance and associated rehabilitation costs resulting from the wear occasioned by heavier loads if no change in current maintenance practices is made. The amount of wear is measured by the reduction in the useful life of existing pavement. Alternatively, the additional pavement thickness required to maintain the level of service currently provided could be estimated.

Reduction in Pavement Life

One way to calculate the cost of the change in road maintenance costs resulting from the heavier traffic consists of the following steps:

1. Estimate the load distribution on each group of axles of the truck,
2. Obtain the total number of equivalent single axle loads (ESALs) that the pavement under consideration is designed to sustain during its lifetime. The total number of ESALs divided by the life of the road in years would be the total number of ESALs the pavement should sustain on a yearly basis,
3. Obtain the average maintenance costs for the road section allocated by the yearly expected traffic volume, and
4. Determine the additional variable maintenance cost required resulting from the heavier loads.

Given the paucity of available records on road maintenance, it might prove difficult to obtain accurate data required for Steps 2, 3, and 4 as described. As a result, some of these data would be somewhat speculative.

Increased Pavement Thickness

Alternatively, pavement life can be increased by adding a new pavement layer, and the new variable maintenance cost can then be computed. The American Association of State Highway and Transportation Officials' design procedure (*18*) is used to determine the required pavement thickness. The cost of the additional layer of pavement is then estimated based on the unit cost of paving material for the particular geographical area.

DATA SOURCES AND ASSUMPTIONS

Highway transportation in rural areas is currently experiencing a host of problems, including a deteriorating physical infrastructure and fiscal difficulties. In this context, the transportation of agricultural products over rural roads presents a possible market niche for a new truck-highway design, and grain hauling was selected as a case study.

The case study involves the comparison of the costs of hauling one year's corn production from an average-size farm in Hamilton County, Iowa, to the local country elevator. Hamilton County was chosen because of the availability of road condition and maintenance data.

The analysis assesses how six truck configurations compare with current practice in terms of total costs, operating costs, and road maintenance costs (Figure 2). Configurations consist of a pair of single trailers, a pair of double trailers, and a pair of triple trailers. The GVW for each truck configuration varies from 36 tonnes (80,000 lb) to 136 tonnes (300,000 lb), subject to the constraint of realistic tractor and trailer dimensions. Truck configurations with a payload requiring unrealistic trailer dimensions were automatically discarded. When smaller loads required shorter trailer lengths, a default minimum of 6 m (20 ft) was used when computing truck tare weight. Furthermore, the truck configurations investigated do not comply with the axle load limits mandated by Bridge Formula *B*, as the following list indicates:

- The distance from the farm to the local elevator is assumed to be 16 km (10 mi), which is consistent with the average distance reported by a number of studies (*19,20*).
- Backhauls from elevators to the farm are assumed to be empty.
- Information regarding the rates of loading and unloading grain at country elevators was obtained by calling elevator operators in Iowa, Illinois, and Minnesota. Typical unloading rates vary with trailer size and are assumed to be 10 to 15 min/trailer.
- Information on grain-hauling truck configurations and equipment (hopper dimensions, GVWs, tire sizes, expected lives, etc.) was obtained from a number of sources. Tractor and trailer tare

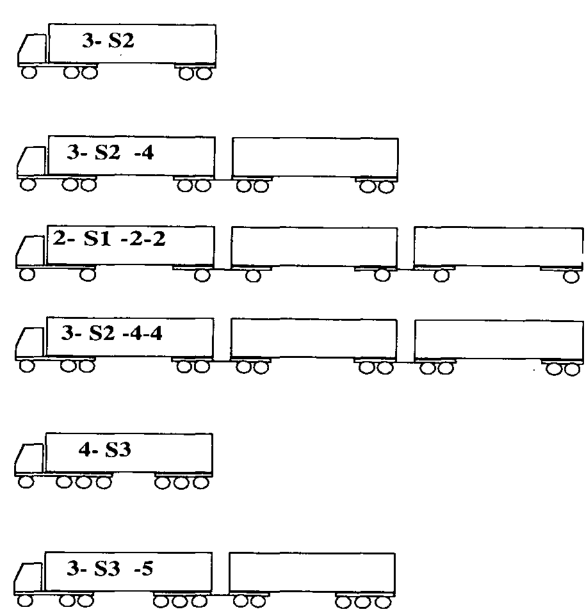


FIGURE 2 Six truck configurations.

weights and dimensions from Winfrey's study (*3*) were complemented by specification catalogs from grain truck manufacturers and the *Chilton Commercial Carrier Journal* (*21*). These values were extrapolated to obtain the tare weight and dimensions of larger and heavier truck configurations. As a further simplification to reduce the need for lane widening, trailer width and height were maintained at 2.45 m (8 ft) and 2.3 m (7.5 ft), respectively, throughout the study, whereas trailer length was allowed to vary as a function of GVW.

- The cost of labor for truck drivers was obtained from the Bureau of Labor Statistics and assumed to be $12/hr. This reflects direct cost.
- Diesel fuel cost was obtained from the United States' Statistical Abstract.
- Tire sizes, expected life in miles, and costs were obtained from tire manufacturers.
- Data on road conditions and maintenance costs were obtained from previous rural roads studies that surveyed highway officials and county engineers on the status of local road conditions, such as the study by Baumel (*22*) and the Iowa Quadrennial Need Study (*23*). As a further simplification, all roads on which the trucks will travel are assumed to have structural pavements.

EMPIRICAL ANALYSIS

Three different scenarios are analyzed. It is assumed that in each scenario only one type of truck configuration would carry the entire yearly farm production so as to provide a comparison of the relative efficiencies of each of the six vehicle classes.

The first scenario compares the total transportation costs for the six truck configurations under consideration with truck GVW allowed to increase to 136 tonnes (300,000 lb). The trucks haul the yearly production of corn from an average farm to the local elevator. Each truck configuration is compared with present-day typical trucks. The total transportation cost is the sum of the VOC and the road variable maintenance cost (RVMC). The VOC represents the cost of running the truck. The road maintenance cost consists of two parts. First, a fixed portion that is independent of the level of traffic and its composition. It includes the costs of signing, slope erosion, and snow removal. Second, the RVMC (the portion of the maintenance cost that varies directly with the number of axle loadings) provides for a comparison of the road wear and resulting pavement costs associated with each truck configuration.

The second scenario investigates the impact of letting the road deteriorate and compares the resulting increase in vehicle operating costs. The third scenario investigates the effect of an increase in pavement thickness on total transportation costs and determines the volume of grain movement that would be required to compensate for the cost of the added pavement. By varying the hauling distance, the last simulation looks at the effect of distance on the total cost per ton-mile for the six truck configurations.

Strategy 1: Higher Axle Loads Over Existing Roads

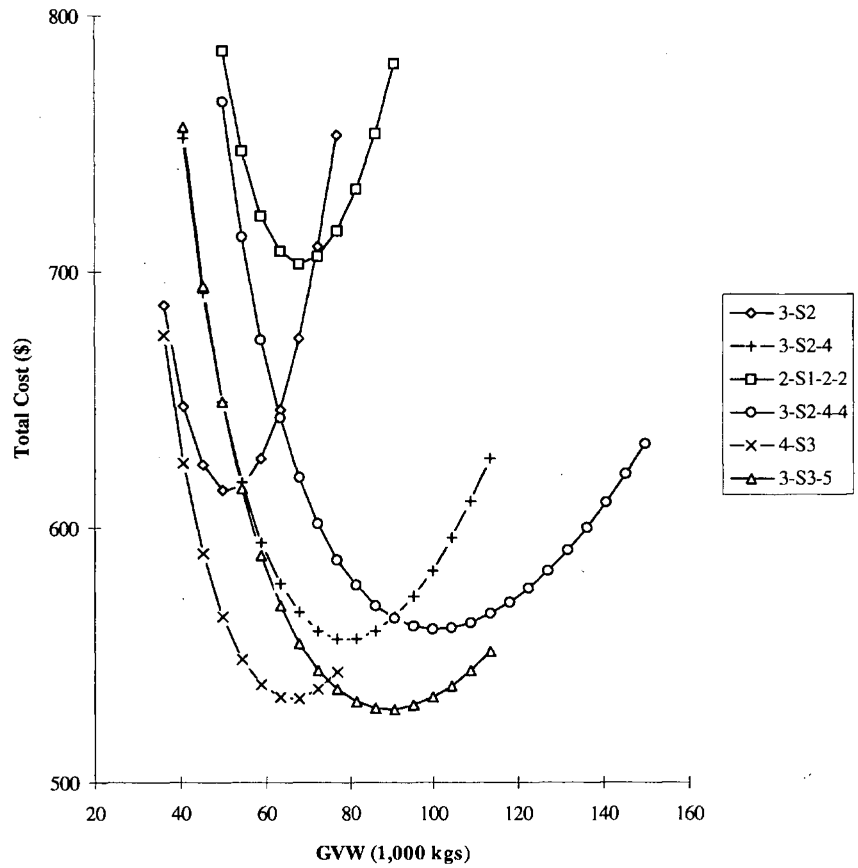
In this scenario, the total farm production of 636 tonnes (700 tons) of corn is shipped a distance of 16 km (10 mi) to the local elevator in each of the six truck configurations. The trucks' GVWs are increased from 36 to 136 tonnes (80,000 to 300,000 lb) and trucks travel over existing roads. The simulations estimate the vehicle operating costs and the road variable maintenance costs as defined earlier. Shown in Figure 3 is the combined effect of VOC and RVMC for each of the six truck configurations as the GVW for each truck configuration is increased in 4,540 kg (10,000 lb) steps. The total cost curve for each of the six truck configurations decreases over a range of weights before reaching a minimum and then increases. The minimum cost point varies considerably between trucks, the extremes being the 2-S1-2-2 with the highest total cost and the 3-S3-5 with the lowest. The number, as well as the type, of axles proves to be the more important factor as trucks with a larger number of axles (3-S2-4, 3-S2-4-4, and 3-S3-5) provide for the larger decreases in total costs. The type of axle group is equally important. Despite having a lower number of axles, the 11-axle 3-S3-5 truck provides for consistently lower total costs in comparison with the 13-axle 3-S2-4-4. This is mainly because the load in the former truck configuration is distributed over two tridem and two tandem axles that cause less damage to the road, whereas the latter has six tandem axles. Also contributing to the lower total cost is that for equal GVW, the double trailer has a lower unloading time than the triple trailer, thus reducing the cycle time and consequently the labor cost. Finally, for trucks with the larger number of axles, the 3-S2-4-4 and the 3-S3-5, the GVW beyond which costs cease to decrease is in the range of 91,000 to 99,000 kg (200,000 to 220,000 lb).

The total cost for the six different truck types under consideration was then compared with typical present-day grain-hauling trucks. At present, grain from farms to elevators is shipped by a myriad of different trucks, ranging from pickups to semi-trailer trucks, including farm tractors pulling one or two grain wagons. Chicoine and Walzer (*24*) report that straight trucks and farm tractors are the vehicles most frequently used by farmers in four Midwestern states, accounting for some 70 percent of all grain shipments, with tandem axle trucks accounting for about 10 percent. Therefore, it was decided to base the comparison of alternative truck configurations on three representative trucks: a 2-axle, 14,000-kg (30,000-lb) straight truck, a 17,000-kg (38,000-lb) farm tractor and a 350-bushel wagon combination, and a 24,500-kg (54,000-lb) commercial truck (one tandem and one drive axle). The total costs for these representative arrangements were computed using the same cost models as for the six truck configurations previously discussed.

The ratio of total costs of each of the six truck configurations to the costs of today's representative grain trucks was then calculated, showing that heavier truck combinations represent substantial savings over present-day grain trucks. At their highest points, the ratios vary between 4.7 and 3.5 in comparison with the farm-tractor and wagon, and between 3.8 and 2.9 when compared with a straight 14,000-kg (30,000-lb) grain truck. The ratios are 2.3 to 1.7 when the trucks are compared with a 24,500-kg (54,000-lb) tandem truck. The 3-S3-5 truck combination represents the highest overall savings of all trucks, whereas the 2-S1-2-2 triple-trailer achieves the lowest overall gains.

Strategy 2: Letting the Road Deteriorate

In this scheme, the analysis looks at the impact on the cost of hauling the grain from the farm to the country elevator when the road is allowed to deteriorate (i.e., eliminating variable maintenance cost). Of course, the fixed component of maintenance costs,



Note: 1kg = 2.2 lbs

FIGURE 3 Total cost per function of gross vehicle weight for six truck configurations.

which consists of snow removal, blading, and graveling, will be maintained. It is assumed that as the road condition deteriorates, vehicle speed will be reduced and tire life will be diminished, thus increasing truck operating cost. Because of the lack of data, other increase in truck maintenance costs caused by the deterioration of the road surface were ignored as a simplifying assumption. However, given that the HRB equations overestimate the truck maintenance costs, this simplification should not affect the overall results. Shown in Figure 4 is a typical curve depicting the changes in vehicle operating cost as truck speed increases from 8 to 96 km/h (5 to 60 mph) and GVW increases from 36,000 to 114,000 kg (80,000 to 250,000 lb). The vehicle operating cost curves for all six truck configurations display similar patterns, dropping sharply as the speeds increase from 8 to 32 km/h (5 to 20 mph) and then leveling off. The initial drop in operating cost becomes much less pronounced as the GVW increases.

Because the impact on pavement is not taken into account, trucks with lower operating costs present the highest overall savings. The 2-S1-2-2 remains the least efficient of all six truck configurations. The 3-S2-4-4 also loses the advantage of having a higher number of axles, and becomes a less attractive alternative because of higher operating costs, in part because of the much larger number of tires. The double trailers, 3-S2-4 and 3-S3-5, result in better overall savings. The range of speeds over which the savings are achieved is relatively narrow. The cost curves do not cross the $500 mark until truck speed reaches 40 km/h (25 mph) and a GVW of 68,000 kg (150,000 lb) for the 3-S2-4 and a 48 km/h (30 mph) speed and 77,000 kg (170,000 lb) GVW for the 3-S3-5. The single trailer semi-trailer truck results in the largest overall savings over the broadest range of speed and GVW, indicating that semi-trailer trucks (3-S2 and 4-S3) traveling at speeds of 24 to 40 km/h (15 to 25 mph) (speed being constrained as a result of surface condition) with a GVW range of 45,000 to 73,000 kg (100,000 to 160,000 lb), present the lowest overall operating cost. At higher loads, such as in the 91,000 kg (200,000 lb) range, the tandem trailers become the superior truck configuration.

The comparison with existing trucks was made by computing the ratios of total costs to the costs of presently operating farm tractors. The results indicate savings ratio of 4 to 5 times for truck speeds of 16 to 40 km/h (10 to 25 mph) and GVW of 41,000 to 68,000 kg (90,000 to 150,000 lb). Such savings in operating costs of the 3-S2 and 4-S3 over present-day trucks (about 4 times) and farm tractor-wagons (about 5 times), strengthen the argument in favor of letting some rural roads deteriorate or turning them into low-maintenance gravel roads.

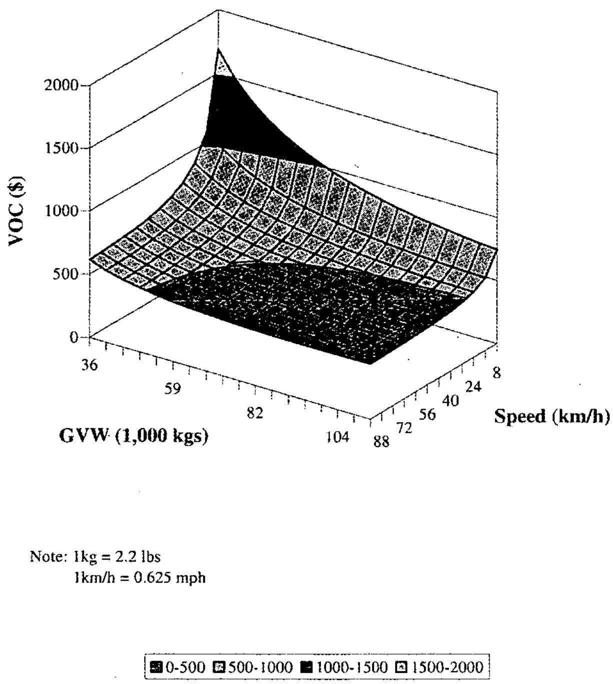


FIGURE 4 Vehicle operating cost as a function of speed and gross vehicle weight for Truck Configuration 4-S3.

Strategy 3: Increasing Pavement Thickness

This scheme considers the effects of increasing pavement thickness on the total cost for each of the six truck configurations. The first scenario assessed the impact the different trucks have on road damage and associated added costs, based on the assumption that the road would be maintained according to previous county practices. The road variable maintenance cost was estimated using 5,000 yearly applications of ESALs and the remaining life of the pavement. This scenario consists of upgrading the existing pavement by adding an additional 6 in. of pavement, thus lengthening the lifetime ESAL loading of the road to 500,000 applications. Assuming a 20-year life, the additional 6 in. of pavement would withstand 25,000 ESAL applications per year. Although the pavement life data were based on Baumel's interview with county engineers (*22*), admittedly these are simplifying assumptions that may not be fully supported by real-life performance data.

When restricted to the transportation of a single farm's production, the cost of upgrading the road represents a dramatic increase in the road maintenance cost, completely overwhelming the cost of the relative road damage inflicted by individual trucks. The cost of shipping jumps to more than $5/ton-mile. Thus, upgrading the road at the low volume of traffic generated by a single farm is hardly justified. The next step was then to increase the volume of grain shipped to determine the amount of traffic at which the cost of increasing road thickness would be justified. The dramatic effect of increasing grain volume on the resulting decrease in cost per ton-mile for a 68,000-kg (150,000-lb) 3-S3-5 truck combination displayed to scale is shown clearly in Figure 5. The drop in cost per ton-mile as the volume increases from 3,600 tonnes (4,000 tons) to 45,000 tonnes (50,000 tons) is steep and becomes minimal beyond the 90,000 tonnes (100,000 tons) mark.

Different trucks reach a minimum at quite different volumes of grain. If the $0.2/tonnes-km is considered a minimum mark, the results show that the cost of most trucks will cross that mark at about 90,000 tonnes (100,000 tons). Furthermore, as mentioned earlier, the HRB maintenance costs equation resulted in overall VOC overestimates. Thus, the ton-mile cost shown in Figure 5 is an overestimate by a factor of about 4 or 5 cents. This, of course, means that the ratios of costs for heavy vehicles versus conventional vehicles shown are conservative. Cost ratio calculations show that savings of 3 to 4 times over farm tractors begins at 45,000 tonnes (50,000 tons) and increases to 4 and 5 times for volumes just over 90,000 tonnes (100,000 tons).

The volume of grain that would justify an increase in pavement thickness is about 90,000 tonnes (100,000 tons). If this value is to be expressed in terms of an "average farm production," it is roughly equivalent to the total output of 143 average-size farms. Such volumes are common for shipments between country and terminal elevators.

Sensitivity to Distance: Hauling 700 Tons Over a 10- to 200-Mile Range

The three previous scenarios indicated the possibility for important savings over present-day trucks in the farm-to-country-elevator market. In the present scenario, sensitivity to distance is analyzed to assess how the comparative advantage of different truck configurations would change as the hauling distance is increased from the original 16 to 320 km (10 to 200 mi), by 16-km (10-mi)

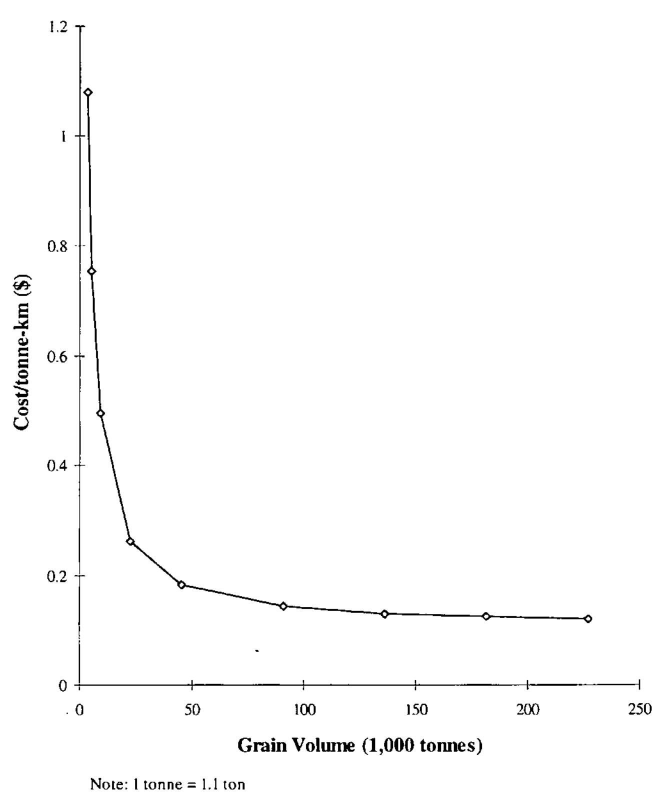


FIGURE 5 Cost per tonne-km as a function of grain volume for a 3-S3-5 68,000-kg (150,000-lb) truck.

increments. Savings over the longer distances are relevant because the number of transhipments between country elevators and elevators serviced by unit trains is on the increase. The changes in total cost per ton-mile as both the GVW and the distances traveled are allowed to vary for 3-S3-5 truck configurations are shown in Figure 6.

As the GVW increases, the cost curves follow the pattern already described in the first scenario, declining until they pass through a minimum before increasing again. The effects of increasing the distance are similar for all six trucks, with different degrees of importance depending on the type of truck configuration. First, the total cost per ton-mile drops steadily as the distance increases—but this effect tapers off relatively quickly. Cost reductions are modest beyond 80 to 100 km (50 to 60 mi), irrespective of the truck configuration or GVW. Second, the decrease in total cost per ton-mile with distance is more pronounced the farther the distance from the GVW that produces the minimum total cost for a specific truck configuration. Put another way, this means that at the configuration and GVW that results in the minimum total cost for each of the six truck configurations, the impact of increasing the shipping distance on the cost per ton-mile is minimal.

Overall, the 4-S3 and 3-S3-5 trucks offer the widest range of GVW over which lower total costs per ton-mile can be achieved. Both these trucks have the lowest costs for a range of truck weights beginning at about 45,500 kg (100,000 lb) and a distance of 16 km (10 mi). The breadth of the distance and GVW ranges over which the 4-S3 and 3-S3-5 trucks reach lowest costs per ton-mile makes them the more appropriate format of all six truck configurations, whereas the 2-S1-2-2 truck remains the less suitable.

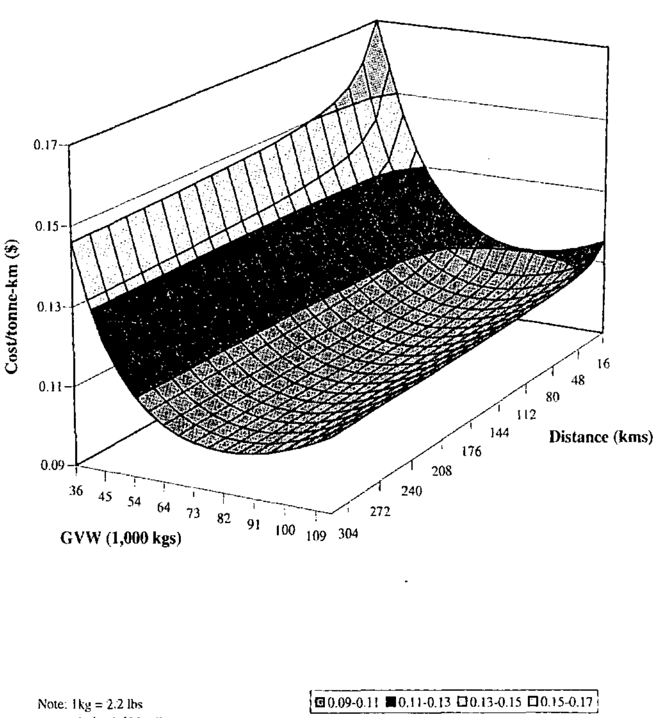


FIGURE 6 Total cost per tonne-km as a function of distance and gross vehicle weight for Truck Configuration 3-S3-5.

The ratio of total cost to today's three representative trucks was again computed for a distance of 80 km (50 mi) to see whether the comparative advantage of the new trucks changes as the shipping distance increases. The benefit margins increase with respect to the 17,000-kg (38,000-lb) farm tractor-wagon combination and now stand at slightly more than 5.1. The benefit margins at 80 km (50 mi), however, do drop slightly with respect to the 14,000-kg (30,000-lb) straight truck as they stand now at close to 3.4 [down from 3.8 for a 16-km (10-mi) distance] and down to about 2.1 from 2.3 with respect to the 24,500-kg (54,000-lb) tandem truck. Despite the decrease, the six new truck configurations would present substantial savings over the present-day trucks for moving grain some 80 or 96 km (50 or 60 mi) between country and terminal elevators or transshipping grain from country elevators to ones served by unit trains.

Geometric and Bridge Costs

This analysis did not include any cost adjustments for geometric considerations. All six truck configurations were restricted to a 2.45-m (8-ft) width limit mainly to avoid having to deal with road widening because of trailer width. Also, the slow speed at which these trucks will operate reduces the need for pavement widening on curves until a curve radius of 10 or 11 degrees is reached, after which an extra 0.61 m (2.0 ft) will need to be added.

Given the relatively short spans of most bridges in rural areas, adding the annualized cost of upgrading bridges on a selected network of high-density freight transportation should not alter in any fundamental way the basic findings presented here. Hamilton County has a total of 31 bridges, with an average size of 73 mi^2 (785 ft^2), and only 3 of those have a less than 36-tonnes (40-tons) GVW rating. The Federal Highway Administration bridge construction unit costs per square foot for the federal-aid system for the state of Iowa is estimated at $38 dollars for 1987 (*25*), accounting for labor, material, and equipment costs. Assuming that all bridges were to be rebuilt, the total cost for Hamilton County would amount to $1 million. This is a very small amount in comparison with the savings that new truck configurations would achieve.

Institutional and Operational Considerations

A road network connecting local country elevators to terminal elevators will likely cross many county jurisdictions. This will require cooperation and coordination on a regional (or multicounty) level. On the state level, a revision of legislation will be needed to adopt flexible standards to accommodate a diversity of transportation needs on local highways. Changes would also be needed in the present maintenance policies from a "maintain as is" approach to one that will allow some roads to deteriorate from paved roads into low-maintenance gravel roads.

Some of the money saved from reduced operating costs could be funneled back into the maintenance of the heavy-truck network. Funds could be collected using the issuance of permits. Furthermore, as heavy truck traffic becomes restricted to a clearly defined network, there will be a reduction of truck traffic on other rural roads, thus reducing the maintenance costs on other parts of the road system.

In addition to new truck size and weight legislation, there will be a need to reclassify the existing roads on which the heavier trucks will be allowed to travel. There are two options: the network can either be shared by trucks and the general public or be used exclusively for trucks.

Given the short distance from farm to local elevator and the volumes of expected traffic on particular links, it might prove feasible to leave gravel truck roads open to the public depending on the density of the network of roads from farms to elevators. The general public traveling on these roads might incur slight inconvenience because of reduced rideability, slower speeds, and increase in vehicle operating costs caused by gravel. There are also some safety concerns when sharing roadways with heavy trucks. These however are somewhat mitigated because trucks will be driving at relatively slow speeds. Also the total number of miles traveled by trucks is actually reduced (because of the lower number of trips), thus reducing the potential for conflict with general automobile traffic.

The lengths of roads connecting country elevators to terminal elevators and the potentially higher traffic, as well as the need for all-year accessibility, makes transforming them into a higher standard (thicker pavement) exclusive (or private) roads an attractive alternative. As some roads are taken out of the present system and converted into exclusive truckways, the reduced mileage of roads will pose some inconvenience to the general public as some private automobiles will have to take longer roads and incur slight increases in travel time and costs. However, given the density of the present rural road network, the effects of choosing alternate routes should be minimal. Another possible alternative would be to reclaim the rights-of-way of abandoned railroads and transform them into exclusive truckways.

The introduction of the new truck configurations might lead to the consolidation of the elevator-terminal system. Because the benefits of using heavier trucks are even greater on longer distances, this could lead to the bypassing (and eventual elimination) of local elevators as grain is hauled directly to terminal elevators.

The new truck configurations, save for the tridem axle, are not very different from today's trucks. The engine sizes required to operate these heavy trucks at relatively slow speeds are well within the limits of presently manufactured engines. The upgrade from present-day trucks to the new configurations should not constitute a major expense increase to truck operators and owners (farmers or seasonal grain-hauling contractors). The larger trucks would cost less per unit of hauling capacity and would require less maintenance (also per unit of hauling capacity) than the smaller ones. Furthermore, the potential for large savings in truck operating costs should entice truckers to switch their fleets to the new configurations.

The tare weights of the new truck configurations are well below existing present highway weight limits. Thus, driving empty trucks between market niches (such as from hauling corn in Iowa to hauling wheat in Minnesota) should pose no problem for the Interstate and other federal-aid primary highways.

POSSIBLE PATHWAY FOR CHANGE

The results of this analysis strongly suggest that the potential for important savings could provide ample incentive for implementing alternative truck and highway configurations, similar to those described here, in one or more grain-hauling markets, if the institutional barriers could be overcome. A possible pathway for change from today's truck system into a more productive system could consist of the following steps:

1. Multicounty or state-level legislation would be adopted to increase the allowable truck GVW over a defined network of roads connecting farms to local country elevators;
2. Current pavement maintenance practices would be changed from a "maintain as is" policy to letting some of the local roads connecting farms to country elevators deteriorate;
3. As the system of slow-moving heavy trucks on gravel roads proves to be a reasonable alternative for serving farm to country elevators at lower overall costs, it would be reasonable to start planning for the expansion of such services. Given the higher volume of grain to be shipped between elevators as well as the need for year round, all-weather accessibility, the cost of upgrading (by increasing pavement thickness) a network of roads connecting country elevators to terminal elevators could be justified based on the savings.

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QRA and Decision Making in the Transportation of Dangerous Goods

F. FRANK SACCOMANNO AND KEITH CASSIDY

Lessons learned from the International Consensus Conference on the Risks of Transporting Dangerous Goods, held in Toronto in April 1992, are used to suggest ways through which quantitative risk assessment can be made more practicable for users and decision makers. The discussion focuses on three aspects of the problem: risk uncertainty (in both estimation and process), communication (as related to perspective, criteria for representing risk, and relevance to decision making) and decision support (acting as a guide to cost-effective mitigation).

Quantitative risk assessment (QRA) continues to be at an infant stage of development, plagued by problems of recognition, precision, and credibility. A recent Royal Society report (*1*) laments the deep methodological division regarding such issues as the quantification and qualification of risks, the response of QRA to public perceptions of risk, and the setting of acceptable standards for decision making. According to Blockley (*2*), this division points to the "open-world" nature of risk problems, which Fischhoff (*3*) ascribes to differences in human interpretation and judgment, an inherent attribute of QRA applications in general.

QRA applications in the transportation of dangerous goods are plagued by a number of practical concerns that compromise their usefulness in decision making. Hubert and Pages (*4*) and Saccomanno et al. (*5*) cite a number of inconsistencies in the values assigned by different groups to various components of risk for similar problems. These inconsistencies, it is argued, have contributed to a general loss of credibility in QRA's ability to provide accurate readings of the threats posed. A 1989 Health and Safety Executive (HSE) report (*6*) argues that the views held by members of the public are often at variance with apparent evidence from QRA applications. Covello (*7,8*) has noted that the reasons for this cannot be dismissed as purely "irrational" or "subjective" thinking by the public concerning risk assessment in general, but rather it rests with the ability of QRA to "communicate risk" in an effective and consistent manner. Glickman et al. (*9*) suggest that there is the wider concern that, notwithstanding the question of inconsistencies in the estimates, existing QRA models have failed to express risk in a manner that is responsive to the specific needs of users and decision makers. They argue that QRA should be made more practicable and not necessarily more technically involved. Before proceeding further along the path to "bigger and better models," a momentary halt in progress is advisable to take stock of our current position on the learning curve and map out future directions for QRA model development. Indeed, there may be many learning curves to consider in risk assessment, for example by industry as well as by country.

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In April 1992, an International Consensus Conference on the Risks of Transporting Dangerous Goods was convened in Toronto. One of the basic aims of this Conference was to review the role of QRA in the transportation of dangerous goods and to suggest ways in which the process could be made more meaningful for users and decision makers. It was agreed that this aim could best be achieved by bringing together groups with a wide range of interests and experiences to discuss the issues within the framework of an open forum. Given the complexity of QRA, its multifaceted role, and the diverse interests of those involved, a consensus-seeking approach was believed to provide the most promising avenue for achieving agreement. Similar consensus-gathering approaches applied in the past, most notably in medical research, have proven to be successful in providing insights into resolving problems of some complexity with far-reaching implications for public policy.

The Consensus Conference deliberations produced a number of useful recommendations (also referred to as consensus statements) on how to improve the QRA process and make it more meaningful to users and decision makers (*10*), as follows:

1. QRA must be more responsive to the needs of users and decision makers. Both information requirements and output must be clearly defined and documented.
2. Uncertainty must be fully accounted for in the reporting of risk estimates. Risk and its components must be accompanied by confidence limits. The sensitivity of output to various assumptions concerning parameter values and inputs must be accounted for in the reporting of the risks.
3. Risk measures must be clearly defined. There should be no ambiguity concerning the nature of risks and their perspective, such as individual and societal, or absolute and relative. Risk communication guidelines need to be developed before the analysis begins.
4. Guidelines for decisions and the mitigation of risk must be incorporated into the QRA models. The process must lead to technically informed decisions. Where appropriate, QRA should present output in a form that can be readily used in a cost-benefit evaluation of alternative types of mitigation.

Several of these recommendations are reviewed in this paper with a view to suggesting a "globally acceptable" code of practice for risk assessment as applied to the transportation of dangerous goods.

ROLE OF QRA

Despite a diversity of interests and experience among the participants at the conference, there was general agreement that QRA has three important roles to play (*10*):

1. Provide acceptable and credible estimates of risks;
2. Inform public perception of the nature and importance of these risks, and interpret the technical results; and
3. Provide advice on mitigation in support of the decision-making process.

Many of the conference participants felt that existing QRA models do not fulfil these roles adequately.

The provision of acceptable and credible risk estimates is an attempt to reduce uncertainty in risk estimation, recognizing that, given the nature of QRA, uncertainty can never be fully eliminated. The questions to be addressed are: to whom should these estimates be acceptable and credible? and how is this to be achieved in QRA? A major U.S. National Research Council report (*11*) addressed part of this issue by noting that QRA can be "successful to the extent that it raises the level of understanding of relevant issues or actions and satisfies those involved that they are adequately informed within the limits of available knowledge."

The Consensus Conference considered ways this aim could be achieved by incorporating the analysis of uncertainty into the QRA process and documenting the various assumptions underlying the model and its application to specific transportation of dangerous goods problems (*10*).

The second role of QRA is to communicate risk effectively; that is, to report and interpret the technical results so as to bridge the information gap between the technical analyst and the decision maker or user (who may or may not be a technical person). The Consensus Conference debated the critical issue of whether existing QRA models suitably "inform" public perceptions on the actual threats posed by a given activity. Participants believed that at present QRA models have not contributed adequately to a complete understanding of the risks involved, so that well-informed decisions have not always been possible. This issue has been echoed elsewhere in the literature. As early as 1983, a Royal Society report on risk assessment stated (*12*):

> It follows that the public not infrequently have different perceptions of events from those suggested by the objective statistical assessments made by scientists or other experts (here referred to as QRA). Since policy is rightly directed towards the alleviation of public anxieties, this disparity can lead to large expenditures on safety measures that have low cost-effectiveness or, conversely, to the neglect of serious risks because the public (and by extension the decision makers) happen to be relatively indifferent towards them.

The absence of communication among those involved in QRA development has contributed to much of the misunderstanding on QRA's role and how well existing models fulfil this role. Closely related to the issue of risk communication is the role of QRA in decision support (i.e., as a guide to evaluating alternative risk-mitigation strategies). In this regard, risks should be reported in a manner that suggests an appropriate course of action for specific problems. The role of QRA will be discussed in this paper from these three points of view; namely, risk uncertainty, communication, and decision support for mitigation.

RISK UNCERTAINTY

The nature and degree of uncertainty in QRA varies with the nature of the problem being addressed and how the relevant issues are perceived by the analyst (*10*). Uncertainty in the quantification of risk can take several forms (*6*):

1. "Measurement error" expressed in the formal scientific sense as the range within which a parameter is known to lie with a given level of confidence;
2. Uncertainty in the modeling process;
3. Uncertainty in whether or not there is indeed an effect to be incorporated in an estimate; and
4. Omissions of possible causes of risk because of incomplete analysis, nonquantification of the ways in which human error can arise, and omission of other extreme external causes.

In many existing QRA models, uncertainty is handled in one of four ways:

1. *Use of the so-called "best estimate" approach for all input components of risk.* Frequently, the best estimate is obtained from sample averages extracted from the literature or from observed data;
2. *Erring on the side of safety.* Estimates are made considering the so-called worst-case scenario for each component of risk. The argument is made that even if the final risk estimate is incorrect, the assessment would not compromise safety. The HSE use what is referred to as a "cautious best estimate" approach, which is essentially a combination of the first two of these methods;
3. *Sensitivity analysis to varying inputs.* If risk component values are uncertain, a range of possible input values is obtained for each component and the implications on the final risk estimates are assessed; and
4. *Comprehensive statistical analysis of risk inputs and outputs.*

There are, of course, serious limitations in several of these ways of handling risk uncertainty in the application of QRA. Rimington (*13*) and Haigh (*14*) argue that the use of the most likely estimate or erring on the safe side alone is simply not acceptable, given the high cost of the decisions involved. Sensitivity analysis addresses how a range of values in selected inputs can affect risk estimates, without addressing specifically the reliability of these estimates. As such, the uncertainty issue is not fully addressed in this approach. Another use of sensitivity analysis is to determine whether the changes in the value of inputs make any difference to the resultant outputs. If the output is insensitive to the selected input values, the question is: why worry about the reliability of these input values? Of the previously listed methods for dealing with uncertainty, a comprehensive statistical review of risk and its inputs appears to be the most desirable course of action to take, although the amount of information required to carry out this type of analysis may not always be adequate.

In adopting a statistical approach, Saccomanno and Bakir (*15*) note that two types of uncertainty need to be considered: (*a*) uncertainty in risk estimation and (*b*) uncertainty in the process. The first type of uncertainty is an "uncertainty of knowledge" concerned with the value of the inputs and their parameters. The second type treats risk as a random variable, with a range of possible values tending about the mean. As in any random variable, the values assigned to risk and its inputs can be represented by their unique probability density functions.

UNCERTAINTY IN RISK ESTIMATION

Uncertainty in risk estimation was addressed at the Consensus Conference by considering unexplained variations in a sample of estimates reported by various independent sources studying a common transport problem. This was carried out using a hypothetical corridor benchmark exercise, the purpose of which was to establish controls on the problem being addressed, its underlying assumptions, and the input data used to specify and validate the models (*16*). The corridor benchmark exercise involved the bulk transport of chlorine, liquefied petroleum gas, and gasoline by road and rail over two designated routes (Figure 1). The presence of uncertainty in the application of QRA to the transport of dangerous goods was investigated in terms of five components of QRA (Figure 2):

1. Involvement of the dangerous vehicle in an accident,
2. Occurrence of a breach of containment,
3. Occurrence of release by type and size,
4. Hazard area for different classes of damage, and
5. Number of people killed or injured along a given route section.

Considering the constituents of risk separately permitted a parallel assessment of internal consistency in the QRA models for different phases of the risk-estimation process. Internal consistency was one of the stated requirements for QRA at the Consensus Conference, deemed to be important in producing meaningful and credible results (*10*).

The corridor exercise indicated that despite attempts to control for major sources of uncertainty (i.e., differences in assumptions, data, and model features), inconsistency in risk estimation, as reported by the participating groups, continued to be problematic. Much of this inconsistency could still be traced to differences in assumptions taken by the different groups in their application. Much of this difference could have been reduced through further controls on the application and a more extensive specification of the corridor features (*16*). Indirectly, the corridor exercise confirmed what many of the participants at the conference had stated verbally, mainly that more attention should be paid in QRA applications to the documentation of assumptions and to the reporting of risk estimates. A similar view was expressed by Williams (*17*) in calling for the inclusion of supplementary "qualitative information" in QRA output, and the provision of information in a form that is free of unnecessary technical jargon.

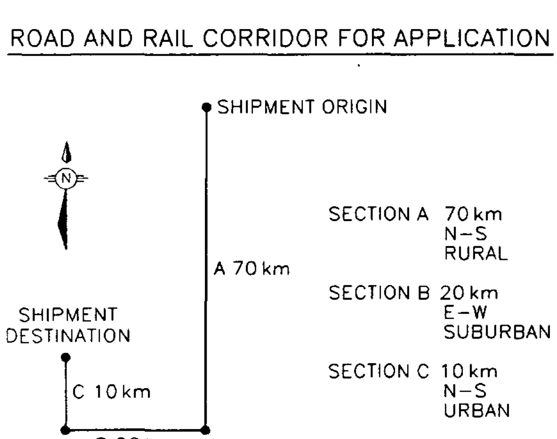


FIGURE 1 Hypothetical corridor features.

UNCERTAINTY OF PROCESS: A DECISION CONTEXT

Although the main focus of the corridor benchmark exercise was to investigate uncertainty in risk estimation, a parallel discussion touched on uncertainty of process and its implications for decision making. An appreciation of uncertainty of process provides a perspective on how risk-tolerance criteria and random variations in risk values can be incorporated into decision making. Risk tolerance refers to a willingness on the part of the public to live with certain risks, in some cases "unacceptable" risks, in order to realize greater benefits. Although these risks may not be negligible, they are perceived as being under some type of control, and hence constantly being reduced.

How does "uncertainty of process" relate to the issue of risk tolerance? Although a given risk may on average be considered to be negligible or acceptable, there may be an "unacceptable chance" that such a risk could in fact attain an intolerable value, given inherent randomness in the process. For example, risks from a given activity may involve on average one or two fatalities per year, but there is a chance that next year a major event may take place that will result in hundreds of fatalities. Notwithstanding the importance of the "average value of risk" in QRA risk estimation, it is the probability of exceeding intolerable values that may be of more concern to decision makers. Although establishing "tolerable levels of risk" is strictly speaking a question of public policy, the Consensus Conference participants expressed a common view that the analyst must be cognizant of this question as it relates to mitigation and the "distribution of risks" (*10*).

RISK COMMUNICATION

A second major role of QRA is the effective communication of the risks involved. Covello (*7*) identified 19 characteristics of risk that must be considered in QRA applications if there is to be sufficient information for evaluating these risks and making appropriate decisions. These characteristics can be grouped under three major headings: (*a*) perspective on risk, which refers to ways in which risks are viewed by users and decision makers within the context of the problem being addressed; (*b*) criteria for measuring risk, which refers to analytical output from QRA; and (*c*) relevance to decision making, which addresses the broader issue of the ability of QRA to advise on an appropriate course of action. This section of the paper focuses on the first two factors; the third factor will be considered in the next section.

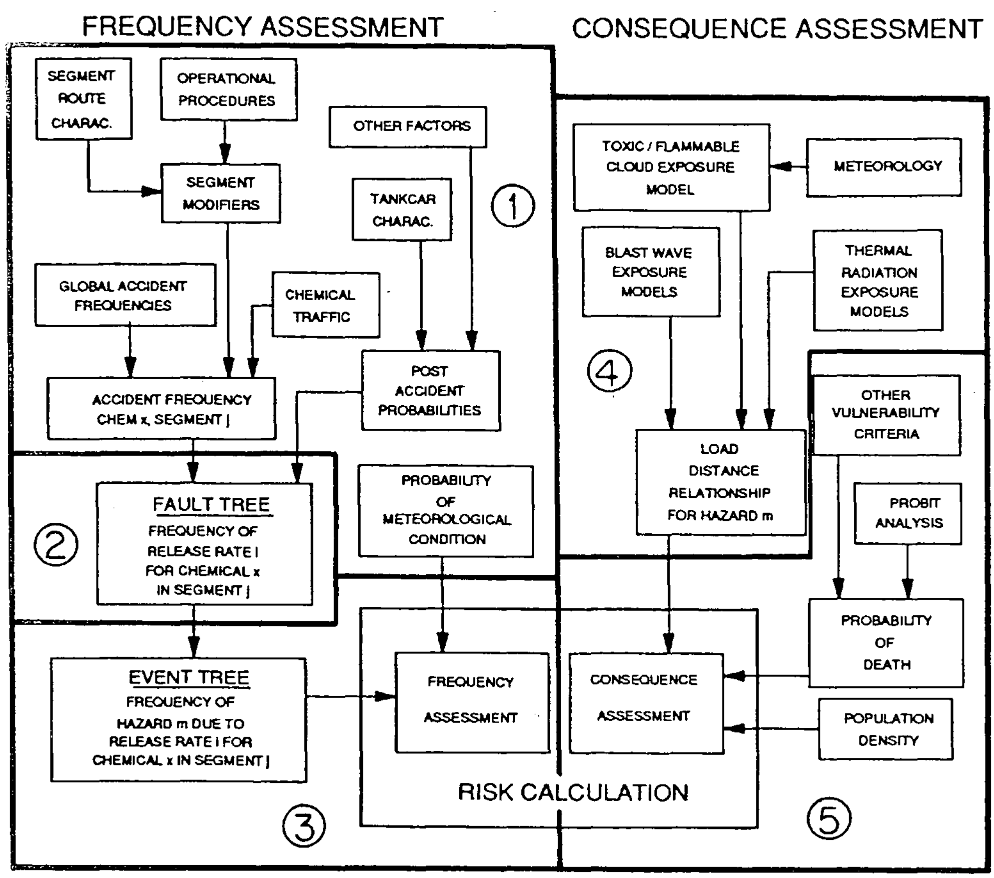
The Toronto Consensus Conference discussed perspective on risk from two points of view: (*a*) individual or societal and (*b*) relative or absolute.

Most QRA models express individual risk as the probability of death (or of receiving a "dangerous dose") per interval of time (usually per year) at designated distances from a given incident involving a specific type of dangerous substance. In transportation, these individual risks are normally represented as equal probability isopleths at various distances from a given incident along the route (Figure 3). Societal risks, on the other hand, refer to the potential threat posed by a given activity to all individuals located within a given hazard area. For the transportation of dangerous goods, this includes all individuals located within a given distance of a threat-producing incident along the route, including both on-route (shared traffic) and off-route population. Societal risks are normally expressed either as an expectation of harm (usually death) or as a plot of the frequency of N or more deaths per year versus the number of deaths. The latter more complete representation of societal risk is referred to as the cumulative F-N curve (Figure 4). Societal risk expectation is simply the expected value of the F-N curve.

Individual risks for the transportation of dangerous goods are considered to be negligible, because exposure time to risk at any point along the route is normally very brief. Accordingly, QRA applications to the transportation of dangerous goods are normally based on a societal risk perspective. This does not obviate the need to consider also under certain circumstances the individual risks involved; for example, when storage and stop-over time en route are high, with a significant exposure to risk at nearby locations.

Despite a general agreement that F-N curves offer the best means of expressing societal risk, Consensus Conference participants suggested a number of ways in which these curves can be better represented:

1. *Extending the range of consequences reflected in the* F-N *relationship.* Several participants suggested that for completeness of reporting, other consequence measures (in addition to fatalities) should be considered because presumably these measures will effect different mitigating responses. These measures can include personal injuries, property damage, and environmental impacts (including the natural environment and health effects) for both short-term (noticeable immediately) and long-term (noticeable after several years) scenarios. Depending on the scope of the environmental effects being considered, the issues can be very



Legend:

1. **Involvement of dangerous vehicle in accident**
2. **Occurrence of breach in containment**
3. **Occurrence of release by type and size**
4. **Hazard area for different classes of damage**
5. **Number of people killed and/or injured along route.**

FIGURE 2 Risk assessment components.

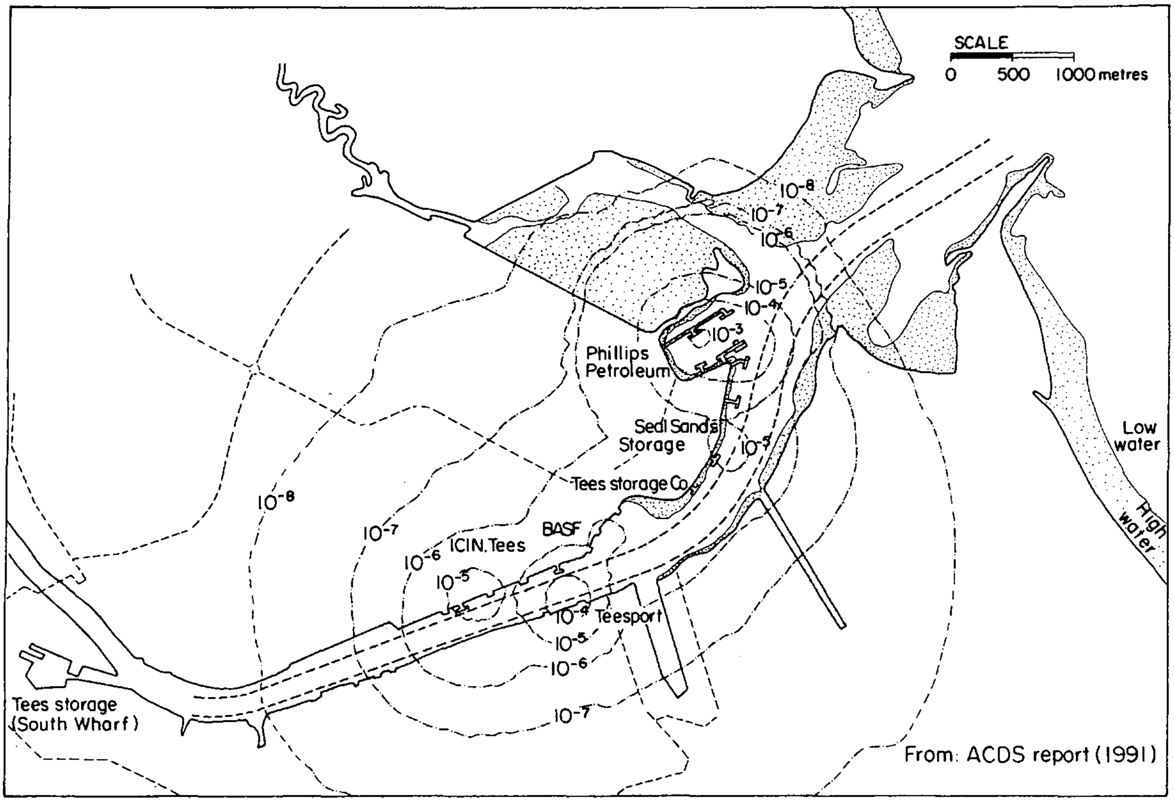


FIGURE 3 Individual risk isopleths (liquefied gas releases at terminal facility). Adapted from ACDS report (*24*).

involved analytically, requiring input from various areas of expertise. As an example of recent initiatives in this area, the HSE and the Department of the Environment (*18*) in the United Kingdom have been exploring ways in which several of these environmental concerns could be incorporated into QRA, based on the 1982 Seveso Directive and the Control of Industrial Major Accident Hazard (CIMAH) Regulations (*19–21*).

2. *Alternative ways of defining risk consequence.* Currently, two types of consequence criteria are used in *F-N* curves for the transportation of dangerous goods: immediate fatalities or "dangerous dose." According to Hurst et al. (*22*), the dangerous dose criterion is a recommended standard, which if exceeded could invite certain controls on development; for example, restrictions placed on certain types of development within a so-called "consultation zone." The HSE-recommended dangerous dose for toxic materials is a function of concentration [in parts per million (ppm)] and exposure time. For liquefied chlorine gas, for example, a dose of more than 108,000 ppm per minute (ppm/min) could give rise to fatalities in the more vulnerable population (*23*). The probability of incurring a fatality in the *F-N* curve requires an additional step in the analysis to translate "exposure to dose" to a "fatality response." To accomplish this, the Advisory Committee on Dangerous Substances 1991 report (*24*) suggests using a probit dose-response formulation, in which the input dose (expressed as a function of concentration and exposure time) becomes an input into a probit expression, with the dependent variable being a measure of the probability of death.

The Consensus Conference did not debate the issue of which criterion better reflects societal risk: fatality/personal injury or

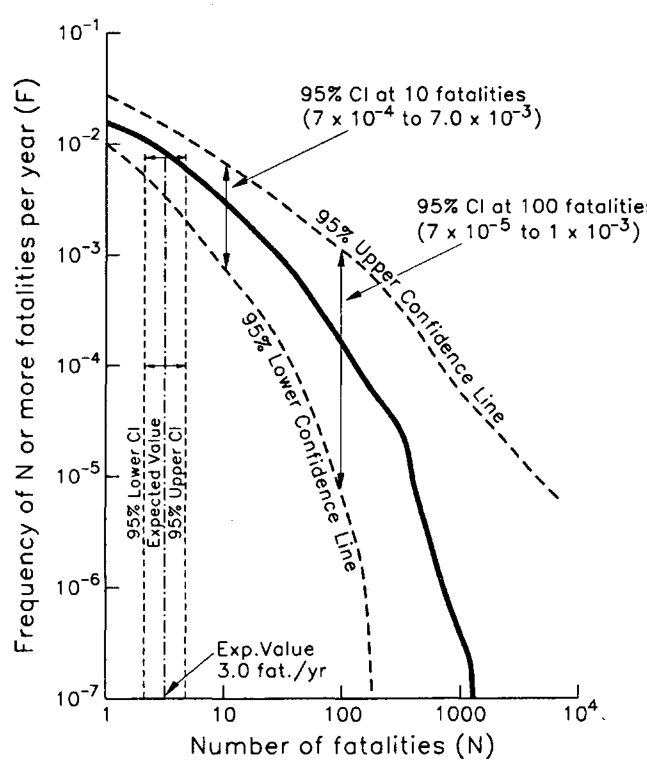


FIGURE 4 Cumulative societal risk *F-N* curve showing confidence intervals.

dangerous dose. However, it was generally recognized that a fatality- (and injury-) based consequence approach may be more readily applied to a further cost-benefit analysis of alternative strategies for mitigation, because techniques already exist for valuing death and injury in discounted monetary terms.

3. *Linking* F-N *curves to mitigation.* The reporting of *F-N* relationships must be linked directly to mitigation. This could include actions taken by individuals in order to avoid the full impact of a potential threat or actions taken by officials in response to incidents that have already occurred so as to minimize their resultant damages. Examples of individual actions include attaining shelter or evacuation. Examples of actions taken by officials include capping or containing the size of the release at the source, advising individuals along the path of potential threat to seek shelter or to evacuate the site, and finally implementing a safe and effective clean-up program.

4. *Including monetary factors.* Decisions are rarely made in the absence of monetary consideration (i.e., the cost of mitigation versus the benefits of risk reduction). According to Rimington (*13*): "Risk assessment is about giving proper structure and weight to any detriments so that we can compare them with the benefits." Many participants at the Consensus Conference echoed this sentiment, suggesting that risk output must be reported in such a way as to permit a thorough cost-effective evaluation of alternative forms of mitigation. This could involve assigning values to deaths, personal injuries, and property damage in the *F-N* curves and assessing the costs of alternative types of mitigation, including emergency response, containment, and clean up, as well as risk avoidance.

5. *Expressing uncertainty in the* F-N *relationship.* Because uncertainty in risk estimation varies with the number of reported cases used in validating the model estimates, the uncertainty associated with very low-frequency/high-consequence events is likely to be greater than uncertainty for high-frequency/low-consequence events. Accordingly, certain regions of the *F-N* curves are more prone to uncertainty than other regions, and this should be taken into account in representing the results. This is illustrated in Figure 4 by establishing confidence limits about each point on the *F-N* curve. The confidence bands associated with low-frequency/high-consequence regions of the *F-N* curve have been drawn wider to reflect a wider band of uncertainty associated with these estimates.

The Consensus Conference acknowledged that imperfect information will always produce risk estimates that are subject to error. The true value of risk will never be known. Confidence bands in the *F-N* curves are helpful to decision makers because they provide a range of values within which the true value of risk (in this case the frequency of *N* or more fatalities) lies, with, for example, a 95 percent level of confidence. These bands also serve as a basis for comparing uncertain estimates from different sources with values reported elsewhere for similar transportation of dangerous goods problems.

Frequently societal risks in the F-N curves are combined over all consequent damages and expressed as a single expected damage value (e.g., expected fatalities per year). This use of expected value for fatalities and injuries resulting from incidents involving the transportation of dangerous goods has created problems of validation for QRA models and has fostered a belief that these models are unnecessarily alarmist when compared with historical experience. A word of caution is advised in using and interpreting QRA results, based exclusively on the expected value of harm. Because in this measure low-frequency/high-consequence events are lumped together with high-frequency/low-consequence events, the resultant expected value will tend to overestimate risks, when compared with historical data that are normally collected over short periods of time. Many existing data bases include reports on dangerous goods incidents that have taken place over the last 10 to 15 years.

CONCERNING ABSOLUTE AND RELATIVE RISKS

Another question of importance in communicating risk is: should risks in QRA be expressed in absolute or in relative terms? The presence of uncertainty in risk estimation has fostered the belief that absolute risks are simply "abstractions posing as truth" (*10*). A number of participants at the Consensus Conference argued that given this uncertainty, only relative risks have any practical validity in QRA applications. These participants stressed that what is of interest to the decision maker is not the true value of risk, but instead insights gained on the risks involved, whether one activity is safer than another, and the degree to which this is the case. Because only relative risks are required to answer this question, uncertainty in obtaining absolute risks would not be relevant.

Notwithstanding difficulties in obtaining reliable estimates of absolute risk, however, the importance of these measures in certain decision situations should not be underrated. Absolute risks are most relevant in setting priorities on the cost-effectiveness of mitigation and in comparing risks to established tolerance criteria. Relative risks are most relevant when one mitigation option is compared with another and the decision maker is interested in some preferred option without a firm statement as to its costs and benefits or its acceptability vis-à-vis public risk tolerance. When the main focus of interest is actual costs or risk-tolerance levels, then only risks expressed in absolute terms would be relevant in decision making.

QRA AND DECISION SUPPORT

Recognizing that decisions have to be made, the issue that needs to be addressed is how QRA can best aid the decision-making process. QRA is useful for setting priorities, for underpinning an effective risk-management program, for evaluating this program, and also for achieving a better and more public perception of the risk by communicating information about this risk (*14*).

Decision making in a risk environment is a four-stage process: identification of hazards, quantification of risks, assessing the tolerance of these risks in terms of community standards, and developing a cost-effective strategy for their control and reduction. Many QRA models have in the past been confined to identifying and measuring risks associated with different aspects of the transportation of dangerous goods problem: the accident, breach of containment, release situation, hazard area, and casualties involved for different levels of damage. However, at its current state of development, QRA is increasingly being recognized as a process which, although still informed technically, must also reflect inherently economic and political considerations (*6*). To discuss QRA and decision making, the issue of tolerance of risk must first be discussed, because it is tolerance of risk that influences decisions on whether actions need to be taken and the form these actions are to take. In applying risk tolerance to decision making, three factors need to be specified: (*a*) an appropriate risk-tolerance criteria, (*b*) a framework of decisions for different levels of tolerance, and (*c*) the cost and benefits associated with these decisions.

The first factor requires the development of risk-tolerance criteria that are reflective of the public perceptions of risks associated with a given activity and their acceptability. The second factor attempts to formulate a suitable decision strategy on the basis of the previous perceptions on risk tolerance. The third factor is concerned with assigning costs and benefits to the activity being considered and assessing how these costs and benefits are modified by alternative forms of mitigation.

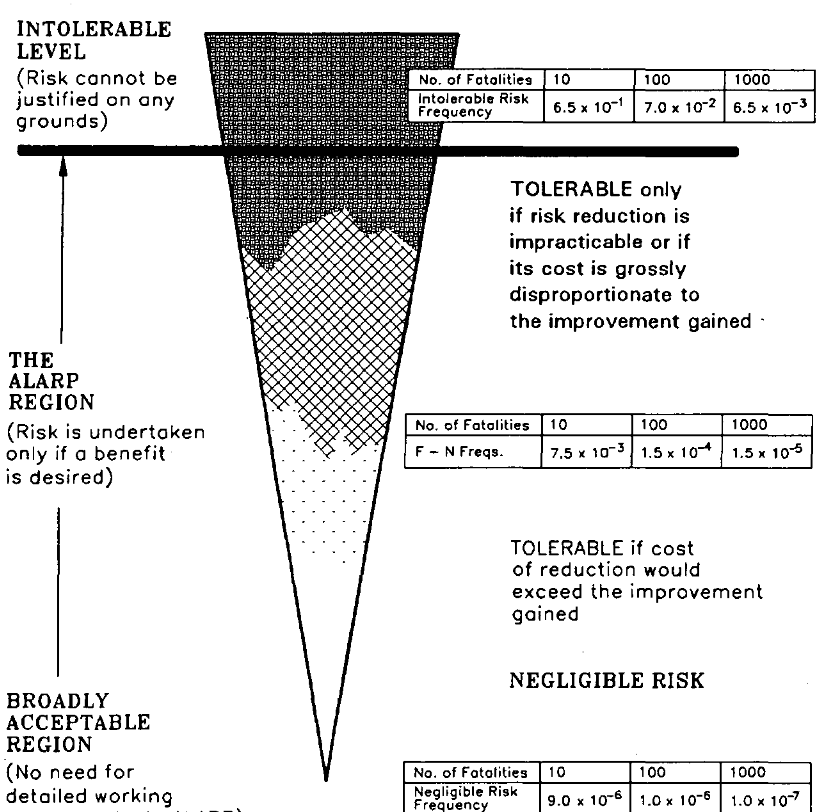
To assist the decision maker in applying QRA, the Advisory Committee on Dangerous Substances (ACDS) report (*24*) suggested an approach for guiding decisions based on comparing risks to established tolerance criteria for advisable action. Three criteria were identified:

1. Risk is so great or the outcome so unacceptable that it must be refused altogether (intolerable);
2. Risk is so small that no further action or precaution is necessary (de minimis);
3. Risks fall between these two states so that they can be reduced to be "as low as reasonably practicable" (ALARP).

How these three "advice regions" were applied in the ACDS report to the national societal risks in the United Kingdom is illustrated in Figure 5. The upper and lower bound ALARP values indicated in this figure have been set for three consequence levels on the societal *F-N* curve in the ACDS report (i.e., 10, 100, and 1,000 fatalities). In general, values of risk from QRA that exceed the upper-bound ALARP values are deemed to be intolerable from a societal perspective. Below the lower-bound ALARP values, societal risks are negligible and do not require further action. Risks in the ALARP region should be reduced as much as is economically practicable. Whether mitigation is advisable is a matter of costs and benefits, supplemented by practical political considerations. As shown in this figure, national societal risks were found to be ALARP at all levels of the *F-N* curve.

Although the application of these criteria may appear on the surface to be straightforward, it is generally recognized that a number of factors act to modify risk-tolerance criteria for different activities and jurisdictions, and this can have serious implications for any suggested advice structure, for example:

1. *National and local interests and customs.* It is generally acknowledged that in some countries the public tolerates certain types of risk more readily than in other countries. Similar discrepancies may take place between different socioeconomic and demographic groups even within the same country or jurisdiction.
2. *Discretionary nature of the risk activity.* This factor distinguishes between risks that are mandated in day-to-day activities and those risks that are discretionary in nature and hence can be avoided simply by lifestyle alterations. (Examples of mandatory



No. of Fatalities	10	100	1000
Intolerable Risk Frequency	6.5×10^{-1}	7.0×10^{-2}	6.5×10^{-3}

No. of Fatalities	10	100	1000
F – N Freqs.	7.5×10^{-3}	1.5×10^{-4}	1.5×10^{-5}

No. of Fatalities	10	100	1000
Negligible Risk Frequency	9.0×10^{-6}	1.0×10^{-6}	1.0×10^{-7}

FIGURE 5 HSE risk tolerance criteria for national societal risks in the United Kingdom. From ACDS report (*24*).

risks are work- and ambient-related, whereas examples of discretionary risks are recreational, such as skiing or hang gliding).

3. *Risk history.* This factor considers the past history of risk associated with a given activity. For example, have there been casualties in the recent past associated with the activity and what were the circumstances surrounding these casualties?

4. *Economic consideration.* A number of monetary factors affect tolerance of risk. It is generally recognized that the assignment of costs and benefits to risk and its mitigation varies inherently from jurisdiction to jurisdiction, and from time to time, depending on wider economic issues.

The Consensus Conference acknowledged that largely because of these factors, QRA may not be able to determine the best decision to take on reducing the risks associated with the transportation of dangerous goods and that there is much that needs to be prescribed to the political arena. QRA enables these essentially political decisions to be technically informed.

CONCLUSION

The lessons learned from the Consensus Conference were summarized into a series of consensus statements that were submitted to the participants to elicit their agreement or disagreement. An attempt has been made in this paper to elaborate on these statements with reference to what is known about QRA from the literature, and from discussion at the Conference.

A number of ways in which QRA can be made more relevant to decision makers have been addressed in this paper. However, there are practical limits on what QRA can accomplish in a decision-making context, given the complexity of issues surrounding the risks of transporting dangerous goods. Conclusions regarding limits of QRA are inevitably subjective and political, and depend (among other factors) on the resources available and the questions being addressed. The Consensus Conference could not map out the limits of QRA, a task which is likely impossible to realize. The Conference was instrumental, however, in identifying a number of important issues that need to be considered to make QRA more meaningful to users, decision makers, and the public at large.

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Use of Quantified Risk Assessment in Evaluating the Risks of Transporting Chlorine by Road and Rail

D. G. LEEMING AND F. F. SACCOMANNO

The Health and Safety Executive (HSE) makes routine use of its computerized quantified Risk Assessment Tool (RISKAT) in order to assess the risks from major industrial hazards. In recent years attention has been directed toward the transport of dangerous substances, and consequently HSE has developed a transportation version of RISKAT. Described is the application of Transport RISKAT to a case study in which the overall risks from a major industrial facility handling chlorine have been assessed. A novel feature of this study is the inclusion of the delivery system into the assessment, and the comparison of two transport modes: rail and road. The proposed switch from rail to road transport significantly reduces the risks from site operations. The study therefore addresses two questions: has any transfer of risks onto the transport system taken place, and if so, are the overall risks reduced as a result of the switch in mode? In addressing these questions, the report concludes that there is a considerable degree of uncertainty in the risk estimates. The effect of variability on the conclusions that can be drawn from the study is illustrated by the use of risk inputs from a number of independent sources.

In 1991 the Health and Safety Commission's Advisory Committee on Dangerous Goods (ACDS) published a report of a major study into the national risks of transporting dangerous goods (*1*). Although concluding that the national risks were tolerable, the report recommended that specific studies should be made of situations in which a concentration of risk from the transportation of hazardous materials is perceived. Such specific studies invariably require the use of quantified risk assessment (QRA) tools in the form of computer codes. For several years HSE has used RISKAT (*2*) to provide land-use planning advice on developments in the vicinity of major industrial hazards at fixed installations. In order to address the ACDS recommendation, HSE has developed a similar suite of codes [Transport RISKAT (*3*)] for assessing transportation risks. The development of Transport RISKAT has been assisted by case work. Described in this paper is the application of the codes to one such case study involving the handling of chlorine by a major industrial facility, together with two options for its delivery system (i.e., by rail or road). The assessment addresses two important issues that have often been neglected in QRA studies.

First, the question of uncertainty in the estimates has been addressed through the use of several data sources, and the implications of any variation in the conclusions between risk estimates produced from each source have been assessed. Second, as a switch in the mode of delivery may have implications for other interacting systems, a more global view of the chlorine delivery system has been taken than would be the case if only the transport risks had been assessed.

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UNCERTAINTY IN QRA

The credibility of QRA's ability to provide accurate predictions of the threats posed by hazardous materials is often undermined by the degree of uncertainty in the estimates. This can be worsened when the findings of QRA are at variance with public perception. One commonly encountered opinion is that rail transport is inherently safer than road. However, although the assumption that rail tankers are less likely than road tankers to be involved in an accident is generally supported by statistical evidence, this perceived safety advantage may be countered by the greater severity of potential consequences because of larger payloads or routing of rail shipments through population centers. In view of such issues, it is important that the assumptions made during the application of QRA and their effects are accounted for in the reporting of risk estimates.

Historically, risk uncertainty has been handled in a number of ways. A "best estimate" approach is sometimes used, in which sample averages are obtained from the literature or from observation. Erring on the safe side is an approach that is biased toward the worst-case scenarios in order that inaccuracy should not compromise safety. HSE adopts a "cautious best estimate" approach to major hazard risk assessment, essentially a combination of the first two philosophies described in this paper. Finally, there are more sophisticated approaches in which the inputs and outputs of a QRA study are subjected to comprehensive statistical analysis.

REGULATORY FRAMEWORK

Fixed Hazardous Installations

The regulatory framework (*4–6*) in the United Kingdom (UK) requires that HSE provide the local authorities with advice on land-use planning around major hazards (*7*). This advice mechanism is triggered when planning applications are made within the consultation distance (CD) of the particular installation, CD being calculated from the notifiable amount of hazardous substance. Developers of new hazardous installations must seek the consent of the appropriate authority.

The criteria used by HSE for providing risk-based advice (*8*) define four development categories with varying sensitivity to risk. The advice to be given on these developments depends on an assessment of the levels of risk as a function of distance and direction from the plant.

Transportation of Hazardous Substances (Rail and Road)

UK regulations specific to hazardous substance transport overland cover the aspects of labeling, vehicle marking, driver training and certification, and the equipment and design of vehicles. The move toward harmonization in the European Economic Community has led to the introduction of dangerous goods transportation and handling agreements (*9,10*). There are no regulations directly concerning the routing of hazardous substance transport.

CASE STUDY

A major industrial facility in the UK (hereafter referred to as "the site") uses chlorine in the manufacture of various products. Currently, this chlorine is shipped overland by rail. Because of operating constraints, the rail delivery system lacks the flexibility required to reduce the lead time for delivery of chlorine to the site. As a result, a large inventory of chlorine is required on site as a backup should it be needed in production.

At this site the notifiable amount of bulk storage of chlorine is large, and consequently the area of land subjected to risk-based development restrictions is considerable. In response to the potential hazard on the advice of HSE, the local authority has imposed a CD of 2.0 km around the plant, which is situated in a highly urbanized region. There are considerable incentives for reducing the CD by lowering the amount of on-site storage of chlorine. To bring this about, the site owners are considering a "just-in-time" system of delivery that more closely matches the requirements of production over time, requiring a switch from rail to road transport. To reflect a much-reduced inventory, a new CD of 1 km has been suggested for the site, reducing the amount of land restricted by 75 percent over the existing zone.

The benefits of reducing the off-site risks as proposed are considerable: 47,000 out of 60,000 residents, 23 out of 29 schools, and 20 out of 25 other sensitive developments will be removed from the consultation zone. There will also be a considerable appreciation in land value because of the reduction in the risk from the site.

Although it is recognized that a just-in-time system of delivery for chlorine will reduce the risks from the fixed installation, the question that needs to be addressed is: are reductions in site risks resulting from a just-in-time system of delivery offset by higher on-route risks associated with a change in the mode of delivery from rail to road?

OBJECTIVES

The case study had four objectives:

1. Carry out a comparative assessment of the on-route risks for transporting chlorine by rail and road to the site;
2. Consider the uncertainty in transport risk estimation by repeating the assessment with several sources of accident and release estimates and to assess the implications of any variability in the risk estimates for conclusions about the relative safety advantages of one mode over another;
3. Carry out a comparative assessment of the risks from site operations before and after the switch in transport mode; and
4. Consider the total risks of site and delivery system with each mode of delivery and assess whether any transfer of risks has taken place. The study of variability (Objective 2) will increase confidence in the conclusions by providing a range of estimates.

In this study, the assessment of the delivery system has included only those risks associated with accident-induced releases of hazardous material.

THE SITE

The site currently consumes some 35,000 tonnes of chlorine/year for the production of various commodities. The handling facility consists of two 150-tonne bulk storage tanks fed from a discharge bay. Pipework from the bulk storage leads to various liquid reactors and vaporizers, which in turn feed a bank of gaseous reactors. The discharge bay holds a maximum of four 28-tonne rail tankers and the reception area another eight. In their initial assessment, HSE has used a total inventory of 360 tonnes to set the CD.

The proposed just-in-time delivery envisages a complete refit. The bulk storage system is to be replaced by one 20-tonne buffer tank, maintained at the 10-tonne level by continuous unloading of road tankers. Unloading operations will mean the presence of one full tanker and one partially loaded tanker on site at any given time. This arrangement allows for a maximum 50 tonne of chlorine on site.

EXISTING AND PROPOSED DELIVERY SYSTEMS

Currently, chlorine is shipped to the plant in 28-tonne pressurized rail bulk tankers. Approximately 8 to 12 tankers/train are shipped three to four times weekly from the supplier to the site. All rail shipments of chlorine take place during the night when passenger traffic on the rail network is negligible.

The existing 319-km rail route, subdivided into 18 sections for the assessment, consists mostly of high-level mainline track. Much of the route is of rural character, with scattered small communities. The route passes through a large town and a large moderately built-up area before entering the highly built-up area containing the site. The maximum allowable freight train speed over much of this track is 100 km/hr, although there may be sections of this route where the maximum allowable speed is lower. The route traverses four railyards. At the rail terminus nearest to the site, the chlorine tankers are shunted onto industrial track for final delivery to the plant.

Specially designed road tankers with a payload capacity of 21 tonnes are proposed for the alternative road supply option. Road shipments would originate from a different supplier to the rail option located nearer to the site. The corresponding road distance is 154 km, subdivided into 14 sections.

The route is motorway (freeway) between Sections 2 and 13. It bypasses urban areas at Sections 4 to 5 and 7. Unlike the rail route, it does not pass directly through population centers until Section 12, when it enters the built-up area around the site.

The average population density varies within 10 km of the route options (Figure 1). Compared with the rail route, the figure shows lower peaks in the population immediately adjacent (nearest 1 km) to the road route, reflecting the tendency for trunk roads to bypass population centers. The motorist population was assumed to be constant along the route and concentrated around an accident site, caused by backing up and "rubbernecking."

COMPONENTS OF RISK ESTIMATION

Illustrated in Figure 2 [adapted from Alp et al. (*11*)] is the structure of quantified risk assessment (QRA) applied to the transport of toxic substances. This structure is the basis of HSE's Transport RISKAT. As in any QRA, the process can be split into three parts: (*a*) identification of hazard type and frequency, (*b*) consequence analysis for each hazard, and (*c*) combination of consequence and likelihood expressed as risk. Hazards associated with the transport of chlorine consist of accident-induced releases during transport and the consequent impacts on nearby population. Heavy gas-dispersion codes are used to estimate the spacial distribution of toxic dose for a range of representative releases and weather conditions. A knowledge of the population distribution and the dose-

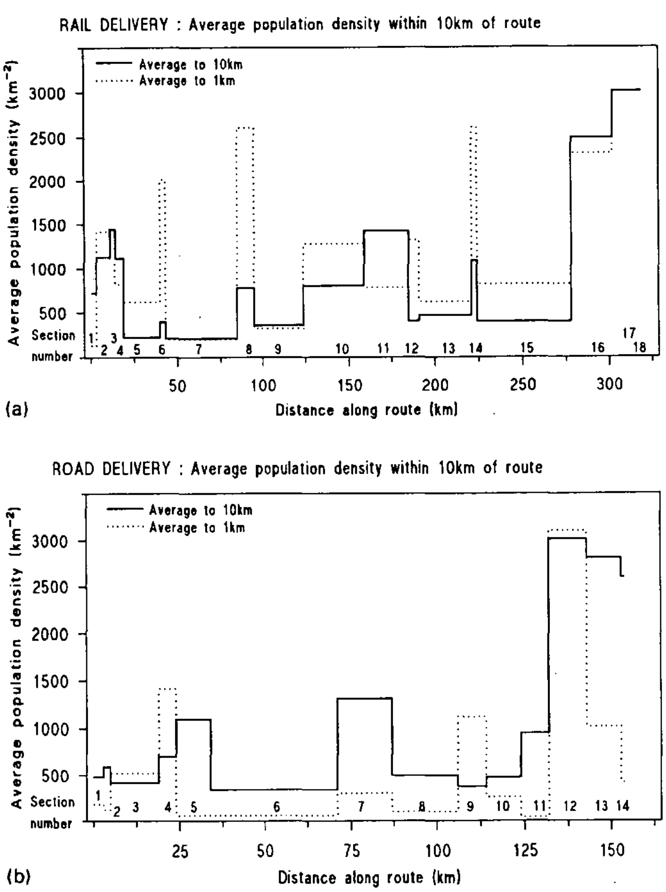

FIGURE 1 Density of population adjacent to (a) rail and (b) road routes.

response relationship (toxicology) allows an estimate to be made of the number of fatalities (or other level of harm) for each event.

The assessment of fixed installations has the same structure, although release scenarios are usually more diverse and their frequencies are derived directly from generic data bases.

COMPARATIVE ASSESSMENT OF RISKS

Estimating Release Frequencies: Site

The chlorine plant on site has been assessed by HSE. Loss-of-containment mechanisms were identified for both the rail- and road-supplied plant designs. These ranged from catastrophic vessel failure, vessel holes above and below the liquid level, to various types of pipework failure in the liquid and vapor phases and tanker coupling failures.

The frequencies were obtained from HSE's data base of generic failure rates, used for its static major hazard assessment casework. These data were derived from a number of sources including the historical record and theoretical studies involving such techniques as fault tree analysis supplemented by expert judgment.

Estimating Release Frequencies: Delivery System

The probability of an accident-induced release depends on three constituent factors:

1. *Accident rates involving rail and road chlorine tankers.* These accident rates are expressed in terms of tanker accidents per vehicle km.
2. *Probability of breach of containment (fault rate).* Fault rates are expressed as a percentage of the accidents that result in some form of release.
3. *Probabilities of specific types and sizes of release.* Release probabilities are estimated for catastrophic failure of the tanker containment system and continuous releases result from holes or equipment leaks.

Unlike the case with static major hazards, HSE has not yet developed a policy on failure rates associated with dangerous goods transportation. Therefore to ensure that the implications of variability in the risk estimates are accounted for, this exercise has used failure-rate data from several independent sources.

1. *Institute for Risk Research (IRR), University of Waterloo, Canada.* Road and rail accident rates are based on a statistical analysis of Canadian-reported accident data. Accident rate models (*12*) were calibrated with Ontario accident data. IRR obtained fault and conditional release probabilities for the rail and road transport using a fault tree analysis of chlorine bulk tanker systems for Canadian conditions (*13*).
2. *Averages from a Group of Experts (CONSENS).* To assess consistency in risk estimation for a common set of transport conditions, a group of experts provided "consensus" estimates of accident rates, fault rates and release probabilities for a common transport problem involving the bulk transport of chlorine by rail and road tanker over a 100-km hypothetical route (*3*). Estimates were derived from a mixture of North American and European data. The mean values were used for this assessment.

3. *Health and Safety Commission, Advisory Committee on Dangerous Substances, UK.* These estimates were taken from the study of national risks published in 1991 (*1*). The ACDS frequencies of large releases were derived directly from an analysis of the historical road and rail puncture records. As UK observations of chlorine road and rail tanker breaches were limited in number, U.S. data and UK thin-walled (i.e., nondangerous goods) tanker breaches were analyzed. Engineering judgment was used to account for operational and design differences.

4. *Health and Safety Commission, Research and Laboratory Services Division, UK.* Road accident rate estimates were derived specifically for conditions that match the main delivery characteristics (i.e., articulated trucks, traveling on motorways, and so on). a base of approximately 12,000 individual injury-accident records and traffic flow (i.e., exposure) data for the entire trunk road network during 1991 was obtained from the Department of Transport (DTp). This provided information on the influence of variation in route and vehicle factors on the likelihood of an accident.

5. *British Rail Railfreight Distribution (BRRF).* BRRF supplied an estimate of derailment frequency for all loaded freight wagons.

6. *Loughborough University, UK.* Davies and Lees (*14*) made a study of the UK road transport environment for conveyance of hazardous materials using DTp statistics for 1986. The fault probability was based on attendance by the fire brigade at all incidents involving hazardous materials transport by road.

National Differences

The various sources previously detailed assumed a variety of North American, European, and UK conditions. Studies (e.g., Davies and Lees *14*) have found lower heavy goods vehicle (HGV) accident rates for the UK compared with those in North America. The majority of UK hazardous substance road tankers are fitted with safety-enhancing features such as anti-skid and jackknife systems, which reduce their accident rate compared with the mean for articulated HGVs in general. In the UK there have not been any observations of significant releases of chlorine from road tankers.

There are also basic differences between the North American and UK rail environment, partly stemming from the need for much longer trains in the former case. For instance, long trains require rigid couplers, which may be hazardous in an accident situation. In the UK, the couplers are recessed behind damped buffers, and buffer over-ride protection is fitted to all chlorine tank wagons.

Estimating Hazard Areas for Different Levels of Health Impact

Transport RISKAT incorporates the dense gas dispersion codes DENZ (*15*) and CRUNCH (*16*) for estimation of the toxic dose distribution (hazard areas) that would result from each release scenario for each of a set of representative weather conditions. Stability, windspeed, and windrose profiles were obtained for a weather station in the vicinity of the site. To compute the impact on the population, a probability-of-fatality approach was used, based on a probit relationship (*1*). The code computes hazard areas for both the outdoor and indoor population, the latter via an infiltration model. Motorists are considered effectively outdoors.

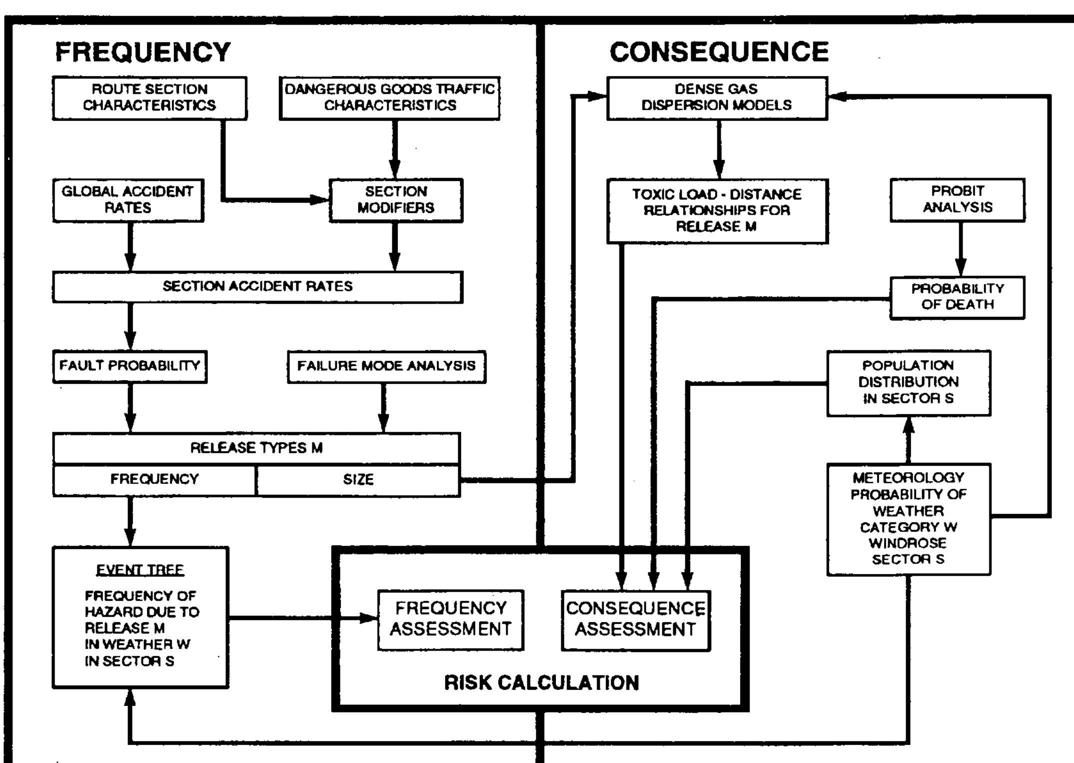

FIGURE 2 Structure of transport-quantified risk assessment.

Individual Risk

Individual risk is defined (*8*) as the risk to which an individual at a particular location is subjected. Because of the mobile nature of transport risk sources, the risks at particular locations are normally de minimus, (i.e., less than 10^{-6} per year) even at distances nearest to the routes, although the risks to unspecified individuals somewhere along the route may be significant. In this exercise, all risks have been expressed from a societal perspective in terms of the expected number of fatalities per year.

Societal Risk Calculation

The number of persons exposed to each representative release can be estimated by matching the hazard areas resulting from each scenario with the population density in the region exposed to the hazard. In this way, an estimate can be made of the mean number killed by each hypothetical release scenario and its probability. Transport RISKAT performs this operation for each route segment in order to calculate on-route risks and over-the-site locality for risks from the plant.

Effect of Population Distribution on Risk Estimation

Societal risk estimation requires the knowledge of how the on- and off-road population is distributed in terms of its density and location. Schemes for estimating this have been developed for static major hazard assessments (*17*). Transport assessments involve much greater areas than static sites. In addition, societal risk estimates are very sensitive to assumptions that are made about the variation of population density with distance. The consequence models need to be sensitive to extreme distributions such as strip developments, where a strip of built-up land exists close to a route and bypasses the section where a sizable clear zone exists between the route and an urban area. In this study, the population contributions were weighted according to their proximity to the routes.

Results

The results are given in terms of three societal risk descriptors:

F-N Curves

These are plots of the number *N* killed against the cumulative frequency of *N* or more fatalities that are representations of the spectrum of potential risks. They are useful when "risk aversion" is an issue (i.e., the relationship between tolerability and the scale of the event).

Expectation Value

This is the long-term average number of fatalities per unit time (year). It is constructed by summing the products of all events and their associated probabilities. This can be used in conjunction with the *F-N* curve to compare results from different cases.

Societal Risk Rate

This is relevant to route risks only. It is given by the expectation value divided by the length of route and can be useful in illustrating the variation in risks along a transport route.

Best Estimate, Upper and Lower Limits

In order to aid interpretation of the results, a best-estimate approach has been adopted. This aims to emphasize those risk estimates that have been obtained using inputs that were most appropriate to the case being studied.

Road

The RLSD results were used as the "cautious best estimate" of the risks associated with the road delivery system. This was appropriate because the accident rates were derived from a large, up-to-date data base of accident and traffic records specifically for articulated HGVs on UK motorways, with no distinction made between hazardous materials tankers and other HGVs.

Rail

The ACDS accident rate included both derailments and collisions occurring on the UK rail network, and as the national differences are likely to be greater for the rail environment than that for road, it was thought appropriate to consider the ACDS results "best estimates."

Delivery System

How the societal risk rate (using IRR estimates) varies with route section for the rail and road routes is shown in Figure 3. The range of estimates for each transport mode for the entire routes are shown in the form of *F-N* curves in Figure 4. The expectation values are also given.

Site

F-N curves and expectation values for the site alone are given in Figure 5. Included in the figure are the tolerability limits for specific localities derived by the ACDS in their study of the risks of transporting dangerous substances in the UK. It should be noted that these tolerability curves were derived for certain marine ports included in the national assessment, and great care should be exercised when transferring tolerability criteria from one situation to another. The range of estimates of the total risks from the site and delivery system are shown in Figure 6.

DISCUSSION OF RESULTS

The objective of this study was to estimate relative rather than absolute risks for each mode of transport. The significance of this is that as the same models and assumptions were applied through-

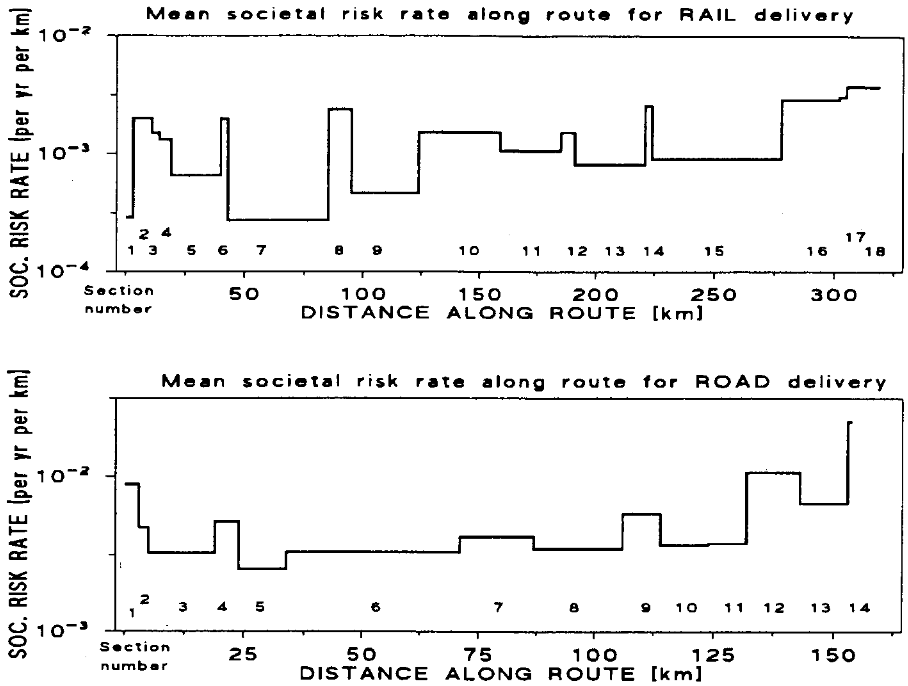

FIGURE 3 Societal risk rates for each delivery system.

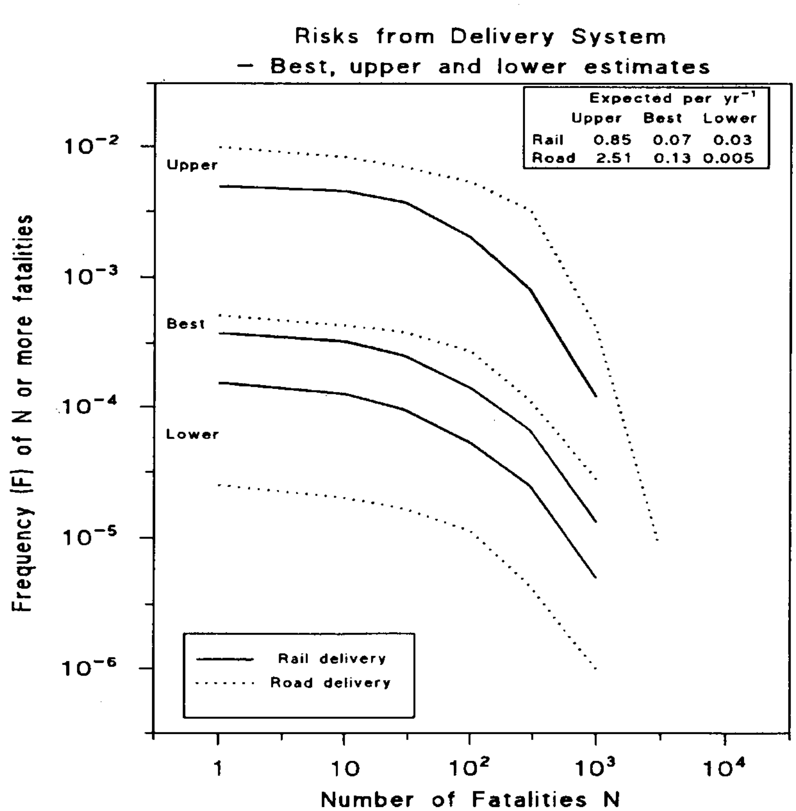

FIGURE 4 Range of estimates of societal risk for each delivery system.

out, the inherent uncertainty will be essentially similar in each case. The results are discussed accordingly.

Route Risks (Delivery System)

Significant differences in the societal risks resulted from variability in the estimates as reported by the independent sources. The estimates for rail delivery range from 0.03 to 0.85 fatalities/year, and the corresponding figures for road span two orders of magnitude from 0.005 to 2.5/year.

The greatest risk estimates for both road and rail were derived from the CONSENS and IRR inputs, which were mostly based on North American conditions. The lowest estimates were derived from the ACDS and BRRF inputs; these were provided for UK conditions.

From Figure 4, the risks associated with each transport mode can be compared. The best estimates are very close, in view of the large variation in the estimates. There is more uncertainty in the estimates for road than for rail, with all the rail estimates being contained within the range of road estimates. As the length of the road route is only half that of the rail route, similar overall risks would seem to indicate greater risks per km for road. The upper estimates indicate higher risks for road.

The motorist population contributed on average about two-thirds of the societal risk because of the road delivery system. This result implies that the model is very sensitive to the assumptions made during the analysis of the impact on the motorist population.

The societal risk rate variations along the route (Figure 3) follow closely the variation of the nearest 1-km population density (Figure 1). This effect is more pronounced with the rail than the road risks because of the large contribution from the motorist population. "Hot-spots" can be perceived along the route (i.e., Rail Section 8, a rail yard in the center of a large town). The results indicate that the model is more sensitive to variations in the population density than in the accident rate.

Site Risks

The risks from the site operations are an order of magnitude lower after the risk-reducing alterations to the design. The expected number of fatalities because of the rail-supplied plant were estimated at 0.2/year, compared with 0.02 for the road supplied "just-in-time" system. The *F-N* curves for both options fall between the ACDS criterion for intolerability at specific localities (*1*) and the negligible line. Note that the transfer of tolerability criteria from one situation to another is a complex issue; the criteria are shown here as a rough guide only.

Total Risks

The total risks of site and delivery system follow a similar pattern to the delivery system alone. The best estimates of the total risks before and after the switch in transport modes are again very close, and there is more uncertainty in the estimates for the road-

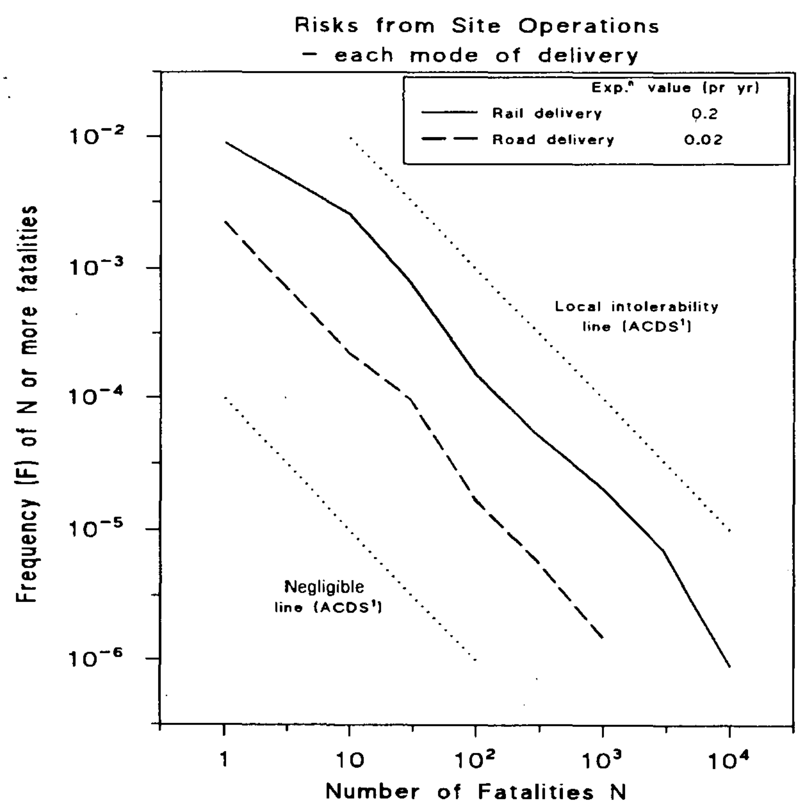

FIGURE 5 Societal risk estimates for site only, before and after change in delivery system.

supplied option. The site risks are lower than the upper estimates for the transport systems, but higher than the lower transport risk estimates. The best and upper-risk estimates support the conclusion that the rail-supplied option is as safe or safer than the road option. A less cautious approach, drawing conclusions from the lower estimates alone, would find the reductions in site risks predominating, with lower risks for the road-supplied option.

Individual Risks

Individual risks to the population resident around the site have been reduced dramatically. This was the basis for the reduction in the consultation zone, which has a radius reduced by 50 percent. Using the ''best estimates'' of accident and release data, the risks of individuals resident alongside either transport route receiving the LD_{50} (dose giving a 50 percent chance of fatality) have been estimated as lower than 10^{-6} yr^{-1} for distances exceeding 50 m.

CONCLUSIONS

Six sources of accident rate and release probability data were used to estimate risks for road and rail transport of chlorine. The risk inputs from the various sources were derived in a number of ways from a comprehensive statistical analysis of a large number of accidents to engineering judgment applied to the specific details of a small number of actual chlorine releases. Some of the estimates were based on North American data, and some on European and UK data.

Illustrated in the study is the large degree of uncertainty associated with quantified risk assessment applied to the transport of hazardous substances. Depending on the source used for the risk inputs, contradictory conclusions can be drawn. It is likely that some of this uncertainty is explained by national or jurisdictional differences between sources, and on this assumption it was possible to derive ''cautious best estimates'' of the risks, using those inputs that were most closely tailored to the specific design of the delivery systems.

The findings of this study can be considered in terms of risks to individuals in specific locations (individual risk) or to society in general (societal risk). The switch in delivery mode indisputably results in a highly significant reduction in risks to the population resident in the vicinity of the site.

The best estimates of the societal risks associated with the two delivery system options are not significantly different in view of the degree of uncertainty, whereas the upper estimates are clearly lower for the existing rail-supplied option. The best and upper estimates of societal risks associated with the delivery systems are similar or greater than those associated with the site, and thus the total risks to society from the combined transport and storage operation will not be significantly different after the site modifications. In fact, if the most pessimistic estimates are considered for the delivery systems, risks to society may be slightly increased. Thus, from the societal perspective, the results neither support nor challenge a change in transport mode.

From the perspective of individuals exposed to the risks from the storage of chlorine on the site, the risks have been greatly reduced. This is emphasised by the 75 percent reduction in the

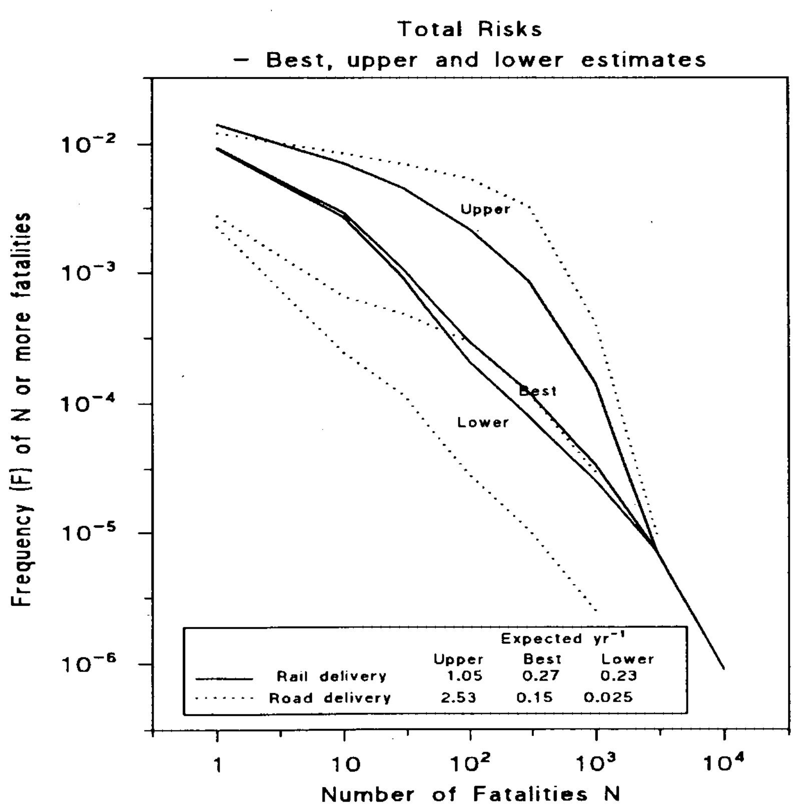

FIGURE 6 Societal risk estimates for combined site and delivery systems.

area of restricted development, which was based on assessments of individual risk. For those alongside the two transport routes, the risks of individuals at specific locations being affected by a release are very low, and in neither route or mode option are the risks significant compared with those from other sources. Therefore, from a consideration of individual risks to the resident populations, the change in mode and accompanying storage alterations should be welcomed.

The study has found that motorists are the main recipients of risks associated with road transport. As both the risk source and exposed populations are mobile, the individual risks will be negligible. However, the chance of a large number of motorists in general being affected by a release will be increased. The significance of this must be related to other societal risks to which motorists are exposed.

Both the societal and individual perspectives are relevant when considering the issue of tolerability. Clearly, no individuals will receive large increases in risk as a result of the change in transport mode. In certain regions (i.e., the site locality) the reverse will be the case. The risks to society in general will not be affected. However, significant increases in risks to one group (i.e., motorists on the road route) have been identified. This implies that dangerous goods-routing decisions should be influenced by considerations of the expected traffic density as well as residential and other exposed populations.

Other issues will also hold weight in the decision-making process. The benefits from the reduction in site risks are great in both economic terms (freeing up land for development) as well as in terms of safety to the large community resident around the site. Political considerations, such as those of public perception and the impetus given to the site alterations as a result of the existing land-planning framework, may in this case outweigh any conclusions drawn from an assessment of risks alone.

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Comparing Risks of Transporting Chemicals by Highway and Rail: A Case Study

ALAIN L. KORNHAUSER, DEXTER J. PASTERNAK, AND MARY ANNE SONTAG

The risks of moving chemicals by rail and highway are compared using a distribution risk decision support tool. Described are the problems faced by those who must evaluate how hazardous materials are to be transported, what attributes are needed in a decision support tool that quantifies the risk along competing routes, and how these results are used to select a mode and a route. This is achieved through the presentation of a case study involving the movement of anhydrous ammonia.

Although great care has always been taken to ensure the safe transportation of hazardous materials, the deregulation of the transportation industry coupled with chemical industry initiatives such as Responsible Care® have caused all involved to place more concern on the safe distribution of all hazardous material shipments. The development of better shipment containers and improved handling practices has led to a significant decline in the release of hazardous material during shipment, especially by rail; however, the industry is dedicated to further improvements, which many feel can be achieved through better planning, mode choice, carrier selection, and routing of individual shipments. There now exists a desire to thoroughly analyze the comparative risks associated with a range of mode and routing options of a much larger portion of chemical shipments. This desire is placing a significant demand on both the development of decision support tools that can effectively compute those risks and on the interpretation and judgments, based on those computed risks, made by the users of the decision support tools.

Addressed in this paper are some of the major issues facing the developers and users of hazardous materials transportation risk analysis tools. Desirable attributes of the tools are presented. The main purpose of the paper is to describe how a routing risk assessment decision support tool is currently being used by one chemical company to address the mode choice and routing issues company. This is achieved through the presentation of a case study involving the movement of anhydrous ammonia. This analysis is made on the basis of the decision support tool, PC*HazRoute™.

HAZARDOUS MATERIAL TRANSPORTATION OVERVIEW

According to the Office of Technology Assessment (*1*), annually in the United States there are more than 150 million shipments of hazardous materials that accumulate to require some 784 billion ton-miles of transportation demand. An extremely small number of these shipments, on the order of 10,000, incur some problem that leads to a release of some of the cargo (*2*). Of these releases, one-third are the result of transportation accidents and two-thirds are nonaccident related; for example, failure to properly load or secure a container (*1*). Most of these incidents are noncatastrophic and result in little environmental impact; however, a very few are severe. In the last few years an average of 12 deaths/year can be attributed to transport accidents involving the release of chemicals (*2*). The main characteristics of hazardous materials transportation in the United States are summarized as follows:

- 150 million shipments annually
- 784 billion ton miles annually
- 10,000 releases/year
- 1/3 are accident related
- 12 deaths on average/year

Thus accidents involving hazardous materials are extremely rare but potentially catastrophic events. The focus of analyses of alternate modes and routes is not only to reduce as much as possible the likelihood of an accident, but to also to reduce the damage to people and the environment in the event of an accident. Thus any risk measure involves the combined effect of release probabilities and intensity of consequences should a release occur. The intensity of the consequences is dependent not only on the environment and population in the vicinity of the release but also on the type of hazardous material being released. The term "hazardous material" spans a wide spectrum of products, from those having extremely high hazard, such as hydrogen cyanide and phosgene, to nonregulated, least-hazardous products like titanium dioxide and ethylene glycol. In Figure 1, hazardous materials are ranked using a product pyramid analogy having the most hazardous at the top and the least hazardous at the bottom. The width of the pyramid represents the inverse of the amount of analysis that has traditionally been undertaken to evaluate the shipment of the materials in each stratum. Those at the top have traditionally had a complete fault-tree analysis done in planning for their distribution. The analyses involve not only mode, container, and route, but also issues of alternate sourcing including reducing the on-site risk with less hazardous raw materials. Those at the bottom have had little quantitative analysis. A main benefit to be derived from the development of less expensive and more effective routing risk assessment decision support tools is that they would be applied to a broader spectrum of the materials contained in the

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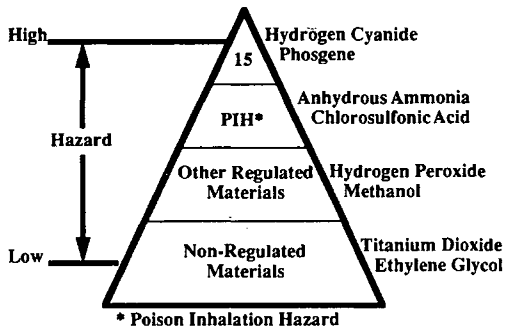

FIGURE 1 Product pyramid ranking hazardous materials.

product pyramid, thus significantly reducing the risk associated with the transport of the entire family of hazardous materials.

ELEMENTS OF THE MODAL DECISION PROCESS

There are several key elements in any modal decision process, of which the distribution risk is but one. Other considerations include volume and frequency of shipments, distance, product handling and inventory considerations at origin and destination, investment requirements in shipping containers, and operating cost considerations. Although each of these other elements is important, their quantification requires economic considerations that are not considered as part of this paper. Instead, the focus is on the identification, quantification, and interpretation of the relative distribution risk associated with alternative routes used by different modes of transport.

Decisions can best be reached when there is a clear understanding of business requirements, including customer and vendor needs. Attention must be given to gathering the best input data and statistics available relevant to the task at hand. The analysis should be objective and performed by persons disciplined in logistics, the risk assessment process, and design features of transportation equipment. Quantitative decision support tools are essential to performing meaningful risk assessment. They move us from the realm of qualitative reviews to quantitative analysis by reducing the analyses to "doable" tasks while providing the ability to perform "what-if" scenarios.

The components of the distribution risk element that must be addressed involve the inherent hazards of the material, the population and environs that are potentially exposed, the accident frequency along the proposed route, and the chances of a release given an accident. The literature contains many models and methods by which distribution risk can be estimated, and the validity of each is strictly dependent on the quality of the data for each of the parameters. Moreover, the precision of the risk estimation is controlled by the least-reliable data element. Thus, a more reliable measure of risk can be obtained from a less precise yet consistent analysis than it can from an analysis that is detailed in parts but fraught with data gaps in other parts. For example, it is more precise to consider plume formation and dispersion, but only if meteorological statistics for all highly populated, environmentally sensitive, or high accident rate locations can be obtained. Only then is it of any value to have detailed geographic distributions of population and environmentally sensitive areas. Although it is desirable for the analysis to use the best models of risk, if the data to support these models are not readily available, the cost of any analysis will become exorbitant and can be justified only when dealing with the most hazardous of materials. Thus there is a distinct link between the availability of data and the risk analysis model used in the decision support tool.

ATTRIBUTES OF A QUANTITATIVE ANALYSIS FOCUSED ON DISTRIBUTION RISK

For each mode to be considered, there must be the capability to obtain quantitative measures for every route to be considered. With these quantitative measures it is then possible to assess the risk of all the alternative routes for all of the modes. This allows the user to determine a candidate "best route" for each mode, which is then incorporated into the broader modal decision process. The ultimate distribution mode selected must attempt to satisfy customer and business requirements while striking a balance among safety, cost, and efficiency. This objective defines many of the components of a quantitative decision support tool.

For each mode to be properly evaluated, a set of realistic routes that may be used must first be identified and the distribution risk along each of the routes assessed. Usually many routes are possible; consequently, the user needs help in identifying a handful of candidate "best" routes among which to choose. Thus a fundamental attribute of a distribution risk decision support tool is that it be able to find realistic "best" routes. This means that if there exist route restrictions for a particular hazardous material; for example, tunnel restrictions, these should be readily excluded from any feasible route. Moreover, when dealing with rail shipments of all but the most hazardous materials when payment for special train services is available, it is important to restrict routes to single carriers, or if multiple carriers are used, to minimize the number of corporate interchanges and restrict the interchange locations at which significant traffic is interchanged among railroad companies. To do otherwise is either operationally unachievable or would submit the shipment to extremely high risks unless very expensive precautions were taken.

In order to have a quality quantitative decision support tool, its data bases must be consistently credible. Because the quality of the data base limits the quality of the analysis, it is imperative that the best available data be used. It is of little value to include more precise data that are not consistently available. For example, precise data available for just one state are of some—but unfortunately little—value unless shipments only within that state are being considered. This does not mean that there should not be an effort to improve the various data bases one state at a time, but it must be realized that the benefits derived from the better data will not be realized until the data for all states have been obtained. This implies that data-enhancement efforts should be focused on those that can be completed for all states. In any case, it is imperative that any decision support tool clearly identify its data limitations and that the user be totally aware of its shortcomings.

Because many different routes need to be compared, it is better if the system automatically finds the "best" route for the user. As each user may wish to weigh different attributes of risk differently, the system should allow the user to easily customize the weighting of different risk measures. In addition, the system should have "what-if" capabilities to allow the user to modify some of the route restrictions, edit data elements, and easily change assumptions.

Possibly the most important attribute is that the system needs to be novice friendly in terms of its dealing with the operation of the software. It is assumed that the user is an expert on the hazardous materials that are being transported, but it should not require that the user be any more than a novice when it comes to the operation of a computer or this decision support tool. The system should provide proper prompts, reminders, simplified editing, and archiving capabilities. It should assume that the user has other work to do besides the operation of this software.

The distribution risk decision support tool used in this analysis is ALK Associate Inc.'s PC*HazRoute™. The data bases and routing methodology included in ALK's products have been used by the transportation industry and its customers for more than 14 years.

For a true analysis of a rail or highway movement, population, accident rates, release rates, and road quality should all be studied. A well-respected paper on rail routing was published in the journal *Accident Analysis and Prevention* in 1983, which pointed out that minimum population routes may not be the safest routes because diverting traffic to these routes results in longer trips under worse track conditions, and the net effect is often a degradation of safety (*3*).

CASE STUDY: MOVEMENT OF ANHYDROUS AMMONIA VIA RAIL AND HIGHWAY

Any transportation distribution risk study involves three key steps: (*a*) identification of the hazards, (*b*) determining the probabilities of an accident and material release, and (*c*) assessing the impact a release might have on the public and the environment. Ideally, efforts should be made to reduce risks in all risk study efforts.

The options for risk reduction can be numerous and include one or more system changes involving container design, mode of transport, route of transport, varying chemical or physical properties of the material, and material exchanges. This case study will focus on modal decision and route selection. Although this paper is based on an actual risk assessment performed by DuPont, certain elements have been "sterilized" to protect business interests.

Proper mode selection is essential to the safe, cost-effective, and efficient distribution of hazardous materials. The distribution system selected must attempt to satisfy all business requirements while striking a prudent balance between safety, cost, and efficiency. The needs of all stakeholders, which include the public, shareholders, customers, and employees, must be met.

In the same way, route selection within a mode is a function of and must strike a prudent balance among accident probabilities, container release rates, effects on population and the environment, and the inherent hazards of the material. This case study will attempt to show how these route and mode elements come into play in the risk-assessment process.

DuPont purchases anhydrous ammonia (NH_3) from a source in West Lake, Louisiana, for consumption at its Gulfport, Mississippi, facility. The material is delivered in vendor-supplied rail tank cars at a volume of 20,000/year. Rail freight is for DuPont's account. DuPont procurement, on reviewing this contract, believed the freight rate was high and in cooperation with the supplier opened this move up for bid.

The historic route ran from West Lake to New Orleans, Louisiana, then up to Jackson, Mississippi, and back to Gulfport, Mississippi. This route involved three railroads and required 6 to 7 days of loaded transit. The route bidding process offered DuPont a viable alternative route at a reduced freight rate (viable from the viewpoint of service and transit time). It was necessary to determine whether this route, designated Alternate 1, was equal to or safer than the historic route. It runs from West Lake north to Shreveport, Louisiana, then east to Jackson and south to Gulfport. Only two railroads were involved and transit time was comparable.

The risk-assessment process began with a review and clear understanding of the inherent hazards of the material, both chemical and physical properties. Anhydrous ammonia (liquefied or solutions with more than 50 percent ammonia) is classified by the U.S. Department of Transportation (DOT) as a nonflammable gas (*4*). However, each bulk and nonbulk package must be marked "Inhalation Hazard." Internationally, NH_3 is classified as a poison gas (*5*). [Corporate Material Safety Data Sheets (MSDS) usually contain the necessary information to characterize the material under consideration. If not, then the specific product group and published technical literature can be consulted.] From the DuPont NH_3 MSDS, it was determined that anhydrous ammonia is an inhalation hazard and thus posed a threat to human life if released. Environmental concerns were low because NH_3 is very soluble in water. Therefore, population along the route becomes significantly important, even though ammonia's intensely pungent odor will cause persons to flee or seek shelter from a release. Flammability and reactivity with other materials are low and were not a consideration in this mode-route study.

DOT regulations also spell out minimum packaging requirements for hazardous materials. Both rail and highway require pressure containers of substantial design (*6,7*). Although pressure ratings, shell thickness, and additional protective features differ between the rail tank car and highway cargo tanks authorized for the transportation of NH_3, as shown in the following table, their relative product containment capabilities are equivalent. This assessment is made on the basis of calculated threshold puncture velocities tempered with years of experience.

	Transport Containers	
	Rail	*Highway*
DOT spec.	112S340W	MC-331
Capacity	180 K lb	40 K lb
Thickness	5/8 in.	3/8 in.
Head shield	1/2 in. full	None
Bottom outlet	No	Yes

DuPont uses ALK Associates' rail and highway networks and accident-incident data base statistics for its transportation risk studies. DuPont chose to use mainline release frequency for pressure tank cars with head shields from data provided to the Chemical Manufacturers Association (CMA) by Arthur D. Little, Inc., Cambridge, Massachusetts, for use by the CMA in its Distribution Code Risk Management Workshops.

ALK provided rail statistics for the historic and Alternate 1 routes based on the specific routing provided by DuPont. ALK's computer program then generated a minimum population route, minimum accident route, and minimum impedance or best service route and all related statistics. For purposes of this study, the historic and Alternate 1 route statistics were analyzed against the minimum accident and minimum impedance route, which in this

TABLE 1 Rail Route Data Analysis

PC*HazRoute™	Historic	Alt. 1	Minimum Acc./Imp.
Annual Vol.-Tons	20,000 →		
Capacity/Trip	90 Tons →		
Trips/Year	222 →		
Loaded Miles/Trip	558	563	292
Ton-Miles/Year	11.15×10^6	11.26×10^6	5.84×10^6
Acc. Prob./Trip	0.8×10^{-4}	0.9×10^{-4}	0.2×10^{-4}
Rel. Prob./Acc.	0.045 →		
Population Exposed	276,120	155,826	175,998

TABLE 3 Highway Route Data Analysis

PC*HazRoute™	Practical	Minimum Soc. Risk	60/40 Weighted
Annual Vol.-Tons	20,000 →		
Capacity/Trip	20 Tons →		
Trips/Year	1,000 →		
Loaded Miles/Trip	267	445	302
Ton-Miles/Year	5.34×10^6	8.9×10^6	6.04×10^6
Acc. Prob./Trip	1.5×10^{-4}	5.6×10^{-4}	1.9×10^{-4}
Rel. Prob./Trip	1.2×10^{-5}	5.4×10^{-5}	1.6×10^{-5}
Population Exposed	276,806	55,346	161,867

case are one and the same. The minimum population route was not viable from a service standpoint.

The goal of the study was to balance the accident-release frequency and population affected along any given route and to avoid the New Orleans population center if possible. Rail route data and calculated indices for each of the three routes under consideration are shown in Tables 1 and 2. Although the historic route offered a release frequency of 1 in 1,235 years and a population-release index of 0.994, the Alternate 1 route provided a 36 percent reduction in this index. The population-release index that was used is the product of the accident rate times the population at risk times the conditional release rate, and is an extension of the Relative Population Risk factor defined by the DOT in their routing guideline (*8*). This substantial improvement was brought about by the 43 percent reduction in population despite the 124-year decrease in years between releases. Although the minimum accident-impedance route offers attractive indices, it does not avoid the New Orleans population center. Thus the Alternate 1 route was selected from the rail mode to compare with the highway mode.

The highway statistics were generated by and obtained from ALK's PC*HazRoute™ computer software for managing hazardous materials routing. There was speculation that direct movement of cargo tank via Interstate highway might provide a viable alternative from a safety standpoint. PC*HazRoute™ was given only the origin, destination, and population impact radius. Route data and statistics were then generated for the most practical route, minimum population, minimum societal risk route, DOT route, and a weighted route. All route statistics were reviewed, and three were chosen for this study: namely the practical, minimum societal risk, and a weighted route. The weighted route is based on 60 practical and 40 percent societal risk.

Highway data and calculated indices for each of the three routes under consideration are shown in Tables 3 and 4. Years between releases vary from 18.5 to 83.3, and the population-release indices vary by less than 15 percent above and below the minimum societal risk population-release index. The practical route was chosen to compare with rail because it provides the shortest, most direct route on quality Interstate highways and avoids the New Orleans population center.

There are no order of magnitude differences in statistics or calculated indices when comparing alternative routes within modes. However, comparison of relative risks between modes reveals significant differences, as summarized in Table 5.

- Years between releases for rail are 13 times greater than for highway;
- Population-Release index for rail is only 19 percent of highway; and
- Despite the greater than 2 to 1 ratio of ton-miles for rail, releases per ton-mile are less than for highway by a factor of 28.

These indices provide the degree of measure necessary to make a prudent decision. Any one index by itself could be challenged

TABLE 2 Rail Route Analysis Indices

PC*HazRoute™	Historic	Alt. 1	Minimum Acc./Imp.
Accidents/Year	0.018	0.020	0.0044
Years Between Acc.	55.56	50.0	227.27
Releases/Year	8.1×10^{-4}	9.0×10^{-4}	1.98×10^{-4}
Years Between Rel.	1,234.7	1111.1	5,050.4
Acc./Ton-Mile	1.61×10^{-9}	1.78×10^{-9}	0.753×10^{-9}
Rel./Ton-Mile	7.26×10^{-11}	7.99×10^{-11}	3.39×10^{-11}
Pop.-Acc. Index	22.1	14.0	3.5
Pop.-Rel. Index	0.994	0.631	0.158

TABLE 4 Highway Route Analysis Indices

PC*HazRoute™	Practical	Minimum Soc. Risk	60/40 Weighted
Accidents/Year	0.15	0.56	0.19
Years Between Acc.	6.67	1.79	5.26
Releases/Year	0.012	0.054	0.016
Years Between Rel.	83.33	18.52	62.5
Acc./Ton-Mile	2.81×10^{-8}	6.29×10^{-8}	3.15×10^{-8}
Rel./Ton-Mile	2.25×10^{-9}	6.07×10^{-9}	2.65×10^{-9}
Pop.-Acc. Index	41.5	31.0	30.8
Pop.-Rel. Index	3.32	2.99	2.59

TABLE 5 Comparison of Relative Risks Between Rail and Highway Modes

	RAIL	HIGHWAY
•Route	Alt.1	Practical
•Trips/Year	222	1,000
• Ton-Miles	11.3×10^6	5.3×10^6
• Population	156K	277 K
• Years Between:		
Accident	50	6.7
Release	1,111	83
• Pop.-Rel. Index	0.631	3.32
• Rel./Ton-Mile	8×10^{-11}	225×10^{-11}

and subject to question. However, when two or more indices are pointed in the same direction (i.e., toward risk reduction), it can be assumed that in fact the potential risk of harm to the public will be reduced.

The difference in transport container capacity can only truly be addressed when performing full-blown quantitative risk assessments in which material dispersion calculations are made on the basis of the nature of the release, rate of release, amount released, meterological data, and geographical location. However in this case, even if the rail indices are arbitrarily adjusted by a factor of 4.5, to try to account for the differences in container capacity, the relative risk comparison would still favor rail.

Modes, routes, or transport containers should not arbitrarily be switched, even though the indices point favorably in that direction. The consequences of any change must be thoroughly evaluated, taking into account business needs while striking a prudent balance between safety, cost, and efficiency.

In this rather straightforward case study, DuPont chose to retain the rail mode and change routes. The rail route change from Historic to Alternate 1 yielded the following results:

	Historic	*Alt. 1*
Population exposed	276K Base	156K 43% reduction
Releases per year	8.1 × 10-4 Base	9.0 × 10-4 11% increase
Pop.-Rel. Index	0.994 Base	0.631 36% reduction

Thus, with the aid of a decision support tool, DuPont was able to make an informed decision, which reduced overall risk to the public by one third without affecting service and decreased freight costs. This provides an excellent example of a cost-driven question being acted on and yielding significant risk reduction.

CONCLUSIONS

There is no one right answer. Informed decisions involve tradeoffs and balance among risk factors. In the quest for risk reduction, care must be taken to reduce risk and not just "transfer" it to another area of the distribution system. For example, certain mode and container size changes could increase on-site inventory or handling requirements. This increase in on-site risk (and potential risk to the plant community) could possibly offset any gains obtained in transportation. The art and science of risk assessment must take into account the consequences of all actions.

Proper analysis can lead to significant reduction in distribution risk. Quantitative support tools are essential to this analysis. Pending regulations and safety performance improvement initiatives like the Chemical Manufacturers Association's Responsible Care® Program are encouraging industry to become more proactive. Easy-to-use management-decision support tools based on respected methodology and credible data bases will enable the transport of more hazardous material to be carried out more responsibly in the future.

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Approximate Delays Caused by Lock Service Interruptions

VENKATESH RAMANATHAN AND PAUL SCHONFELD

The lock structures in the inland waterway system have become major constraints to navigation as a result of increased traffic and facility deterioration, leading to costly delays. Most of the locks have exceeded their design life, and service interruptions occur quite frequently, causing increasing delays to traffic. Hence, a reliable model is necessary to estimate the delay caused by lock service interruptions. In this paper, a model is developed in the form of one relatively simple equation to estimate tow delays caused by a single lock service interruption. A basic equation is derived on the basis of continuous flow theory. Because the waterway flows consist of discrete vessels, an appropriate discrete adjustment factor is developed. To account for the stochastic characteristics of actual waterway operations, an adjustment factor is estimated statistically from simulation results. The resulting model provides accurate estimates of delays far more quickly and inexpensively than simulation. The simple model developed in this paper should be useful in future studies of capacities, delays, service reliability, maintenance policies, and general waterway economics.

Inland waterways are an important part of the transportation network in the United States. They provide low-cost, energy-efficient and safe transportation of heavy or bulky commodities. The National Waterways Study (*1*) identified the structural reliability of the inland waterway system as a major constraint in the system's ability to handle commercial waterborne traffic. More than 100 locks will have exceeded their 50-year design life by 2003 (*1*). Locks and dams are essential for creating stepped navigational pools with reliable depth for navigation. However, many of these facilities have become major constraints to inland navigation because of increased traffic and facility deterioration, leading to costly delays.

The objective of this paper is to develop a model that estimates the delay caused by a single lock service interruption (i.e., a "stall"). An equation is derived using the principles of continuous flow theory. Because the flow in real waterways consists of discrete tows or other vessels, an adjustment factor is developed on the basis of the assumption that the flow is discrete and uniform. Furthermore, the arrival and service distributions at waterway locks are probabilistic. Hence the equation developed using continuous flow is combined with an adjustment factor estimated statistically from the simulation results. This equation provides accurate estimates of delay caused by a lock service interruption.

LITERATURE REVIEW

Prediction of lock delays is essential for evaluating and scheduling waterway investments. Two models based on queueing theory have been found for estimating lock delays. DeSalvo and Lave (*2*) model lock operation as a simple single server queueing process with Poisson distributed arrivals and exponentially distributed service time. The assumption of Poisson distributed arrival and exponentially distributed service time does not fit every lock in the waterway system. Wilson's model (*3*) extends DeSalvo's model by treating the service processes as general distributions. Both models are designed for analyzing single lock delays. Neither of these models explicitly accounts for stalls. Also, the delays estimated with these models did not consider the interdependence between locks, which is highly significant in waterway locks.

Kelejian's (*4*) efforts to model stall frequencies and duration have not yet yielded strong results despite the rigorous statistical method employed. Dai and Schonfeld (*5*) developed a microscopic simulation model that accounts for generally distributed arrivals and service times and interdependence between locks and stalls. As usual with microscopic simulation models, a significant amount of computer time is required for variance reduction to obtain reliable delay estimates. May and Keller (*6*) used the continuous flow theory to estimate the effects of road capacity changes at bottlenecks on delays to users. The continuous flow theory has also been used for various other highway applications.

In this paper, a simple model is developed to estimate delay caused by a lock service interruption using continuous flow theory and an adjustment factor estimated from simulation results. The model is a reliable substitute for expensive simulation.

PROPOSED MODEL

In this section, a general equation is derived that provides a good estimate of the delay caused by a single lock service interruption based on the assumption that the arrival and service rates are uniform and continuous.

The effect of a single stall, assuming uniform continuous flow, is shown in Figure 1. The service interruption would reduce the normal lock capacity (tows/day) c to a partial lock capacity (tows/day) p in a lock with multiple chambers. If the lock has a single chamber, the partial capacity will probably drop to zero. If the service interruption occurs for stall duration (days) d, then the maximum queue length (tows) L formed during this period will be the duration d multiplied by the difference between the tow volume (tows/day) v and partial capacity p.

$$L = d(v - p) \tag{1}$$

After the end of the stall, the queue will start decreasing at a rate equal to the difference between the volume v and capacity c, and would finally become zero. The time s required to dissipate

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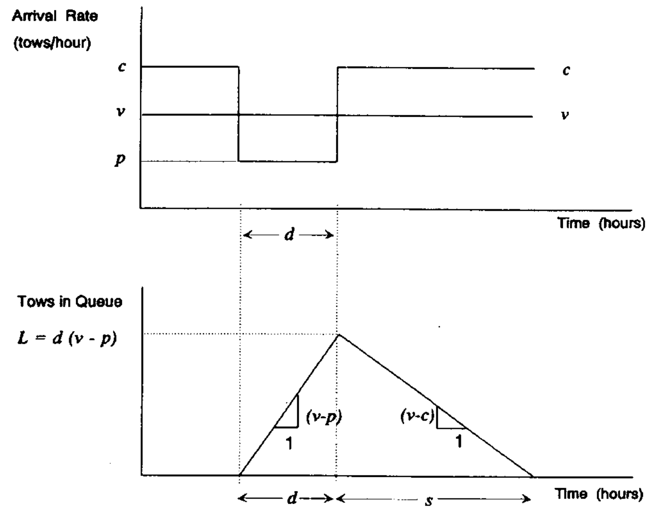

FIGURE 1 Effect of one stall based on uniform continuous flow.

a queue (tows) of length L is

$$s = \frac{L}{-(v - c)} = \frac{d(v - p)}{-(v - c)} = \frac{d(v - p)}{(c - v)} \quad (2)$$

The total delay to tows D_c [small delay assuming continuous deterministic flow (tow days)] caused by interruption in service for duration d would be the area of the triangle or "wedge" shown in Figure 1.

$$D_c = \frac{L(d + s)}{2} \quad (3)$$

Substituting the values of the maximum queue length L and queue dissipation time s from Equations 1 and 2, Equation 3 can be written as

$$D_c = \left[\frac{d(v - p)}{2}\right] \left[\frac{d(v - p)}{(c - v)} + d\right] \quad (4)$$

If the partial capacity p is zero, then the delay D_c in Equation 4 simplifies to

$$D_c = \frac{dv}{2} \left[\frac{dv}{(c - v)} + d\right] \quad (5)$$

For example, if $v = 3$ tows/hr, $c = 4$ tows/hr, $d = 2$ hr and $p = 1$ tow/hr, then the delay D_c using Equation 4 will be

$$D_c = \left[\frac{2(3 - 1)}{2}\right] \left[\frac{2(3 - 1)}{(4 - 3)} + 2\right] = 12 \text{ tow hours}$$

Equations 4 and 5 are general enough to apply to one- or two-way traffic and to single or multiple chamber locks.

DISCRETE ADJUSTMENT FACTOR

At waterway locks, arrival and service distributions are discrete and probabilistic. However, Equations 4 and 5 were derived by assuming uniform continuous flow. In this section, an equation is derived that accounts for the difference in delay between uniform continuous and uniform discrete flows.

A comparison of the probabilistic and deterministic discrete flow patterns is shown in Figure 2. This figure corresponds to the continuous deterministic wedge in the lower part of Figure 1. It can be seen that when the flow is deterministic, arrivals and departures occur at uniform intervals. If the tow volume is v tows/hr and the lock capacity is c tows/hr, then the interarrival time between tows is $1/v$ hr and the service time is $1/c$ hr/tow. However, when the flow is stochastic, interarrival and service times are not uniform. The effect of a single lock service interruption on uniform discrete flow is shown in Figure 3. The delay caused by a single lock service interruption in case of discrete and deterministic flow depends on the stall duration d and tow size (tows/tow) z. As the step size is higher for bigger than for smaller tows, the deviation of the discrete uniform flow from the continuous uniform flow is higher for bigger than for smaller tow arrivals for the same stall duration d. This can be clearly seen from Figure 3. The delay caused by a single lock service interruption can be

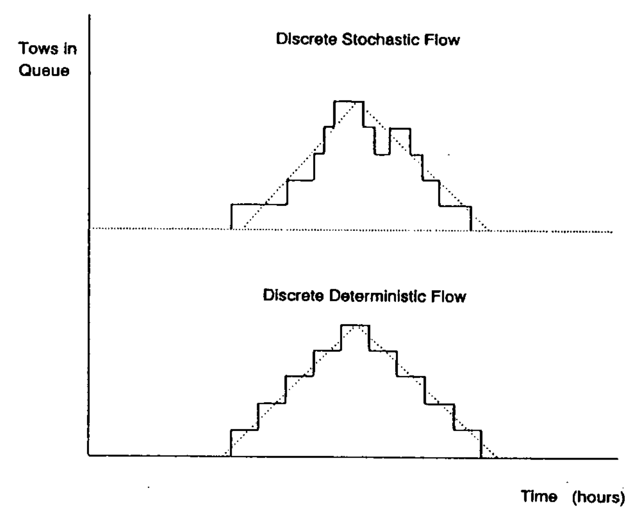

FIGURE 2 Comparison of deterministic and stochastic flow patterns.

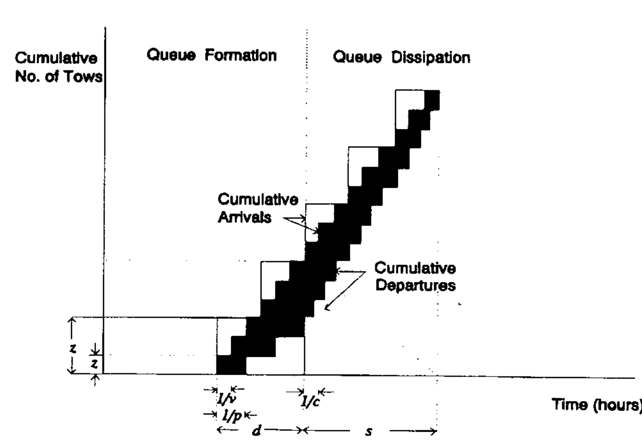

FIGURE 3 Effect of one stall on discrete uniform flow.

determined by expressing the arrivals and departures as the sum of a geometric series. If the tow volume is v, the tow size is z, the partial capacity is p, and the interruption occurs for duration d, then the delay caused by discrete deterministic flow, D_{I}, during the queue formation period is the difference between the area under the arrival and the departure steps (i.e., the area marked I in Figure 3). Because the interarrival time between tows is $1/v$ and the size of each step is equal to the tow size z, the area under the arrival steps is the sum of the areas of the rectangles, the area of each rectangle being the tow size z multiplied by the difference betweeen the duration d and arrival time of the tow ($1/v$, $2/v$, etc.). Similarly, the area under the departure steps can be determined by summing the areas of each rectangle. The area of each rectangle is the tow size z multiplied by the difference between duration d and departure time $1/p$, $2/p$, and so on. Thus, the delay D_{I} on the queue formation side can be written as follows:

$$D_{\text{I}} = \left\{d + \left[d - \frac{1}{v}\right] + \left[d - \frac{2}{v}\right] + \ldots + \left[d - \frac{(dv-1)}{v}\right]\right\}z - \left\{\left[d - \frac{1}{p}\right] + \left[d - \frac{2}{p}\right] + \ldots + \left[d - \frac{(dp-1)}{p}\right]\right\}z \quad (6)$$

Because Equation 6 is a sum of a geometric series, the delay D_{I} can be simplified as follows:

$$D_{\text{I}} = \left(\frac{d^2v + d}{2}\right)z - \left(\frac{d^2p - d}{2}\right)z \quad (7)$$

After the end of the stall, because the queue takes s hours to dissipate to zero length, the delay caused by discrete deterministic flow during the queue dissipation period (tow/days), D_{II}, is the shaded area marked II in Figure 3. Because the departure time of the tows is now $1/c$, $2/c$, and so on, the delay D_{II} can be expressed as

$$D_{\text{II}} = \left(\frac{1}{c} + \frac{2}{c} + \ldots + \frac{cs}{c}\right)z + \left(\frac{1}{v} + \frac{2}{v} + \ldots + \frac{vs}{v}\right)z \quad (8)$$

Equation 8 can be simplified as follows:

$$D_{\text{II}} = \left[\frac{s(cs+1)}{2}\right]z - \left[\frac{s(vs+1)}{2}\right]z \quad (9)$$

The total stall delay D_r assuming discrete deterministic flow (tow days) caused by a service interruption for duration d when the arrival and service rates are discrete is the sum of delays D_{I} and D_{II}:

$$D_r = \left[\frac{d^2v + d}{2}\right]z - \left[\frac{d^2p + d}{2}\right]z + \left[\frac{s(cs+1)}{2}\right]z - \left[\frac{s(vs+1)}{2}\right]z \quad (10)$$

Thus, Equation 10 gives the total delay D_r caused by discrete flow and Equation 4 gives the total delay D_c caused by continuous flow. The ratio of the delay D_r to the delay D_c may be defined as the discrete adjustment factor F_r:

$$F_r = \frac{D_r}{D_c} \quad (11)$$

Assuming the interdeparture time $1/p$ in the partial capacity condition to be less thant the stall duration d and substituting Equations 4 and 10 into Equation 11, the discrete adjustment factor F_r can be written as

$$F_r = 1 + \frac{dz}{D_c} \quad (12)$$

Thus the delay caused by discrete uniform flow D_r from Equations 11 and 12 can be written as

$$D_r = D_c\left(1 + \frac{dz}{D_c}\right) \quad (13)$$

Equation 13 is therefore a good approximation for a waterway with discrete arrival and service times. The discrete adjustment factor depends on tow size z and stall duration d. Thus for the same stall duration d, the factor F_r is larger when tows are larger because the steps in Figure 3 are larger. It is also worth noting that, because D_c is approximately proportional to d^2 (in Equations 4 or 5) the factor F_r (Equation 12) decreases asymptotically toward 1.0 as the stall duration increases. Therefore, Equations 4 or 5 based on the continuous flow assumption provide good approximations of the delay, if (*a*) tows are small or (*b*) service interruptions are long. Even with a discrete adjustment factor, Equation 13 is only an approximation for real waterways with probabilistic arrival and service times.

SIMULATION EXPERIMENT

A microscopic simulation model to estimate delays caused by lock service interruptions has been developed by Dai and Schonfeld (*5*). The actual data, including the stall-related data from real waterway locks, were used for calibrating and then validating the simulation model. As usual with microscopic simulation models, a significant amount of computer time is required for variance reduction purposes to obtain reliable delay estimates. In order to estimate the delay caused by a single stall, it is necessary to compute delays by running the simulation with and without that stall. The delay caused by a single stall is the difference between those two delays.

An alternative to direct application of microsimulation is to employ the simulation model in an experiment to obtain a functional simplification that can be used to estimate the delay caused by a lock service interruption. An experiment was conducted to explore the extent to which the probabilistic nature of arrival and service rates in a real waterway affects the delay caused by one stall predicted by Equation 4. The observed data (1987) from Lock 22 on the Mississippi river was used for the experiment. The variables chosen for the simulation experiment were stall duration d and volume/capacity ratio v/c.

The experiment simulated the lock for various combinations of volume/capacity ratio v/c and stall duration d. To achieve different values for volume/capacity ratio, the volume v was fixed at 10 tows/day and the capacity c was adjusted to yield the desired v/c. For example, to achieve a v/c of 0.4, the capacity c used in simulation was 25 tows/day, because $10/25 = 0.4$. In the existing simulation model (*5*), stalls of various durations were randomly generated based on average stall duration and frequency of occurrence. Hence, the model was modified to estimate the delay caused by a single stall of variable duration starting at some specified time. To reduce the variance of the simulated delay, the final result used for comparison was obtained by averaging the output from 40 independent simulation runs. To ensure that the system reaches steady state before the stall occurs, the first 12,000 tow waiting times are discarded from each simulation run. The results were recorded for a sufficiently long period to ensure that the full effects of the stall were captured. The results from the simulation experiment were then compared with those obtained using Equation 5.

EXPERIMENT RESULTS

The results from the simulation and the values calculated using Equation 5 for volume/capacity ratios ranging from 0.4 to 0.95 are provided in Table 1. The average delay caused by a single stall obtained from simulation and the delay obtained using Equation 5 are shown for various stall durations and volume/capacity ratios. Also shown are the standard deviation of the average delay from the simulation, standard error, and the *t*-test value for 95 percent confidence interval. The ratio of the simulated and the deterministic delay is also computed. This ratio is defined here to be the stochastic adjustment factor F_s:

$$F_s = \frac{D_s}{D_c} \tag{14}$$

This stochastic adjustment factor F_s accounts for the probabilistic arrival and service rates in a real waterway. Thus, the results obtained using Equations 4 or 5, when multiplied by this factor F_s, give the simulated delay. The stochastic adjustment factor is plotted in Figure 4 with stall duration on the horizontal axis and the delay caused by stall on the vertical axis for different volume to capacity ratios. Shown in Figure 5 is the variation of stochastic adjustment factor F_s with simulated delay D_s. Each point in these plots represents the average of 40 independent simulation runs. These plots are helpful in the assessment of the functional form of the stochastic adjustment factor F_s. It appears from these plots that the factor decreases at a decreasing rate with the stall duration d and the simulated delay D_s. The factor increases with the volume/capacity ratio v/c.

The comparison of simulated and deterministic delay suggests that the results are consistent with the basic principles of queueing theory. The deterministic delay was calculated on the basis of the assumption of uniform continuous flow. However, in a real waterway the arrival and service are probabilistic and discrete. It can be seen from Equations 4 and 5 that the delay D_c varies roughly with the square of the stall duration. Thus it is expected that the deviations between the deterministic delay D_c and the simulated delay D_s are higher at smaller stall durations than at longer ones. Hence, the stochastic adjustment factor F_s is larger at smaller stall durations and smaller for the longer (and costlier) stalls.

TABLE 1 Comparison of Simulated Delay with Deterministic Queueing Delay

a) v = 10 tows/day; c = 25 tows/day; v/c = 0.4

Stall Duration (days)	Delay(D_s)[1] (tow days)	Delay(D_c)[2] (tow days)	Factor (F_s)[3]	Simulation Estimates		
				(1)[4]	(2)[5]	(3)[6]
0.3	0.99	0.75	1.313	0.41	0.07	3.63
1	9.59	8.33	1.152	2.25	0.36	3.56
2	36.63	33.33	1.099	9.31	1.47	2.24
3	79.74	75.00	1.063	12.34	1.95	2.43
4	138.40	133.33	1.038	21.26	3.36	1.51
6	306.16	300.00	1.020	39.85	6.30	0.98
8	541.92	533.33	1.016	71.21	11.26	0.76
10	843.50	833.33	1.012	86.50	13.68	0.75
12	1208.40	1200.00	1.007	116.23	18.38	0.46

b) v = 10 tows/day; c = 12.5 tows/day; v/c = 0.8

Stall Duration (days)	Delay(D_s)[1] (tow days)	Delay(D_c)[2] (tow days)	Factor (F_s)[3]	Simulation Estimates		
				(1)[4]	(2)[5]	(3)[6]
0.3	3.25	2.25	1.445	1.71	0.27	3.70
1	31.92	25.00	1.270	12.28	1.94	3.56
2	117.89	100.00	1.179	28.06	4.44	4.07
3	252.95	225.00	1.124	51.21	8.09	3.45
4	437.90	400.00	1.094	69.29	10.95	3.45
6	956.10	900.00	1.062	110.40	17.46	3.21
8	1672.11	1600.00	1.045	199.29	31.51	2.28
10	2586.61	2500.00	1.034	300.90	47.58	1.82
12	3682.85	3600.00	1.023	348.40	55.09	1.50

[1]Simulated Delay
[2]Delay due to Continuous flow
[3]Stochastic Adjustment Factor
[4]Standard Deviation of Simulated Delay
[5]Standard Error of Simulated Delay
[6]t-test value of Simulated Delay

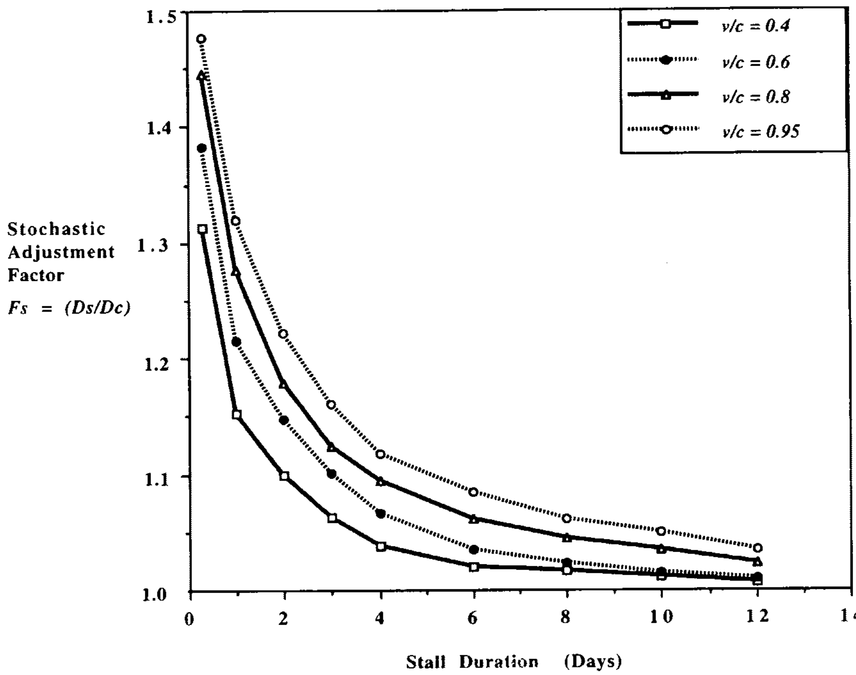

FIGURE 4 **Variation of stochastic delay adjustment factor with stall duration.**

ESTIMATION OF STOCHASTIC DELAY ADJUSTMENT FACTOR

In this section, a mathematical function that reasonably fits the observed stochastic adjustment factor F_s is derived. The experimental results suggest that the functional form of the stochastic adjustment factor is nonlinear with respect to the stall duration and linear with respect to the volume/capacity ratio. A functional form that increases linearly with the volume/capacity ratio v/c and decreases exponentially with the stall duration d appears to closely fit the data. One tractable mathematical form expressing such a relation is the following:

$$F_s = 1 + a \left(\frac{v}{c}\right) e^{bd} \tag{15}$$

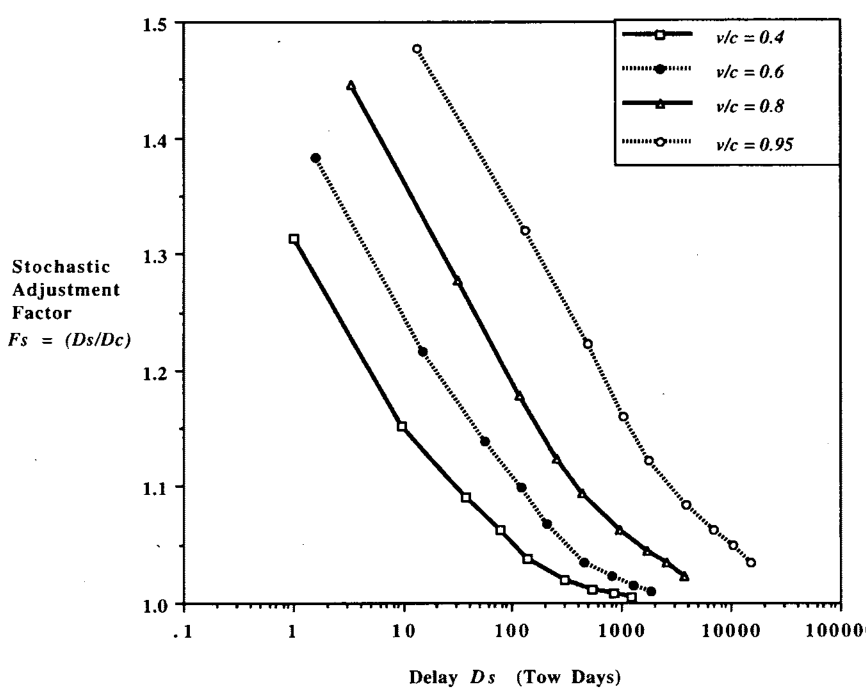

FIGURE 5 **Variation of stochastic delay adjustment factor with simulated delay.**

where a is a magnitude parameter and b is an exponential decay parameter. This relation may be interpreted to have a lower bound of 1.0, with the second term representing a quantity accounting for the stochastic effects. The parameters a and b were statistically estimated using ordinary least-squares linear regression. Hence Equation 15 becomes

$$F_s = 1 + 0.6 \left(\frac{v}{c}\right) e^{-0.432d}, \quad R^2 = 0.93 \tag{16}$$

The stochastic adjustment factor F_s together with Equation 4 may be used to commute the total delay caused by a single stall, D_e:

$$D_e = [F_s]\,[D_c] \tag{17}$$

Substituting Equation 16 for the stochastic adjustment factor F_s and Equation 4 for D_c in Equation 17, a complete expression for the stall delay can be obtained, as follows:

$$D_e = \left\{1 + \left[0.6 \left(\frac{v}{c}\right) e^{-0.432d}\right]\right\} \left\{\left[\frac{d(v-p)}{2}\right]\left[\frac{d(v-p)}{(c-v)} + d\right]\right\}, \quad R^2 = 0.93 \tag{18}$$

The basic linear regression procedure used to estimate the parameters 0.6 and −0.432 in Equation 15 assumes that the data are homoscedastically distributed; that is, that the variance of the dependent variable does not vary with the independent variable. However, the simulation results (shown in Figures 4 and 5) indicate otherwise. To eliminate this problem of heteroscedasticity, the parameters were re-estimated with a logarithmic transformation (*7,8*) of Equation 15. Converting the transformed variables back to their original form yielded the following transformed model for the stochastic adjustment factor:

$$F_s = 1 + 0.42 \left(\frac{v}{c}\right) e^{-0.259d}, \quad R^2 = 0.92 \tag{19}$$

Substituting Equations 19 and 4 into Equation 17, the estimated total delay caused by single stall is found to be

$$D_e = \left\{1 + \left[0.42 \left(\frac{v}{c}\right) e^{-0.259d}\right]\right\} \left\{\left[\frac{d(v-p)}{2}\right]\left[\frac{d(v-p)}{(c-v)} + d\right]\right\}, \quad R^2 = 0.92 \tag{20}$$

A comparison of the simulated delay D_s and estimated stall delay (tow days) D_e obtained using Equations 18 and 20 is given in Table 2. Shown in Figures 6 and 7 is the variation of the es-

TABLE 2 Comparison of Simulated Delay with Estimated Delay

a) v = 10 tows/day; c = 25 tows/day; v/c = 0.4

Stall Duration (d) (Days)	Simulated Delay (D_s) (tow-days)	Estimated Delay (D_e) (tow-days)		% Deviation 100 x $(D_e-D_s)/D_s$	
		Before[1]	After[2]	Before[3]	After[4]
0.3	0.98	0.91	0.87	-7.80	-12.02
1	9.59	9.63	9.41	0.32	- 1.95
2	36.63	36.70	36.67	0.19	0.09
3	79.74	79.93	80.79	0.23	1.32
4	138.40	139.01	141.28	0.44	2.08
6	306.16	305.39	310.66	-0.25	1.47
8	541.92	537.37	544.61	-0.84	0.49
10	843.50	835.99	843.83	-0.89	0.04
12	1208.40	1201.61	1209.01	-0.56	0.05

b) v = 10 tows/day; c = 12.5 tows/day; v/c = 0.8

Stall Duration (d) (Days)	Simulated Delay (D_s) (tow-days)	Estimated Delay (D_e) (tow-days)		% Deviation 100 x $(D_e-D_s)/D_s$	
		Before[1]	After[2]	Before[3]	After[4]
0.3	3.25	3.19	2.95	-1.67	-9.33
1	31.92	32.79	31.48	2.73	-1.37
2	117.89	120.23	120.02	1.99	1.80
3	252.95	254.55	259.76	0.63	2.69
4	437.90	434.11	447.69	-0.87	2.24
6	956.10	931.34	963.93	-2.49	0.82
8	1672.11	1624.24	1667.70	-2.86	-0.26
10	2586.61	2515.96	2563.02	-2.73	-0.91
12	3682.85	3609.69	3654.06	-1.99	-0.78

[1]Estimated Delay before Transformation
[2]Estimated Delay after Transformation
[3]% Deviation before Transformation
[4]% Deviation after Transformation

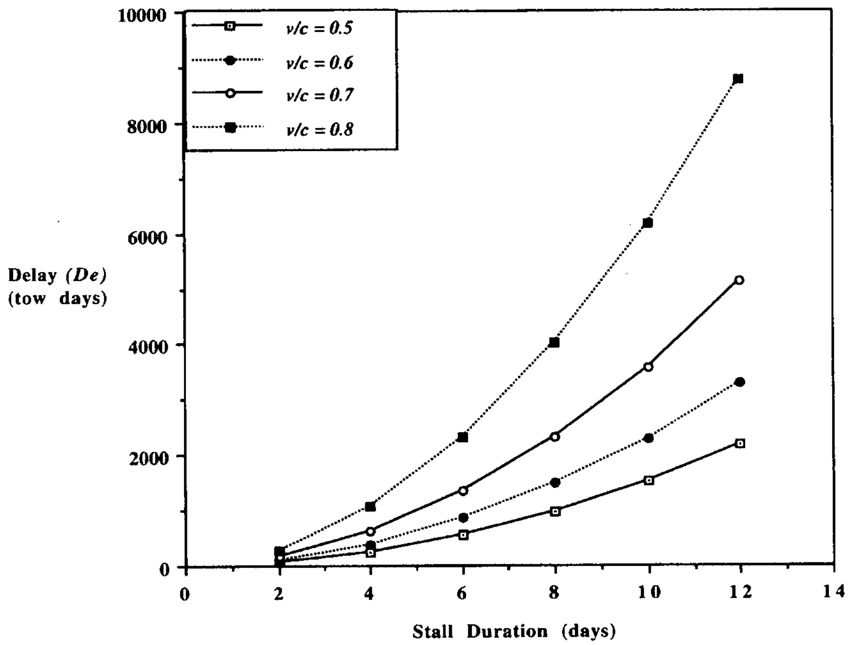

FIGURE 6 Variation of delay caused by a single lock service interruption with stall duration.

timated delay D_e, with stall duration and v/c, respectively. A comparison of the stochastic adjustment factor F_s obtained using Equations 16 and 19 is shown in Figure 8. It is observed that the deviation between the simulated delay D_s and the estimated delay D_e obtained using Equations 18 or 20 is less than 2 percent for stall durations exceeding 2 days and volume/capacity ratios below 0.6. Equations 18 and 20 both provide accurate delay estimates. Although Equation 18 provides slightly more accurate estimates when stall durations are less than 2 days, the transformed model in Equation 20 should be preferred in all cases because of its greater theoretical soundness and in order to have a single general model.

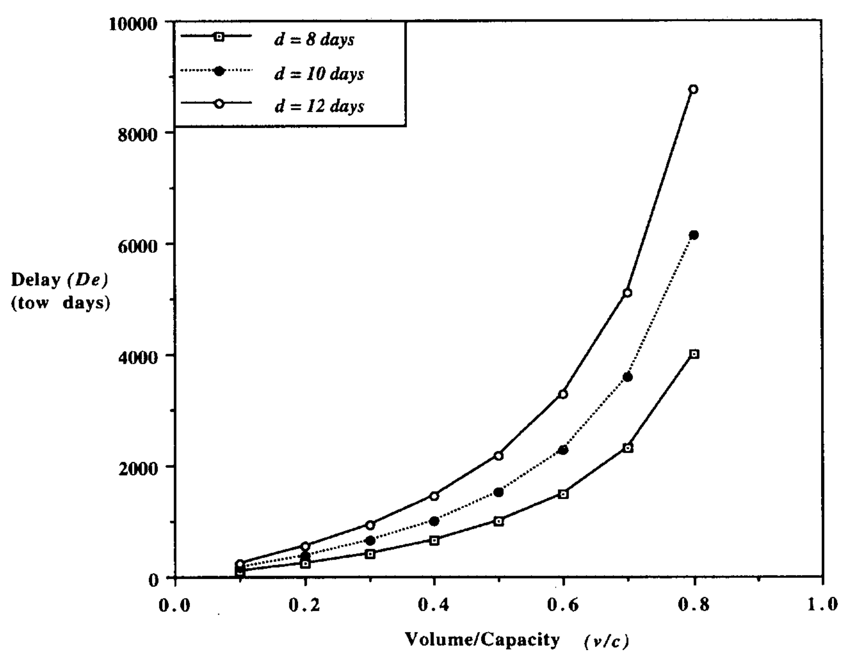

FIGURE 7 Variation of delay caused by a single lock service interruption with volume/capacity.

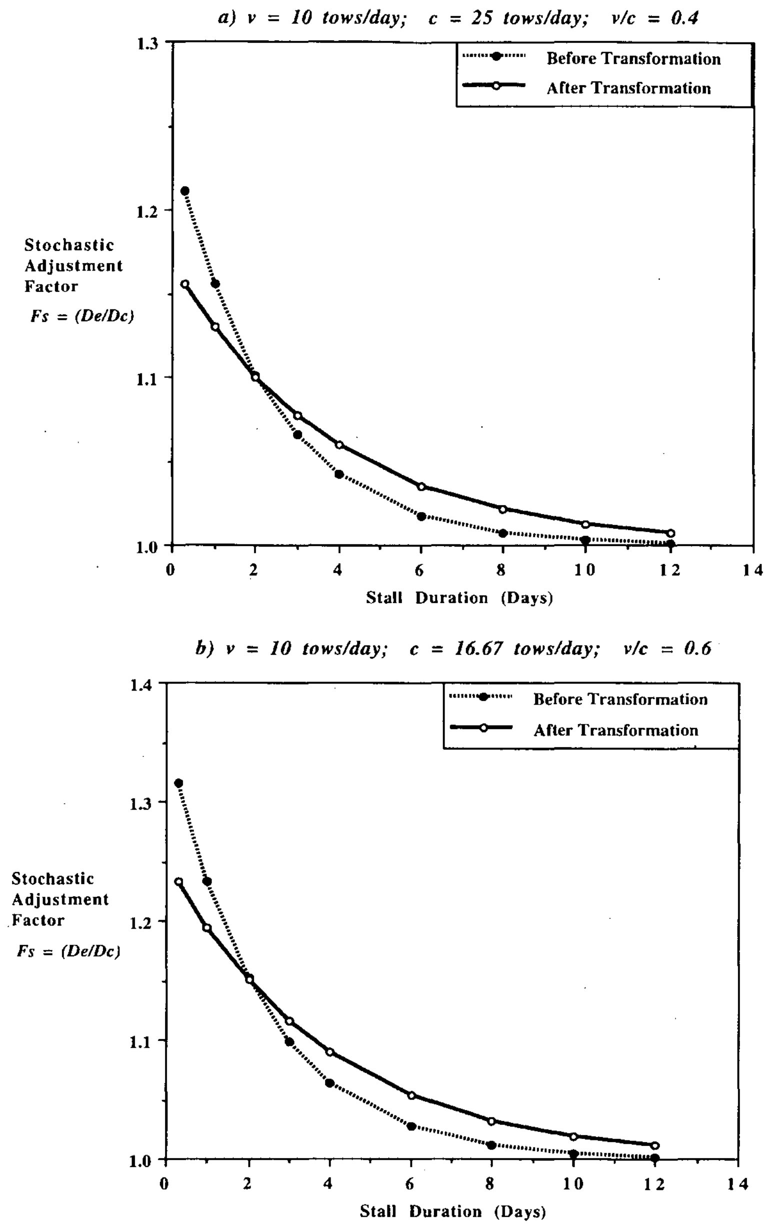

FIGURE 8 Comparison of stochastic delay adjustment factor.

SUMMARY AND CONCLUSIONS

With many inland water locks now becoming older than 50 years, it is important to have reliable and efficient means of modeling the delays at locks for evaluation, reliability analysis, and maintenance and investment planning. Presented in this paper has been the development of a quick and simple model that approximates simulation results in estimating lock delays caused by a single stall.

An equation was developed on the basis of continuous flow theory. This equation is a close approximation for stalls producing large delays but not for those producing small delays. Because this equation was derived on the basis of uniform flow, it is only an approximation for a real waterway with discrete arrival and service rates. To account for discrete arrival and service times at locks, a discrete adjustment factor was derived assuming uniform discrete flow. This model has some explanatory value but is superseded in this paper by a probabilistic model. Because the vessel flows are probabilistic in real waterways, a simulation experiment was conducted to estimate the delay caused by a single stall. A single general "metamodel," combining a structural form obtained from queueing theory with the stochastic adjustment factor statistically estimated from simulation results, fits the simulated delays quite well and constitutes an accurate, quick, and simple substitute for simulation.

The model was further improved with a logarithmic transformation that compensates for heteroscedasticity in the data. Although the transformed model (Equation 20) is slightly less accurate than the untransformed model (Equation 18) when stall durations are low, it is slightly more accurate for longer durations, which are more significant in economic evaluations. Henceforth it is recommended that only the transformed model be used, because it is more justified theoretically and provides a single general model. For an even better approximation of the model, the stochastic adjustment factor may be re-estimated when the chamber configurations or arrival and service distributions change significantly.

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