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Contents

Foreword

The papers in this Record deal with topics related to modal shifts and modal connections in freight transportation, hazardous materials transportation, waterway planning, tracking of freight transport segments, shore crane efficiencies, and predictive modeling for passenger ferry operations.

Gabel and Nihan assess the possibility of shifting drive-on ferry users to walk-on ferry services in the Seattle to Vashon Island service.

Spasovic and Morlok examine marginal costs for the trucking component of rail-truck intermodal movements and suggest that railroad management needs to understand the characteristics of the drayage operation and the effects of drayage movements on the cost of intermodal operation.

Guha and Walton present possible applications of automatic vehicle classification systems in the collection of traffic data in marine terminals. Kiesling and Walton examine approaches to a time-motion study of wharf crane operations.

Casavant et al. study grain transport and pricing interrelations for intermodal movements via truck-barge. Leavitt presents a methodology for estimating waterway tonnage from lock data. Martinelli et al. study investment efficiencies in inland waterways.

Hazardous materials transport and the usefulness of models in estimating risk are discussed by Saccomanno et al. Hancock et al. present a methodology for assessing responses to emergencies in the transportation of hazardous materials.

Goods movement in urban areas in the Canadian context is discussed by Stephens et al. Schlappi et al. present a model to forecast truck travel demand in the California coastal corridor.

Passenger-Only Ferry Service Between Vashon Island and Seattle, Washington

MARK J. GABEL AND NANCY L. NIHAN

On April 23, 1990, passenger-only ferryboat service was offered as an alternative to automobile ferry users commuting between the Seattle/Tacoma mainland and Vashon Island. The consequences of introducing this regularly scheduled passenger-only ferry service on Puget Sound are discussed. The results are being used by the Washington State Ferry System Planning Office to assist in decisions for expanding passenger ferry service in the future. Results of a survey of passenger-only and automobile ferry service riders were used to fit a logit model for predicting future mode shift. Since the survey data were attitudinal, the logit model was intended to identify the target populations most likely to shift mode from automobile ferry to passenger-only ferry service. The attributes of the ferry system that are most important in selecting between the two modes of transportation were investigated. The results indicate that providing passenger ferry service can cause a mode shift from drive-on automobile ferry passengers to walk-on passengers. For the passenger ferry service studied, 11.7 percent of the passenger ferry users were former single-occupant vehicle (SOV) drivers. Since the new passenger ferry carried 10.7 percent of the total afternoon ferry rides, this meant that a mode shift of nearly 2 percent of SOV drivers to walk-on passengers was realized after 1 year of passenger ferry service between Vashon Island and Seattle. The degree of mode shift depended on the ferry routes and location of the ferry terminals. Travel time was a significant factor in the choice between passenger ferry and automobile ferry service. The results indicated a significant number of new riders (25 percent). Some people moved to Vashon Island because passenger service was made available. It was concluded that the passenger ferry contributes to the regional goal of reducing reliance on the automobile.

The Pacific Northwest of the United States contains nearly every feasible transportation mode in existence. One type of transportation often associated with the Pacific Northwest is the ferry system. There are other ferry systems in the United States, but the Washington State Ferry (WSF) System is the largest in the Western Hemisphere and is crucial to the Puget Sound region. The WSF System carries more than 20 million passengers each year and approximately 9 million vehicles.

The WSF System operates as the Marine Division of the Washington State Department of Transportation (WSDOT). The ferry system, in an effort to contribute to the regional goal of reducing reliance on the single-occupant vehicle, recently began passenger-only ferry service and has plans to increase the use of these ferry vessels in the future. To maximize the effectiveness of using passenger-only ferry service, it was necessary to measure the impact of the newly established passenger-only ferry service. This paper documents that study.

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PROBLEM STATEMENT

Passenger-only ferryboat service was offered as an alternative to automobile ferry users commuting between Vashon Island and the Seattle-Tacoma mainland (see Figure 1) beginning April 23, 1990. There have been no previous studies of the behavior of ferry commuters when offered this alternative. The objective of this study was to determine the consequences of introducing regularly scheduled passenger-only ferry service on the Seattle-Vashon route on Puget Sound.

The WSF System planning office seeks to increase its knowledge base on passenger-only ferry service to enhance future policy decisions. It is likely that increased passenger-only ferry service on Puget Sound will be considered in the near future. By understanding the existing passenger-only service, it is hoped that some inferences can be drawn about future service on other routes and about policy decisions on fares, frequency of service, and effect on mode choice.

STATE OF THE ART

An exhaustive literature search was undertaken to identify the state of the art in passenger-only ferry service. Private consultants' reports for the WSF System were reviewed and ferry systems in New York and British Columbia were contacted. The search revealed a variety of information on the history of ferry service and vessel characteristics but very little on passenger-only ferry service and its effect on mode choice.

A few surveys were conducted for the WSF System before establishment of the first passenger-only ferry service. In February 1988 a one-page mail-back survey was sent to all Vashon/Maury Island households with a 25 percent response rate (*1*). The result indicated that the passenger-only ferry would have a usage of about 370 weekday round-trips with 15 to 36 percent of the vehicles being driven on the Vashon/Fauntleroy ferries removed by the passenger-only ferry service. Another survey conducted in January 1989 analyzed the trip characteristics of commuters traveling between Vashon Island, Southworth, and the Seattle-Tacoma mainland (*2*). Information on origins and destinations, departure times, travel patterns, attitudes, ferry information sources, and interest in passenger-only ferries was gathered. The interest in passenger-only ferry service was significant, with more than 40 percent of the respondents indicating that they would be very likely or somewhat likely

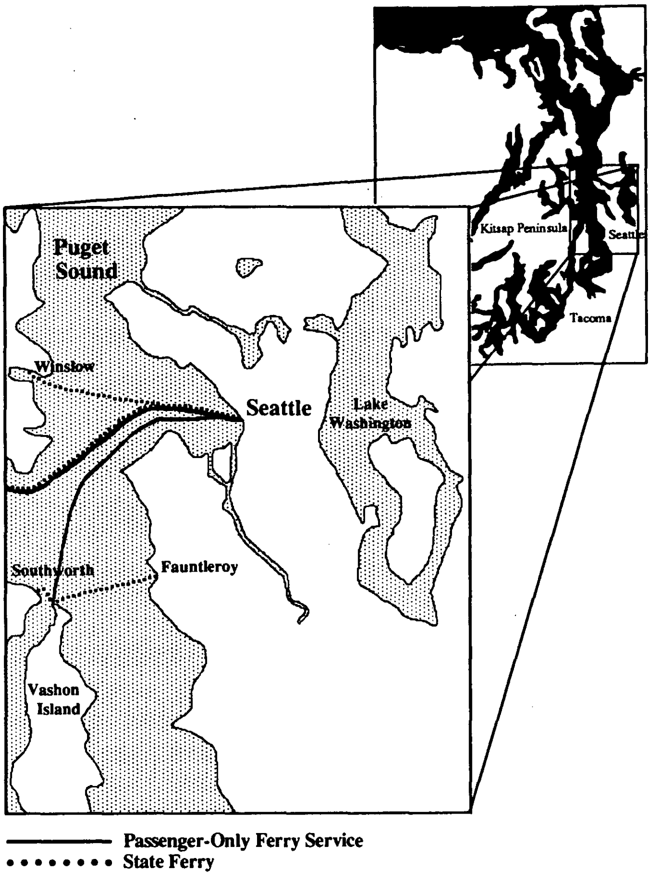

FIGURE 1 Vicinity map.

to use passenger-only service if the schedule met their personal needs.

Some pilot studies were also conducted before establishment of the passenger-only ferry system in the state of Washington. In August 1987 a study documenting the 1986 demonstration of passenger-only ferry service between Bremerton and Coleman dock in Seattle (*3*) indicated that the potential for converting noncommuters to passenger-only ferry service seemed much higher than that for converting commuters. Another passenger service test using a Boeing Jetfoil was documented in an internal report produced by WSDOT in December 1978 (*4*). The study concluded that there was a high degree of acceptance of high-speed passenger-only ferry service. However, the study also found that the test service was not successful in attracting a large number of cross-Sound commuters, particularly those who would have otherwise driven their vehicles. Although the report concluded that in the short term there were few routes that would make the service a viable option, a long-term commitment to promote passenger-only travel and reduce automobile usage had potential.

Two relatively recent studies of the Staten Island Ferry in New York hold promise for expanding passenger-only ferry service. The first, a case study of passenger-only ferry service between Staten Island and the Manhattan central business district (CBD) (*5*), evaluated high-speed passenger ferries operating at a cruising speed of 35 mph. The other modes available to these commuters involved commuting across one of two bridges or taking one of three automobile ferries. The report concluded that high-speed passenger-only ferry service holds great promise as a transportation alternative for this origin-destination pair. A second study by the same author (*6*) used a mail-back survey sent to more than 5,000 households in a selected area on Staten Island. The survey response produced approximately 1,000 observations for fitting a logit model. The model was developed to predict the mode split between ferry, express bus, and automobile. The results indicated that travel time is of extreme importance to persons using the ferry service. Other variables found to be significant for ferry riders were cost, access time to terminal, and comfort.

Although the transportation archives contain very few articles on this mode of transportation, interest in passenger-only ferry service seems to have increased in the last few years. As transportation agencies and policy makers review ways to maximize efficiency and reduce, or at least slow, the growth of automobile use, alternatives to the single-occupant vehicle are constantly being sought. The potential ridership for passenger-only ferry service will depend on the route selected and various factors influencing people's decisions to use this mode.

STUDY APPROACH

The primary objective of this research was to quantify the mode shift occurring after the passenger-only ferry service alternative was provided to commuters traveling between Vashon Island and the Seattle CBD. A secondary objective was development of a statistical model that predicts the likelihood of a person choosing passenger-only ferry service over the automobile ferry. The necessity of gathering information on commuters and the attributes of the ferry system that influence their decisions regarding mode choice led to the selection of a self-administered questionnaire for the data collection. The vicinity map in Figure 1 shows the routes under study.

The majority of the systemwide ferry service is provided by 22 automobile ferries ranging in vehicle capacity from 40 to 206 cars. The ferry system also operates three passenger-only ferryboats, two monohulls and one catamaran, each with a passenger capacity of 250. The catamaran is used when one of the monohull vessels is out of service due to routine maintenance or mechanical failure.

The automobile ferries that serve Vashon Island have broad, spacious, heated seating arrangements with large open windows and areas to walk outdoors on deck. The automobile ferries also have cafes on board and newspaper racks. The passenger ferries have two decks; one deck has four television sets, and there is also a small snack bar. The sailing and fare schedules in effect when this study was conducted are given in Tables 1 and 2.

SURVEY

The survey gathered results from one of three automobile ferryboats sailing between Fauntleroy and Vashon/Southworth. This boat accounted for three of nine weekday afternoon sailings. The survey also gathered results from all afternoon sailings of the passenger-only ferry from Seattle to Vashon Island for that day. The total observations of 711 riders were composed

TABLE 1 Sailing Schedule, Seattle/Vashon, Tuesday, May 14, 1991 (Approximate Crossing Time 25 min)—Passenger-Only Ferry

Leave Seattle	Leave Vashon
6:00 a.m.	5:30 a.m.
7:30	7:00
8:40	8:10
3:05 p.m.	9:25
4:35	3:45 p. m
5:50	5:15
7:00	6:20
8:00	7:35
11:30[A]	8:30
	12:00 Midnight[A]

BASIC FARE
$3.30 per passenger, round trip.
(10% discount with a commuter book)

[A] *Fridays only*

of 404 observations from the automobile ferry and 307 from the passenger-only ferry. The total number of afternoon automobile ferry users was 1,752, and the total number of afternoon passenger-only ferry users was 348, for a total of 2,100 afternoon ferry users on the date of the study. The automobile ferry users represent 83.4 percent and the passenger-only ferry users represent 16.6 percent of the total afternoon ferry users.

The timing of the project survey was designed to capture the afternoon commuter; the survey was conducted on Tuesday, May 14, 1991. As with many transportation studies, the best months for data collection are May and October. The typical days for data collection to capture commuter behavior are Tuesday, Wednesday, or Thursday. May 14th was selected because there was enough time between the study date and the Memorial Day holiday weekend to avoid any fringe effects from holiday traffic variations. The time for the survey was from 3:00 to 7:00 p.m. This included all westbound sailings on the passenger-only ferry. In addition, three westbound sailings of the automobile ferry *Klahowya* were surveyed. The exact sailings that composed the sample groups for this study are given in Table 3; the overall response rate was 79.5 percent.

The following seven modes on the automobile ferry were identified: walk-on, bicycle, motorcycle, single-occupant vehicle, shared ride, WSF-certified carpool, and bus. A specific category for handicapped passengers was not provided; if they used a wheelchair to board they were counted as a walk-on passenger for this survey. It may be useful in future studies of the passenger ferry to identify wheelchairs as a separate boarding mode. Persons living on the Kitsap Peninsula can take the passenger-only ferry to Seattle by riding the automobile ferry from Southworth to Vashon Island and transferring to the passenger-only ferry. Hence, the percentage of ferry users living in different areas had to be identified. Changing modes from the automobile ferry to the passenger-only ferry inherently involves a change in routes; hence, the distance of the final destination of each of the respondents to the ferry terminal was determined.

SURVEY RESULTS

More than 80 percent of the respondents who use the passenger-only ferry use it 4 or more days per week, indicating that it is a commuter service. Figure 2 shows the percentages of the former modes that provided the passengers on the passenger-only ferry. The observation total of 299 reflects the fact that 8 of the 307 passenger ferry observations did not respond to the question about former mode of boarding.

It is interesting to note that 25 percent of the passenger-only ferry riders are new to the system. This may be explained by the fact that there is a certain turnover on Vashon Island,

TABLE 2 Sailing Schedule, Seattle/Vashon, Tuesday, May 14, 1991 (Approximate Crossing Time 15 min)—Automobile Ferry

Leave Seattle		Leave Vashon	
5:30 a.m.	4:35 p.m.	5:05 a.m.	1:50 p.m.
6:20	4:55	5:30	2:10
6:55	5:30	6:00	2:45
7:55	5:45	6:25[T]	3:35
8:55	6:10	6:50	4:30
10:25	6:35	7:00	5:00
11:15	6:55	7:20	5:20
11:50	7:25	7:55	6:10
12:45 p.m.	7:50	8:15	6:30
1:15	8:15	8:30	7:05
2:20	9:20	9:30	7:50
2:35	10:15	10:00	8:35[J]
3:15	11:20	10:45	9:45
4:05	12:30 a.m.	11:25	10:35[J]
	1:50	12:20 p.m.	11:40[J]
		12:50	1:20

BASIC FARE
$2.15 per passenger, round trip.
$7.50 Auto and driver, round trip.
(10% discount with a commuter book)

[J] *Via Southworth, crossing time 35 minutes.*
[T] *Loads foot passengers and carpools/vanpools only*

TABLE 3 Sailings Sampled for Project Survey, Tuesday, May 14, 1991

PASSENGER-ONLY FERRY		
Passenger-Only Ferry Sailing Times	Total Passengers on Sailing	Total Number of Observations
3:05 p.m.	60	49
4:35 p.m.	150	124
5:50 p.m.	112	108
7:00 p.m.	26	26
TOTAL	348	307
AUTO FERRY		
Auto Ferry Sailing Times	Total Passengers on Sailing	Total Number of Observations
4:05 p.m.	182	124
4:55 p.m.	199	146
6:10 p.m.	190	134
TOTAL	571	404

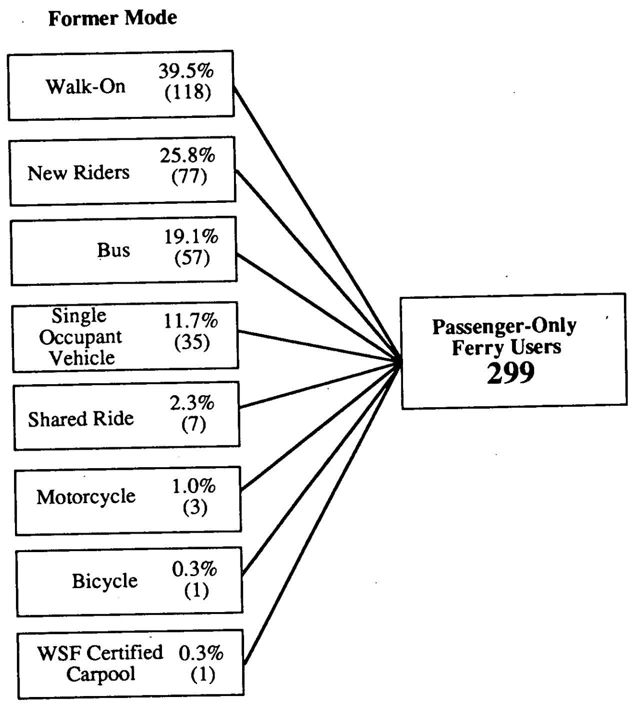

FIGURE 2 Former boarding modes of passenger-only ferry users.

that is, a constant migration of residents moving onto and off the island. In addition, there has been steady growth in the region, and some persons moved to Vashon Island because passenger-only ferryboat service was made available, as indiccated by their written comments. On the passenger-only ferry, 11.7 percent of the passengers were former single-occupant vehicle riders on the automobile ferry, which represents about 2 percent of the total passenger traffic between Seattle and Vashon/Southworth. Figure 3 shows where passenger-only ferry riders live.

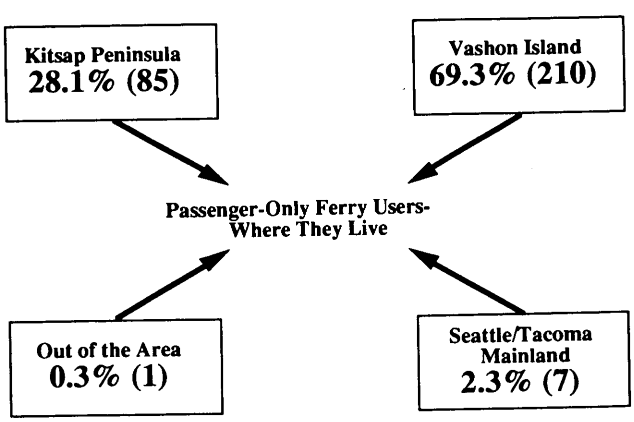

FIGURE 3 Passenger-only ferry users—where they live. Of 307 observations, 303 responses were provided.

MODE CHOICE MODEL

To understand what influences a commuter to choose the automobile ferry or passenger-only ferry, a number of attitudinal and demographics questions were asked. The information provided from the responses to these questions facilitated the development of a logit model. This model predicts the likelihood of a person with a given set of attributes choosing to ride the automobile ferry or the passenger-only ferry. Using logit regression techniques, a binary choice model was developed to model the behavior of the ferry commuters traveling between the Seattle-Tacoma mainland and Vashon/Southworth. The selected model is presented in Table 4; Table 5 describes each of the variables in the model.

The independent variables included in the final model demonstrate the significant factors ferry commuters take into consideration when choosing between the automobile and passenger-only ferries. The model, with these independent variables, is an attitudinal model rather than a model based on physical characteristics of the alternative transportation modes or demographics of the population. Several goodness-of-fit measures were used with other criteria to select the best model. For each of the estimated coefficients, the *t*-statistics are presented in Table 6.

Along with the *t*-statistics in Table 6, several auxiliary statistics for the model are provided in Table 7. Using the likelihood ratio test, we can test the null hypothesis that all coefficients are zero, that is, $b_1 = b_2 = \ldots = b_k = 0$. Assuming a chi-square distribution, the critical value for χ^2 with eight degrees of freedom and $\alpha = .05$ is 21.95, and for our model $21.95 < 217.68$, so we are 99.5 percent confident that the null hypothesis, that all coefficients are zero, can be rejected. The ρ^2 statistic is analogous to R^2 used in regression, but the accepted values of ρ^2 are generally much lower than the values for R^2. Using the estimated coefficients, the following utility function results:

$$U = 1.398 - 0.537(\text{carper}) + 0.726(\text{ttvi}) - 0.948(\text{ttfvui}) - 1.038(\text{farevi}) + 0.635(\text{endvi}) - 0.736(\text{sov}) + 2.238(\text{bus}) + 0.753(\text{walk}) \quad (1)$$

Using the utility function in Equation 1, the probability of a decision maker selecting each of the modes can be predicted.

TABLE 4 Estimated Coefficients for Logit Model

Independent Variable	Estimated Coefficient	Standard Error	t-Statistic
constant	1.398	NA	NA
carper	-0.537	0.108	-4.966
ttvi	0.726	0.189	3.832
ttfvui	-0.948	0.571	-1.660
farevi	-1.038	0.188	-5.529
endvi	0.635	0.182	3.488
sov	-0.736	0.243	-3.023
bus	2.238	0.379	5.905
walk	0.753	0.207	3.635

Number of observations = 711
NA = Not Applicable

TABLE 5 Description of Variables

Independent Variable	Description of the Independent Variable
constant	constant term
carper	number of cars per workers who work outside the household
ttvi	total travel time 'important' (0=no,1=yes)
ttfvui	ferry travel time 'very unimportant' (0=no,1=yes)
farevi	the fare 'very important' (0=no,1=yes)
endvi	endpoint of the ferry trip 'very important' (0=no,1=yes)
sov	used as prior boarding mode (0=no,1=yes)
bus	used as prior boarding mode (0=no,1=yes)
walk	used as prior boarding mode (0=no,1=yes)

TABLE 6 Discussion of Coefficients

Ind.Var.	Est. Coeff.	Discussion of Variable and Estimated Coefficient
carper	-0.537 (t=-4.97)	As the number of cars available to the worker increases, the less likely the person will be to use the passenger-only ferry. This seems intuitively correct.
ttvi	0.726 (t=3.83)	If total travel time is very important, the decision maker may be more likely to choose the passenger-only ferry. Especially if the ferry component is the major component of the trip, as with most passenger-only ferry commuters.
ttfvui	-0.948 (t=-1.66)	If the travel time on the ferry is very unimportant, the rider is less likely to take the passenger-only ferry. If the ferry component of the trip is small, relative to the total trip, the leg of the trip on water is less significant. This reflects that many persons using the auto ferry retain the use of their personal transportation, and the shorter crossing time of the auto ferry.
farevi	-1.038 (t=-5.53)	If fares are very important to the user, the likelihood of using the passenger-only ferry is reduced. Currently, fares on the passenger-only ferry are higher than the fare for a walk-on passenger on the auto ferry.
endvi	0.635 (t=-3.49)	If the endpoint is very important to the user, it is more likely the passenger-only ferry will be used. Over 80% of persons using the passenger-only ferry had their destination within five miles of the passenger-only ferry terminal.
sov	-0.736 (t=-3.02)	A person who used a single occupant vehicle on the auto ferry is less likely to use the passenger-only ferry. This may reflect a commitment to personal transportation.
bus	2.238 (t=5.90)	A bus rider is more likely to use the passenger-only ferry. The size of this coefficient suggests a strong correlation between bus riders and passenger-only ferry use.
walk	0.753 (t=3.63)	As with the bus the sign is positive, but the size of the coefficient is smaller. This may reflect the fact that some persons who walked on the auto ferry did so because the auto ferry terminal is convenient to their final destination.

The equation for predicting the probability of selecting the passenger-only ferry is provided in Equation 2:

$$P(m_1|U) = \left[\frac{1}{1 + e^{(-U)}}\right] \qquad (2)$$

where m_1 = Mode 1 = passenger-only ferry.

This model was developed directly from the responses given by ferry users. Specific questions about weather were not asked, but questions about the importance of ferry terminals being located conveniently to the origin and destination were asked. It may be inferred that responses to questions on the location of ferry terminals reflect some consideration given to weather.

The use of this model can be illustrated by examining a hypothetical decision maker (dm) with the following attri-

TABLE 7 Auxiliary Statistics

Number of Observations	711	
Likelihood Ratio (χ^2)	217.68	
ρ^2	.221	
corrected ρ^2	.213	
Log Likelihood	at convergence	initial
	-383.99394	-492.82765

butes: the dm's household has 1.5 cars per worker working outside the household, the total travel time is very important to the dm, the ferry travel time is very unimportant, the fares are very important, the endpoint of the ferry trip is very important, and the former boarding mode on the automobile ferry was walking. Using this description of the decision maker gives the following:

$$U = 1.398 - 0.537(1.5) + 0.726(1) - 0.948(1) - 1.038(1) + 0.635(1) - 0.736(1) + 2.238(0) + 0.753(0)$$

$$P(m_1|-0.769) = \left[\frac{1}{1 + e^{(0.769)}}\right] = .317$$

For this hypothetical decision maker, the probability of choosing the passenger-only ferry is 0.317, and, hence, the probability of this person choosing the automobile ferry is 0.683. The choice model has one continuous independent variable, carper, the number of licensed, working automobiles per worker working outside the home. The elasticity of this variable was computed as −0.51. This indicates that a 1 percent decrease in the number of automobiles per worker results in only a 0.51 percent increase in the probability of the decision maker choosing the passenger-only ferry; hence this variable is inelastic.

Subsequent to the analysis of the data and completion of the model, the authors examined the influence of frequency of service on the behavior of ferry commuters. The frequency of service variable was tested during the development of the logit model and found to have low *t*-statistics (less than 1). The ferry system has experienced increased ridership on automobile ferries in the past by increasing the frequency of service. Our study indicated that frequency of service is nearly equal in importance to passenger-only and automobile ferry riders. Thus, although it is an important variable in attracting ferry ridership, its importance to one mode or the other was not unique. This fact accounts for the low *t*-statistics of the frequency of service variable in the logit model. Hence this variable was excluded from the final model. Whereas this finding may be counterintuitive when considering weather conditions (frequency is expected to be a greater factor for the passenger ferry than for the automobile ferry), several factors may influence its lack of significance in the study. One is the fact that the study was conducted on a beautiful spring day with warm sunny weather. Hence the weather may have been taken for granted by the respondents. Another factor is that most people living in the Pacific Northwest accept the fact that rain is a part of life in this region and are less sensitive to rainy weather than those in other regions of the United States.

Another reason why frequency of service may not be a strong attribute in the model has to do with how people perceive frequency or service as opposed to how people perceive travel time. If commuters depart at a regular time each day, the provision of additional trips may not be as readily perceived by the commuter as a reduction in travel time. This reasoning, along with the observation stated earlier regarding frequency of service being nearly equal in importance to automobile ferry and passenger-only ferry users, may explain the lack of its significance in this model. This should not be interpreted to mean that the frequency of service is inconsequential to passenger-only ridership.

CONCLUSIONS

Statistical analysis of the survey results contributes to the data base of knowledge regarding waterborne transportation. As the country grows in population, there will be an increasing demand for land and space. Land and space near the water will be especially desirable. It is unlikely that the passenger-only ferry will replace the automobile ferry. Increased automobile ferry service may be inevitable. However, if the ferry system is to truly serve as an extension of the Washington State highways, it must have the means to carry out that role. The passenger-only ferry service can be an integral part of the ferry system network. The passenger-only ferry service can potentially slow the growth of automobile use on the ferries, an environmentally sound goal.

This study indicates that providing passenger-only ferry service can result in a mode shift from drive-on ferry passengers to walk-on passengers. Former single-occupant vehicle users composed 11.7 percent of the persons responding to this passenger-only ferry survey question. Extrapolated to the entire passenger-only commuter population, this represents approximately 40 persons who shifted from single-occupant vehicles on the automobile ferry to walk-on passengers on the passenger-only ferry. This results in a mode shift of 1.94 percent out of the total afternoon ferry commuter population of 2,100 after approximately 1 year of passenger-only ferry service between Seattle and Vashon Island.

The degree of mode shift depends on the ferry routes and the location of ferry terminals. Whether the amount of mode shift measured in this study will prove economically viable remains to be determined. The study revealed that passengers believe that travel time on the passenger-only ferry is important and will influence their decisions regarding mode choice. In addition, the door-to-door travel time is a significant factor when people choose between passenger-only ferry service and automobile ferry service. The study also indicated a significant number of new riders (25 percent). This is primarily a result of land use turnover and growth in the region. Some people actually moved to Vashon Island specifically because the service was made available. A consistent advertising program regarding the availability of alternative modes of transportation could have a significant impact on this market. Such a program should be considered to maximize use of the passenger ferry.

Should another transportation alternative, such as a cross-Sound bridge, be chosen at some time in the future, it will only replace a small portion of the ferry system's network.

The value of the passenger-only ferry to the transportation system of the Pacific Northwest and its contribution to the overall ferry system is clear. WSDOT's plan for future accommodation of efficient and environmentally desirable modes of transportation must consider increasing the number of passenger-only ferries serving Puget Sound ferry commuters. The passenger-only ferry contributes to the regional goal of reducing reliance on the automobile.

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Using Marginal Costs To Evaluate Drayage Rates in Rail-Truck Intermodal Service

LAZAR N. SPASOVIC AND EDWARD K. MORLOK

An operations planning model of the highway portion, or drayage, of rail-truck intermodal transport is used to develop pricing guidelines for drayage service. The model, originally developed and used to evaluate the potential of reducing cost and improving service quality of drayage, also generates marginal (incremental) costs of moving loads in the drayage operation. The marginal costs are used to evaluate the efficiency of drayage rates charged by truckers in the current operation as well as rates used in a proposed operation with centralized planning of tractor and trailer movements. The insights gained from this analysis are used to develop guidelines for using marginal costs in the areas of pricing intermodal door-to-door movements, load solicitation, and decisions regarding load acceptance. Application of the model as a decision support tool for assisting intermodal management in developing proper strategies for pricing and marketing of intermodal service is illustrated. The need for railroad management to become aware of the characteristics of drayage operation and the systemwide impacts of drayage movements on the cost and thus profitability of intermodal operation is indicated.

The use of an operations planning model of the highway portion, or drayage, of rail-truck intermodal freight transport for developing pricing guidelines for drayage service is described. In rail-truck intermodal operations, highway trailers or containers are moved by rail in line-haul between rail terminals and by tractor-trailers from the terminal to receivers (termed consignees) and from shippers to the terminal in the service area. The local tractor-trailer movement is referred to as drayage—the term coming from the earliest such movement, wherein the freight was hauled in wagons pulled by dray horses. Currently, despite its short distance compared with the rail movement, drayage accounts for a large fraction of intermodal origin-to-destination costs and is a major factor in service quality as perceived by shippers. Various railroad industry estimates indicate that the prices paid for drayage for a typical 1,000-haul is 40 percent of the total door-to-door rate (*1*). This high drayage cost is widely regarded by intermodal and railroad executives as a major factor preventing intermodal from becoming competitive with intercity motor carrier in short- to medium-haul markets and inhibiting the profitability of longer movements.

Research was undertaken to evaluate the potential of both reducing cost (and hence price) and improving service quality of drayage (*2*). The central part of the research was the development of a detailed mathematical model of drayage that was used to evaluate cost savings of an operation in which the movements of trailers and containers are centrally planned compared with the current decentralized drayage operation. Drayage companies (truckers) would be paid rates that are based on their costs. The research findings revealed that substantial cost savings could be achieved by introducing a centralized operation (*2,3*).

However, the primary motivation for this paper was to use the marginal costs of drayage (generated by the model) to evaluate the current drayage rates that are charged by truckers to move trailers. Intermodal service is typically marketed through separate organizations, called intermodal retailers or third parties, who are the actual agents arranging for the transportation. Whereas there are some important recent exceptions to this arrangement, such as in the case of Conrail Mercury service and the QUANTUM service offered by the Santa Fe and J. B. Hunt, third-party retailing remains the dominant form for most domestic intermodal. The intermodal retailers also arrange directly with separate trucking companies for the drayage of trailers (or containers) at the rail terminals. The railroad does not deal directly with the shippers and consignees and in effect receives a division of revenue for the line-haul portion of the service. Because of this pricing arrangement, it is important for the railroad to understand the costs of the drayage operation so that it can properly establish its line-haul rate.

A second purpose was to examine the pattern of marginal costs to ascertain how they varied by direction and location and whether there were any stable patterns. This is important, for if they vary in a seemingly random manner, a marginal cost-base pricing scheme would yield vacillating rates that probably would be unacceptable for both carriers and shippers. Also, profitability of individual loads would be difficult to determine a priori. On the other hand, stable marginal costs would provide an important input to price setting and should prove valuable in establishing a pricing strategy vis-à-vis competitors.

A third purpose was to use the model to evaluate the rates the draymen would be paid in a centralized operation as a measure of the true cost (marginal cost) of tractor and trailer movements. The objective here was to find out whether the rates were smaller or larger than the model-generated marginal costs of trailer movements in the least cost drayage operation. Often in complex transportation systems charac-

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terized by load imbalances and terminal congestion, the movement of an additional shipment (trailer) may result in a substantial increase in the cost of operation. This cost may be significant and exceed the rate charged for the movement. Alternatively, it could add little to the overall cost. If the railroad were to introduce centralized operation of drayage and presumably along with that set the origin-to-destination rate for each intermodal shipment, the actual costs of drayage should be the basis for paying for the drayman and for the overall shipment price. Thus, the objective was to ascertain whether the rates represented a good approximation of incremental costs. If so, they would provide an easy-to-use and stable basis for payment. If not, the payment scheme would have to be more complex, perhaps involving assessing the incremental cost of each drayman for each movement. Similar considerations would apply to the inclusion of the cost of drayage in the pricing of the origin-to-destination movement.

BACKGROUND

Intermodal has great potential to offer shippers a competitive product—in terms of price and level of service—by combining the best features of both modes: the efficiency of truck in local operation with the economy of scale of rail in a long haul (*4–6*). Despite these facts, intermodal has not yet achieved its full potential either in terms of increasing its market share relative to its prime competitor, intercity motor carriers, or profitability. As stated by Allen, it has been "a great revenue business but a poor net revenue business" (*7*).

Fragmented Structure of Drayage

A critically important characteristic of intermodal services, which has a major impact on the cost and service quality of intermodal, is the fragmented organizational structure associated with rail-truck movements. As was mentioned earlier, in the case of all shippers except for very large ones, such as UPS and the U.S. Postal Service, and selected services, intermodal service is marketed through intermodal retailers. The intermodal retailers' pricing arrangements between the railroad and drayage are kept confidential. It has been noted that the agents in the system often have different profit/level-of-service frameworks in which they operate (*8*). Thus, they could be attempting to maximize their own profits rather than cooperating in maximizing the profit of the entire intermodal system. In this context, excess profit could be generated by intermodal retailers or drayage carriers, or both, by charging for their service a rate in excess of their incremental costs. Many years ago, Allen (*9*) suggested that the high cost of drayage could be a result of inefficient fragmented operation as well as excess profit extraction by the partnerships between the drayers and the intermodal retailers.

The lack of coordinated pricing and marketing of the overall service, where it exists, is facilitated by the lack of knowledge on the part of the railroad about the drayers' cost structures. An early study of intermodal rail pricing strategies by Horn (*10*) evaluated the efficiency of railroad intermodal rates and analyzed how these rates related to the railroad's overall pricing strategy. His findings indicated that there were no consistent pricing objectives that the railroad followed in deriving its line-haul rates. In addition, the study pointed out that there was no knowledge about the draymen's operating practices and cost structure. This lack of knowledge resulted in the origin-to-destination rate (combined railroad line-haul plus drayage rate) either being lower than it need be considering the competitive truck rate or being higher than the competitive truck rate, driving business to the truckers. Horn suggested that the railroad reevaluate its pricing policies and bring them in line with its marketing and management objectives. Otherwise, there would be no further penetration of intercity truck markets and thus no substantial growth in market share or profit for intermodal. Since pricing must be based on both competitive factors and costs, these results and conclusions underscore the importance of the type of cost analysis described in this paper.

Inefficiencies in Drayage Operation

In addition to these pricing and marketing problems, the fragmentation prevents efficient operation of the entire drayage function. In a typical intermodal market, around the rail terminal, there are at least a dozen intermodal retailers and as many truckers. As a result, drayage is characterized by a large percentage of nonrevenue movements, which contribute to the high cost of operation. For example, it is not uncommon to find one drayman, working for one retailer, delivering a loaded trailer to a consignee in a particular town, waiting while it is unloaded, and then returning the empty trailer to the terminal, while at about the same time another drayman is hauling an empty trailer to a shipper in the same area for loading and then bringing it back to the terminal loaded. Half of each round-trip thus is to move an empty trailer. If information on all deliveries and loads were available at a single location and delivery and pickup schedules were coordinated, these two round-trips might be replaced by one: delivering the loaded trailer, unloading it, repositioning it to the shipper, loading it, and returning to the terminal with a full load. Thus unproductive movements could be reduced or even eliminated if the trailer movements are planned as a whole instead of in a fragmented manner. This efficiency would result in an operation with increased loaded (revenue) miles and thus a lower cost of operation.

The operation of drayage and its pricing are also closely interrelated. As the operation becomes more coordinated using single tractor round-trips to serve more than one load, pricing becomes more difficult. The reason is that costs are no longer essentially only direct in the sense that blocks of tractor (and driver) time (or activities) are associated with single loads. Instead, costs are shared, requiring a more sophisticated determination of costs attributed to each load (trailer).

To understand this, it is necessary to consider the drayage process in more detail. In drayage operations, loaded trailers (or containers loaded on flatbeds or skeleton trailers) are moved from the rail yard (upon their arrival by rail) to the consignee as well as from the shippers to the rail terminal for loading onto trains that carry the trailers to the destination area, from which drayage is used again for final delivery. In addition, once the trailer is emptied by a consignee, it is either moved back to the terminal, from which it will be taken later to a shipper, or repositioned directly from the consignee to a shipper needing an empty trailer for loading. Since the trailers are entirely separate from the tractors, tractors with drivers must be scheduled to support all trailer movements. Furthermore, there may be considerable movement of tractors without trailers, termed bobtailing. The separability of tractor and trailer modules permits trailers to be moved according to two procedures: stay-with and drop-and-pick. The stay-with procedure means that the tractor stays with the trailer during unloading and loading. The drop-and-pick procedure means that the tractor leaves the trailer during unloading or loading and departs to some other location for another assignment. A tractor eventually returns to pick up the trailer and take it to the terminal, or, if the trailer is empty, the tractor can reposition it to a shipper. Discussions with persons in the industry suggest that almost all movements now appear to use the stay-with procedure.

At the present time, the prices charged by draymen are based primarily on the assumption that each trailer delivery is undertaken independently of other deliveries. Thus, as in the earlier example, a tractor delivering a load will return the empty trailer to the terminal rather than pick up an outbound load on the return trip. Since the tractor's time and mileage on the round-trip are uniquely associated with the one delivery, the attributable cost is easily determined, and the price is set slightly above that cost, factoring in overhead and other nondirect costs. Similarly, drop-and-pick rates would then involve two round-trips, so they would be almost twice as high (the reduction being due to saving the loading or unloading time). Indeed, some drayage firms (and some railroad drayage subsidiaries) charge double for this service (perhaps partly to discourage its usage). In practice, prices could deviate from these levels, as economies and diseconomies appear. As for economies, some retailers and draymen would notice opportunities to move loads in both directions on a round-trip.

The basis for pricing under centralized operation, in which multiple loads may be moved by a tractor during one round-

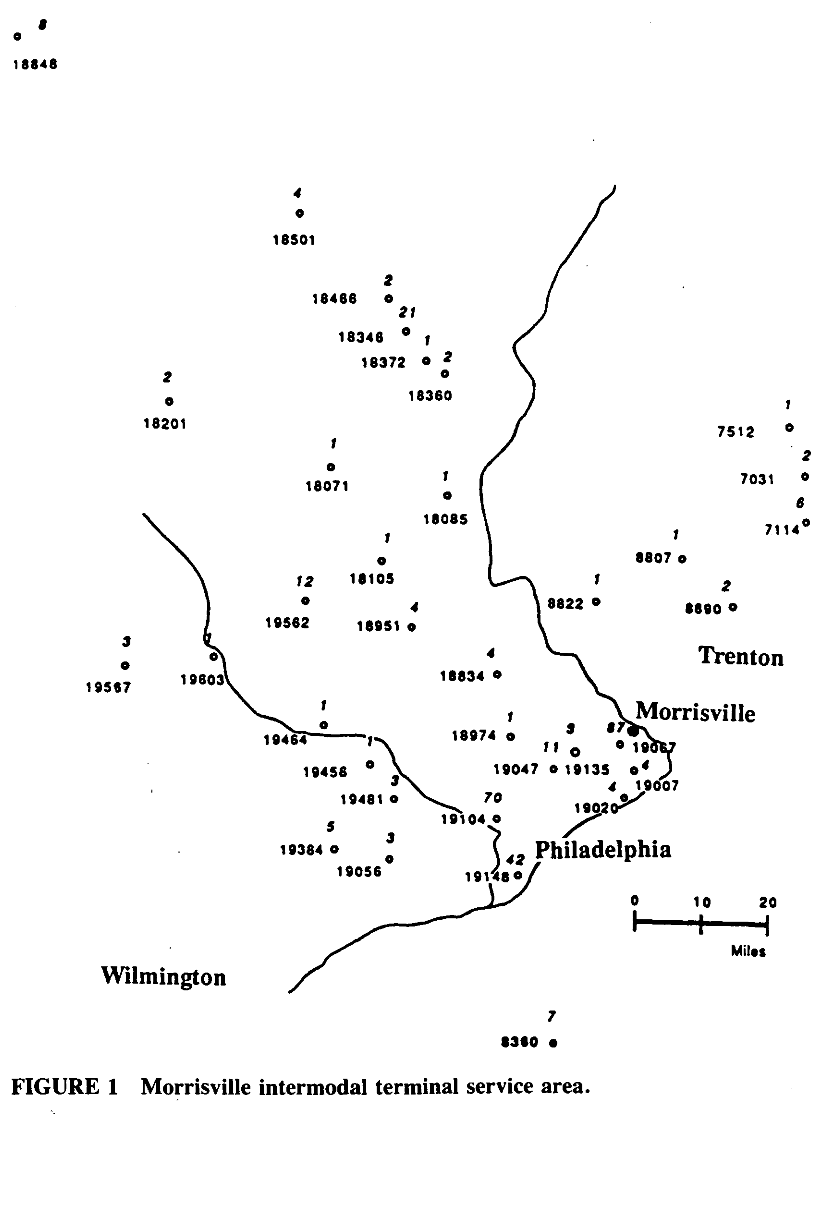

FIGURE 1 Morrisville intermodal terminal service area.

trip from the terminal (perhaps stopping at two or more shipper/consignee locations), is more difficult. The cost of such a round-trip (perhaps including an allocation of unproductive time as well) could be allocated to the loads handled, but this would result in substantial variations for any one load—depending on the availability of other loads to marry with it. This would play havoc with stable pricing. Another approach is to calculate the actual marginal cost of loads to (or from) each area served on the basis of typical or expected traffic patterns. Prices would then be set at or above the marginal cost, thus reflecting market conditions and the possible need for unit revenue in excess of marginal costs in order to cover fixed costs (i.e., total revenue must be at least equal to total cost for the system to be self-sustaining).

Envisioned Drayage Operation

As stated previously, the improved drayage operation envisioned centralized drayage operations planning in which tractors would be assigned to support trailer movements to (*a*) meet service requirements for timely delivery of trailers to and from shippers and consignees and (*b*) minimize the cost of drayage. To this end, a model of a tractor and trailer delivery, repositioning, and pickup system that would capture the nature of the drayage operation closely was developed. The model was applied to a real-world case study of drayage to evaluate the cost savings and service improvements possible from a centralized operation. The model was structured as an integer linear program with time windows and service constraints. The general model statement is as follows: Minimize total costs of tractor and trailer activities subject to

- Service quality constraints for deliveries of loads to consignees,
- Service quality constraints for pickups of loads from shippers,
- Tractor flow conservation constraints,
- Trailer flow conservation constraints, and
- Nonnegativity and integrality constraints.

Of primary concern in this paper are the results in terms of pricing drayage services. The model formulation itself is described in detail elsewhere (*2,3*).

CASE STUDY

The case study was based on the trailer movements in the area of the Conrail intermodal terminal at Morrisville, Pennsylvania, during the 8-day period February 26 to March 5, 1989. It was found that 330 trailer loads were available to be moved between the terminal and the consignees or shippers. The traffic was highly imbalanced—215 loaded trailers arrived by rail to be delivered, whereas only 115 loads were to be picked up from the shippers and delivered to the terminal for outbound movement by rail. This imbalance is not atypical for Conrail or any northeast railroad operation. Shippers and consignees, shown in Figure 1, were grouped together into 14 areas according to their zip codes. The scheme for grouping the zip codes into the areas is given in Table 1. The trailer volume and day they were available to be moved are also

TABLE 1 Temporal Distribution of Demand for Deliveries and Pickups of Loads (Shown in Parentheses) at Areas

Area	Day								Empty
(with ZIP CODES)	1	2	3	4	5	6	7	8	Trailer
A 18834, 18951	1 (2)	1 (-)		- (1)	2 (-)		1 (-)		8
B 19020, 19007 19067, 19147,19135, 19047, 18974	25 (7)	5 (6)	14 (7)	10 (4)	16 (3)	5 (3)	- (4)	- (1)	84
D -- 19104	16(4)	8 (6)	4 (3)	5 (2)	6 (2)	6 (3)	- (1)	2 (2)	27
F -- 19148	3 (3)	3 (3)	5 (3)	5 (2)	7 (-)	2 (1)	2 (2)	- (1)	15
G 19562, 18105, 18071, 18085	4 (1)		3 (1)	- (2)	2 (-)	- (1)		- (1)	8
H 19063, 19567	1 (-)				2 (-)	1(-)			0
I 19481,19464, 19456			- (1)	1 (-)	2 (-)	1 (-)			0
J 07114,07032,07512	- (1)	- (2)	- (1)	1 (1)	1 (1)	- (1)			6
K 08360		1 (-)		5 (-)	1 (-)				1
L 08890,08822, 08807	1 (2)	- (1)	- (1)						2
M 19056, 19348	2 (1)			1 (-)		- (2)	1 (-)	- (1)	2
N 18346,18466,18360 18372, 18201	10 (2)	1 (2)	2 (1)	- (1)	3 (2)		1 (1)	1 (1)	13
O -- 18501	1 (-)		1 (-)		- (1)		1 (-)		1
P -- 18848	2 (2)	1 (-)	2 (1)	(1)	3 (1)	- (1)		1 (-)	8

given in Table 1. Within centralized drayage operations planning various forms of payments of draymen were considered. The results herein are based on a piecework payment plan, which means that a drayman would be paid separately for each movement of a trailer—empty or loaded—on an origin-to-destination–specific or mileage basis. The payments were derived from the current pricing guides of draymen in the Morrisville area using regression (*2*). The payments are linear functions of the distance between the terminal and the areas. The payments for loaded trailers are higher because they take into account the additional time associated with handling them (paperwork, bill of lading inspection, etc.).

Given the piecework drayage rates (cost) for each alternative and traffic data, the model produced an optimal operations plan with integer flows of tractors and trailers that minimized the cost of moving the loaded trailers and distributing empty trailers for loading on return movement, while satisfying the customer's schedules for pickup and deliveries. Considering the simplifications necessary in any modeling, some weaknesses in the demand data, and assumptions necessary because of data limitations, it was concluded that a 40 percent reduction in cost was a reasonable target for savings resulting from optimized operations planning. The actual results, discussed in detail elsewhere (*1*), specified somewhat larger savings depending on assumptions and payment plans.

MARGINAL COSTS

Besides estimating the overall cost, the model yields the marginal or incremental cost of an additional drayage movement. This is computed by considering the change in total cost resulting from moving an additional load. The marginal costs would in general differ considerably from the direct cost that could be associated with the loaded move (if any, as argued before).

The marginal costs are used for two purposes. One is to examine their stability spatially and over time, important features if they are to be used as a basis (along with others) for pricing. The other is to compare the incremental costs of loaded trailer movements with two rates: current drayage rates and the piecework costs for single moves derived from the current rates. The rationale for this is to ascertain the extent to which current or piecework pricing would reflect marginal costs.

Calculation of Incremental Costs of Moving Trailer Loads

The drayage model, when solved as a linear program, yields shadow (dual) prices associated with constraints on the delivery and pickup of trailer loads. The shadow price represents a change in the total cost of operation resulting from moving an additional trailer load, within a time window, between the terminal and a particular consignee/shipper. These model-generated shadow prices are used to approximate the true incremental costs of moving trailer loads.

The shadow prices and thus marginal costs are calculated in two ways. One is to solve the continuous-variable version of the model to optimality, thus yielding the marginal costs associated with the real-valued tractor-trailer flows. These costs are given in Columns 2 and 3 of Table 2. The real-valued flows mean that, in the model, an additional trailer may be moved in fractional amounts (e.g., 0.3 of a single trailer may be moved on one day and 0.7 on the next day). Of course such moves are not physically possible. The second way is to solve the model to yield marginal costs associated with integer-valued tractor and trailer flows. However, these integer flows were not necessarily optimal, as noted by Spasovic (*2*). The marginal costs associated with the integer-valued flows are given in Columns 4 and 5 of Table 2.

Table 2 indicates that the marginal costs associated with the real-valued flows vary considerably with the time when the load is available for movement. In Area K, which receives seven loads from the terminal and sends zero, accepting a delivery of an additional load from the terminal in either Day 1, 6, 7, or 8 would increase the total cost of the operation by $118. Accepting the load on Day 2, 3, 4, or 5, however, would increase the cost of operation by $202. In the reverse direction, though, the pickup of an additional load at K on any day of the study period would increase the cost of operation by only $18. The last two columns of Table 2 indicate that the marginal cost of delivering an additional integer-valued load from the terminal to Area K is $202, whereas the cost of picking up a load is $18. Note that the marginal costs associated with the integer flows do not vary with the time the trailer load is available for delivery or pickup.

The comparison of marginal costs associated with real- and integer-valued flows is shown in Figure 2. The marginal costs associated with real-valued tractor-trailer flows are plotted against the marginal cost associated with integer-valued tractor-trailer flows. The square symbols along the 45-degree line in the graph represent identical values of marginal costs for moving loads to and from consignee/shipper areas. The triangle symbols show the values of costs that are different; the magnitude of this difference can be measured by the triangle's distance from the 45-degree line. Since marginal costs are almost equal, and considering the fact that in the real world the movements of tractors and trailers are integer valued, only the marginal costs associated with integer flows of tractors and trailers are used in further analysis.

When marginal costs are used for pricing, an important feature is whether they yield revenue sufficient to cover the cost of the drayage operation. It is of course typical in a transportation context for there to be economies of scale and density and for prices set at marginal costs to yield total revenue less than total cost. In the case where marginal costs are greater than average costs, if the drayage were priced at marginal costs, total revenue would be sufficient to cover the cost.

There are economies of scale and density in this linear model of drayage operations. For example, if the traffic volume is halved, the cost of operation would not necessarily decrease by 50 percent. Because of the systemwide impacts, opportunities for combining movements to reduce inefficiencies (e.g., deadheading and bobtailing) may be lost.

Pattern of Marginal Costs

The pattern of marginal costs presented in Table 2 reveals many interesting features. First, the cost of moving a load in

TABLE 2 Comparison of Calculated Marginal Costs of Deliveries and Pickups of Loads

Area	Marginal Costs[1] ($) of		Marginal Costs[2] ($) of	
	Delivering Load	Picking Up Load	Delivering Load	Picking Up Load
A	146	18	146	18
B	72	18	72	18
D	128	18	128	18
F	148	18	148	18
G	233	Days 1-7 17 Day 8 57	233	17
H	Days 1-4 283 Days 5-8 293	Days 1-7 17 Day 8 29	283	17
I	Days 1-3 142 Days 4-8 185	Days 1-3 31 Days 4-8 18	180	18
J	Days 1-3 94 Days 4-5 136 Days 6-8 63	102	128	110
K	Days 1, 6-8 118 Days 2-5 202	18	202	18
L	Day 1 115 Day 2 41 Days 3-8 18	Days 1-3 39 Days 4-8 18	107	47
M	Days 1-2 187 Days 3-5 151 Days 6-8 158	Days 1-5 17 Days 6-7 43 Day 8 47	161	43
N	348	42	340	50
O	384	18	384	18
P	534	18	534	18

[1]Marginal costs are associated with the real-valued flows of tractors and trailers.

[2]Marginal costs are associated with the integer-valued flows of tractors and trailers.

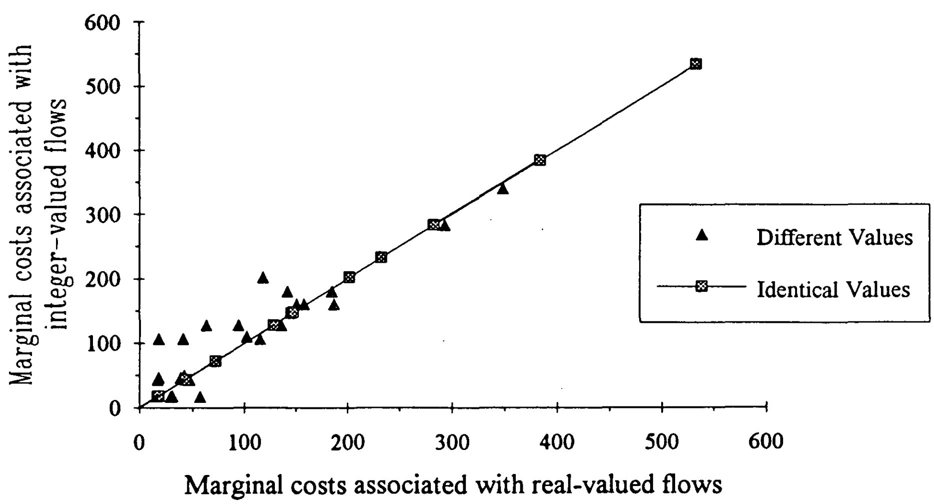

FIGURE 2 Comparison of marginal costs from integer-valued solution with those from real-valued solution.

the higher-volume direction (delivering a load from the terminal) is much higher than that of picking up a load. That there is a difference is expected, but the magnitude of the disparity is noteworthy. The average ratio of marginal costs of delivery to pickup is 9.95, reflecting the traffic imbalance.

The expected pattern of cost increasing with distance is also evident for deliveries but not for pickups, as shown in Figure 3. Increases in cost with distance for deliveries can be explained by the fact that each additional delivery generally requires an additional tractor round-trip. But many pickups can be moved by a returning tractor and empty trailer, and thus the additional cost is simply the added time for loading and added mileage for repositioning. The variations in pickup cost are explained primarily by the variability in added mileage.

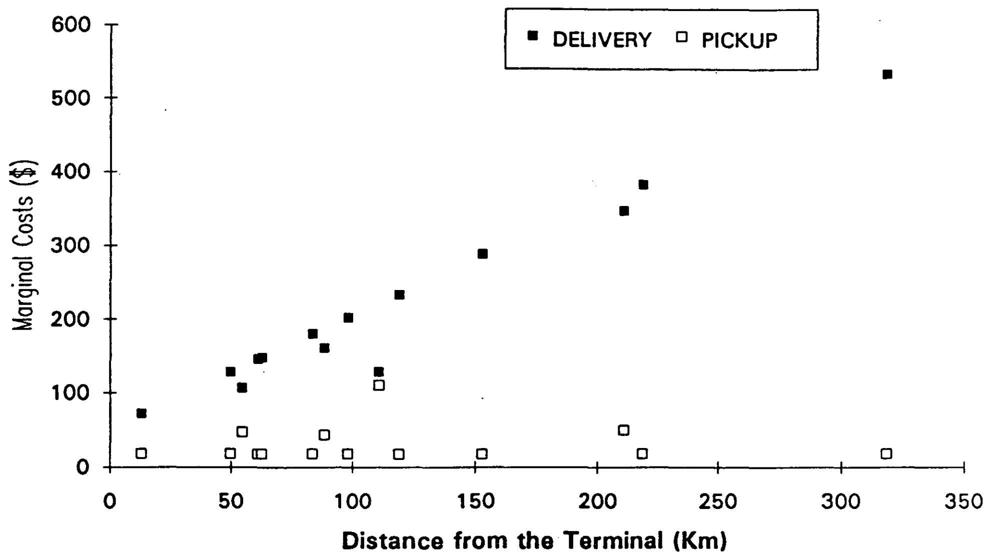

FIGURE 3 Marginal costs for pickups and deliveries versus distance from the terminal.

Evaluation of Current Rates

The comparison of marginal costs with rates for drayage in the current operation is given in Table 3. The marginal costs of delivering loads are always smaller than the current rates. On the average, the marginal costs are 73 percent of the current rates, with all values being in the 40 to 93 percent range. These values indicate that there is room for reduction in the current rates. The current rates for loads to Areas A, B, D, G, H, I, O, and P are approximately $50 larger than their respective marginal costs. These differences represent the cost of 2-hr tractor idling at the areas at $25/hr. This implies that tractors moved to and from these areas in the drop-and-pick operation. The reason is that there is sufficient two-way traffic so that tractors can be engaged in productive work (i.e., they can leave trailers at the areas and depart to new assignments) rather than having to wait while the trailers are loaded or unloaded. Thus, from Table 3 and the above analysis, it can be concluded that the current rates can be reduced on the basis of the criterion of revenue covering costs.

TABLE 3 Comparison of Current Drayage Rates and Marginal Costs

Area	Stay-With Current Rate ($) for Loaded Trailers	Marginal Costs[1] ($) of Delivering Load	Marginal Costs[1] ($) of Picking Up Load
A	195	146	18
B	123	72	18
D	179	128	18
F	198	148	18
G	283	233	17
H	334	283	17
I	230	180	18
J	271	128	110
K	251	202	18
L	268	107	47
M	237	161	43
N	421	340	50
O	434	384	18
P	484	534	18
Ratio of Marginal Costs to Stay-With Rates for Loads			
Average		0.73	0.12
Range		0.4-0.93	0.03-0.41

[1]Marginal costs are associated with the integer flows of tractors and trailers.

The marginal costs of picking up loads at Areas A, B, D, F, G, H, I, O, and P are significantly smaller than the current rates. They are, on the average, 12 percent of the current rates with actual cost for all areas being in the range of 3 to 41 percent. An issue in setting prices is of course that for any firm to remain in business its total revenue must at least equal its total cost. The cost of the centralized operation is about $ 38,300, 60 percent of the current cost. Using the marginal costs in Table 4 as the prices for all movements yields a total revenue of $37,834, only about 1 percent less than the cost. Thus prices would have to be set 1 percent higher than the marginal costs, on the average. However, this is still much below the level of current prices. Again, we can conclude that the current drayage rates could be significantly reduced.

These conclusions about possible reductions in the current rates must be viewed in the context of assuming that all trailers are moved according to a unified plan for the entire terminal area. As stated earlier, in the current operation the draymen and intermodal retailers lack the comprehensive information on trailer movements necessary to achieve such a system-optimal operation.

Evaluation of Piecework Costs

The comparison of marginal costs and piecework cost for moving trailers in a centralized operation is given in Table 4. The marginal cost of delivering a load from the terminal to Areas A, B, D, E, F, G, H, I, K, O, and P is, on the average, 1.71 times higher than the one-way piecework cost. For these areas, a marginal cost equals the sum of piecework rates for loaded and empty trailer terminal-area movements. Looking, for example, at Area K, the marginal cost of delivering a load from the terminal, $202, represents the sum of piecework costs

TABLE 4 Comparison of Piecework Rates and Marginal Costs

Area	Piece-Work Rate ($) for Delivery or Pick Up of		Marginal Costs[1] ($) of	
	Loaded Trailer	Empty Trailer	Delivering Load	Picking Up Load
A	82	64	146	18
B	45	27	72	18
D	73	55	128	18
F	83	65	148	18
G	125	108	233	17
H	150	133	283	17
I	99	81	180	18
J	119	102	128	110
K	110	92	202	18
L	77	59	107	47
M	102	85	161	43
N	195	177	340	50
O	201	183	384	18
P	276	258	534	18
Ratio of Marginal Costs to Piece-Work Rates for Loads				
Average			1.71	0.28
Range			1.08-1.93	0.07-0.92

[1]Marginal costs are associated with the integer flows of tractors and trailers.

for loaded and empty movements between the terminal and the area (i.e., $110 plus $92). This finding implies that, because of the present traffic imbalance, an additional trailer delivered from the terminal cannot be reloaded or advantageously repositioned to a new area and loaded and thus must be returned empty. Therefore, for the delivery of loads to these areas, the shipper should be charged a drayage rate that is at least equal to the marginal cost. Otherwise, this load is moved at a loss, and the load should be rejected. To summarize, it is clear that directional imbalance and volume of traffic are the major factors affecting the magnitude of marginal costs.

The marginal cost of picking up a load at Areas A, B, D, E, F, G, H, I, K, O, and P is on the average 28 percent of a one-way piecework cost for loaded trailers. The railroad should take advantage of this low marginal cost and solicit loads from these areas and balance the flows in order to increase its market share and in the long run the profitability of service.

Currently, it is common practice for the intermodal retailers to ask for reduced rates at which to sell the movement of trailers in the westbound (or light traffic) direction. However, despite the general traffic imbalance, for some of the areas (e.g., Areas J and L), the traffic is heavier in the westbound direction, and thus these areas will have a higher marginal cost for pickup. This marginal cost should be considered in determining the drayage rates for trailer movements and, thus, the door-to-door rate in the westbound direction. The use of marginal costs will eliminate the current practice of granting a lower rate for door-to-door movements that have costly drayage.

The general conclusion from this analysis is that the piecework costs (rates) of draymen are definitely not a proper basis for deriving drayage charges to shippers. The marginal costs vary too much by direction and location, being more than drayman rates in some instances and far less in others. This means that in general some sort of overall drayage system model that can determine marginal costs will be essential for economically sound pricing of the drayage component of intermodal service. This is true even if rates are set above the marginal cost.

CONCLUSIONS

The primary conclusions from this research are as follows:

1. In the system studied, current drayage rates bear no resemblance to the cost of moving trailers in an optimized system. In general, they are higher than needed to either cover marginal costs or yield revenues greater than overall costs, but by widely varying amounts depending on the customer location and direction of haul. Whether prices should differ as much as marginal costs depending on direction depends on competitive conditions that were not addressed in this research.
2. Charges of draymen for the individual moves involved in handling a trailer are also a poor guide to the marginal costs of accommodating loads for pickup or delivery.
3. Therefore, a systematic procedure for determining the incremental costs of handling each trailer is necessary. Whereas any model that incorporates an assignment of tractors to loaded trailers and supporting empty trailer movements would provide a basis for calculating these costs, a model that optimizes this assignment (and movements) to meet service requirements at minimum cost has obvious advantages. Given that such a model exists, in research prototype form, it is a natural basis on which to develop a daily operations support and costing model.
4. If centralized operations planning were introduced and drayage prices varied primarily by direction and location rather than by mileage or time required for the movement, payments to draymen could not be based on those prices (because they would not in general yield, for any arbitrary set of moves, overall revenue greater than overall cost). Therefore a means of paying draymen that meets tests of revenue adequacy and

fairness would have to be developed. In principle, this is not difficult, but in practice it may be.

5. Given that current drayage prices found in the case study are generally higher than the incremental costs of drayage and that total current expenditures for drayage are much higher than those of an optimized system—even after allowing for inevitable cost escalation from the model estimates—the cost of the drayage component of intermodal door-to-door prices can be reduced substantially. Thus intermodal carriers could reduce the door-to-door rates for the service, increasing its competitiveness with over-the-road trucking, and also retain some of the cost savings as added profit. This would help to overcome the widely reported low profitability of intermodal to the rail carriers in many markets.

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Intermodal Container Ports: Application of Automatic Vehicle Classification System for Collecting Trip Generation Data

TATHAGATA GUHA AND C. MICHAEL WALTON

With the evolution of containers and growth in intermodalism, intermodal seaports have experienced a tremendous growth in containerized trade associated with international and domestic trade. With the increase in port activity has come a comparable increase in port landside traffic. The results of a case study of a container port (Houston's Barbours Cut) are reported, and the impact of existing container port operations on urban infrastructure and mobility is addressed. The application of an automatic vehicle classification system used to collect the necessary traffic data is presented. Commercially available photoelectric sensors were used to collect accurate traffic volume and classification data over a period of 7 days. The data collection procedures provide quantitative information on the traffic characteristics of the container port. Mathematical models were then developed to accurately forecast travel demand for use in planning and designing transportation facilities. The results of the analysis provide trip generation rates for both average weekday and peak hour of generator, and they show the variation in traffic demand by vehicle types. The existing trip rates calculated were consistent with the ITE trip generation rates. The other interesting finding is that only 30 percent of the total traffic were container trucks; the rest were two- and three-axle vehicles.

Intermodal freight transportation involves the movement of goods using various modes of transport. The concept of intermodal freight transportation began to be used widely in the late 1950s (*1*). It eased the transfer of freight from one mode of travel to another. An intermodal transfer is the movement of goods or commodities between two modes. The modes are as follows: by water, ocean vessels, coastal vessels, and inland waterway barges; by air, airplanes and helicopters; and by land, rail freight trains, highway trucks, belt conveyers, and pipelines (*1*).

One of the most significant forms of intermodal shipping is containerization. The cargo is packed in a container, which can be used for several modes of travel: ship, railroad, truck, and airplane. The use of these containers has improved intermodal transfer of general cargo to a great extent. After the 1956 "container revolution," containerization of ocean cargo for intermodal purposes was widely practiced (*1*). Well over 60 percent of the world's deep-sea general cargo is containerized (*1*). Recent studies indicate that containerized traffic would grow to 430 million mt in 1990 and 607 million mt by 2000 (*2*). Figure 1 shows an optimistic forecast of container growth by world port regions in 20-ft equivalents (TEUs) between 1978 and 1998 (*3*).

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Container movements have continued to increase at United States ports and are expected to rise in the future. Today about 80 percent of all U.S. liner trade by volume is containerized. In 1991 the ports of Los Angeles, New York, and Long Beach were among the top three in the United States with 2.03 million, 1.86 million, and 1.76 million TEUs throughput, respectively. Port of Houston handled 0.53 million TEUs in 1991 (*4*). Figure 2 shows the increase in container throughput for a few selected container ports in the United States between 1983 and 1991 (*4*).

As ocean carriers seek to reduce costs and receive higher percentages of open ocean operation from their ships, they confine their operation to fewer ports of call, relying on the ground transportation network for more of the cargo's movement (*5*). Inland transport to and from the ports may be by coastal waterways, road, rail, or a combination of road and rail. Providing access for coordinating the interface of two or more different modes of transportation systems is essential (*1*). The inland distribution of the cargo depends on the local market area of each individual port (*6*). Railroads' intermodal service is price competitive with that of trucks on traffic movements of more than 500 mi for containers and 700 mi for trailer on flatcars (*7*). The modal split at Port of New York–New Jersey is 96 percent truck and 4 percent others (*6*) (pipeline, barge, or on-site use). At San Francisco, 71 percent is carried by trucks, 20 percent by rail, and the remaining 9 percent by other modes (*8*). At Houston's Barbours Cut container facility, 95 percent of containers use trucks and only 5 percent rail (T. Guha, unpublished data). The landside network must be extensive for the cargo to be moved at higher peak volumes and for greater distances.

International and domestic trade through seaports has increased to a great extent, and containerized freight movements have facilitated this growth. Trucking continues to dominate the movement of containers to and from ships at U.S. ports (*5*). Good ground access facilities are needed to move the goods quickly and efficiently through the ports (*9*). The rise in container traffic has increased landside traffic to and from the port terminals. Traffic congestion due to the increased truck and automobile volumes near the port is becoming an issue that should be addressed.

CASE STUDY SCOPE AND OBJECTIVES

To plan an efficient ground access system, it is first necessary to determine the impact of port-related traffic on the urban

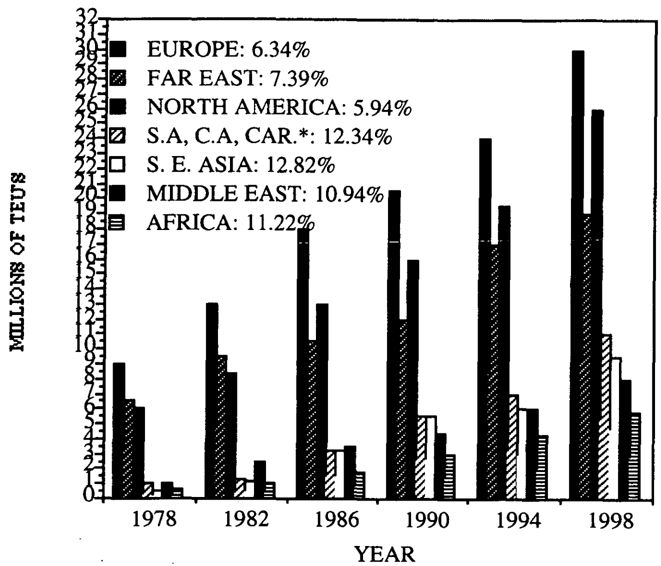

FIGURE 1 Containers handled by world port regions 1978–1998, optimistic forecast.

roadway network to ascertain the extent to which the existing system can accommodate the increased movement of containers and other traffic. The objective of the paper is to present the findings of a case study of the landside traffic characteristics of an existing container port. The research that provides the basis of the paper explored the traffic generation associated with a container port, the methodologies and techniques of collecting landside traffic and vehicle data, and the association with typical container port components. From this study, recommendations are made for further, more detailed experiments necessary to characterize container ports and their landside traffic characteristics.

Container port operations in the Port of Houston were observed and documented. Containers are usually 20 or 40 ft in length. However, containers of other sizes—45, 48, and 53 ft—are also being used. The containers are carried by five-axle tractor-trailers to and from the port, yet they represent only 30 percent of the total traffic typically using the terminal (*10*). Therefore, it is necessary to consider all types of vehicles that make up port traffic. Traffic volume and classification data can be collected manually or automatically. Though manual collection seems to be the most accurate, it is labor intensive and expensive. Automatic counters are used to obtain a larger data base for vehicle counts and are being supplemented by manual classification and vehicle occupancy data. Recently, infrared sensors (*11*) have been used to count and classify vehicles accurately. These sensors, when properly designed and installed, can be used to obtain a variety of information about traffic characteristics. In an effort to collect data regarding vehicle volumes and classification for this study, such sensors were used to count and classify vehicles entering and exiting the site at Houston's Barbours Cut Terminal (*10*). The classification criteria used for design of photoelectric sensors in this study include number of axles per vehicle and number of containers carried per vehicle.

After the data were collected, the impact of port-related traffic on the surrounding highway network was assessed. Many mathematical models have been developed by transportation professionals to describe various relationships between land use and travel. The ultimate goal of the modeling is to replicate actual travel and facilitate the forecast of traffic volume ousted by similar land usage.

There are traffic-generating characteristics associated with various land use categories, and appropriate roadway facilities to accommodate the trip demands are required *(11)*. Transportation demand is affected by a number of factors, such as land use character, intensity of land use, and location. The amount of travel and its characteristics are functionally related

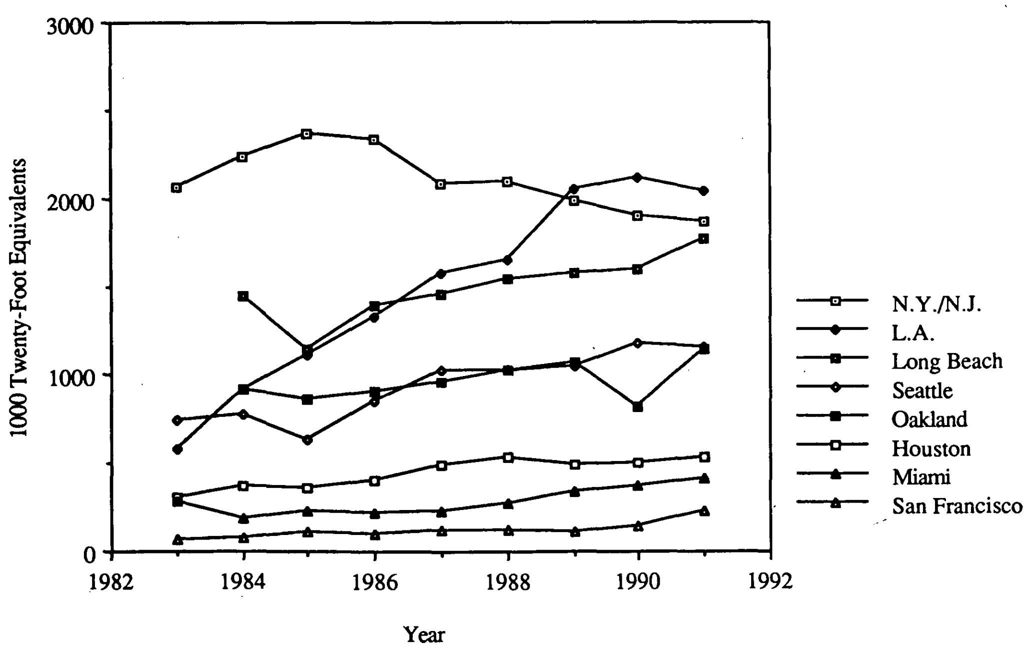

FIGURE 2 Total container movements by selected U.S. ports.

to the use of land. Trip generation analysis is important in a number of phases of transportation planning and traffic engineering activities. One of the uses of trip generation is to assess the impact of a new or existing development on surrounding transportation infrastructure (*12*).

Land development also has an impact on the existing facilities because of the increase in trip attractions and productions, which can create the need for transportation system improvements.

By collecting data on trip generation rates at existing sites of a particular land use category (or categories if a mixed use site), the information can be used, within certain limits, to estimate vehicle trips expected to be generated by other similar land development projects (*13*). Likewise, container terminals affect the roadways adjacent to the port area because of the traffic that is directly associated with the terminal. It is necessary to calculate and document trip rates of these types of land uses for use by transportation professionals in the same manner in which trip rates for other land use categories are used.

Only seven trip generation studies have been documented for seaports (*14*). Trip generation studies on seaports have used only land area, number of berths, and revenue tons throughput as independent variables to calculate trip rates. Trip rates were calculated for an average weekday because of insufficient data. This study uses an automatic vehicle classification system to collect detailed data on travel demand patterns for the container port. The demand patterns have been related to land use characteristics used in previous trip generation studies, and a new land use characteristic has been included in the calculation of trip rates: TEUs.

DATA COLLECTION

This study focused on the Port of Houston's Barbours Cut container facility. Field traffic volume counts were performed at the site, and data were also collected on the independent variables of the site. Then actual trip generation rates were calculated for average weekday, a.m. and p.m. peak hour of the generator.

Site Configuration

Barbours Cut has three access roadways leading into the terminal. Trucks and other vehicles used these roads. The main road is a public road and is the main access to the terminal. It has two 12-ft lanes in each direction divided by a median. The other access is a private, two-directional road, which is mainly used for carrying containers that are taken to the railhead, from where it is distributed to the final destination.

Initial visits to the site were made to observe the traffic flow and select the most suitable spot for installation of the automatic vehicle classification equipment. The system was set up at the site so that all entering and exiting vehicles were counted and classified. Each system consisted of photoelectric sensors and reflectors mounted on steel posts on either side of the road. Two such systems were set up on the public road for each direction to count and classify entering and exiting vehicles. It was observed that vehicles on the two-lane entry and exit roads seldom passed each other, and therefore very rarely did two vehicles cross the sensor beams at the same time. Hence, the error of counting two vehicles as one was negligible. The third system was set up on the private road. That system counted vehicles irrespective of their direction. Manual counts were made during the data collection period to adjust the directional distribution on this road. Data were collected using this methodology and then were input into the trip rate calculations.

Automatic Vehicle Classification System Arrangement

At Barbours Cut Terminal an effort was made to collect data on traffic volumes and vehicle classification by using photoelectric sensors. The procedure included designing the needed hardware and software and installing the systems at selected field sites so that the desirable data could be collected. Commercially available photoelectric sensors were used to acquire traffic data for a period of 7 consecutive days, 24 hr per day, or 168 hr of data. These sensors, along with microprocessors, made up the data collection system.

The sensors were arranged at the sites to allow all vehicles to be counted and classified. The classification data required for this study and from the data collection system were (*a*) number of axles (six or more, five, four, three, or two) and (*b*) container length (20 or 40 ft).

As previously stated, photoelectric sensors were installed on the roadside at the site. The sensors and the reflectors were mounted by using steel posts and other diagonal support. The sensor and the reflector arrangements S1, S2, S3, S4, and S5 and R1, R2, R3, R4, and R5, respectively, of each system are shown in Figures 3 and 4. These sensors can be used to collect different types of data, such as

- Vehicle counts,
- Vehicle classification,
- Vehicle speed,
- Spacing between successive axles,
- Approximate size of the tire/pavement contact area, and
- Overall dimension of the vehicle body (*9*).

Batteries were used to provide power to the sensors. The sensors used an infrared light beam to detect the presence of vehicles. The beam was focused on a reflector located across the roadway from which it was reflected and sent back to the

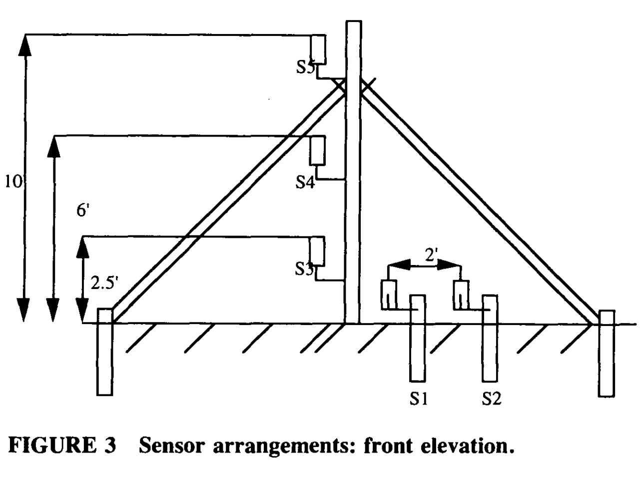

FIGURE 3 Sensor arrangements: front elevation.

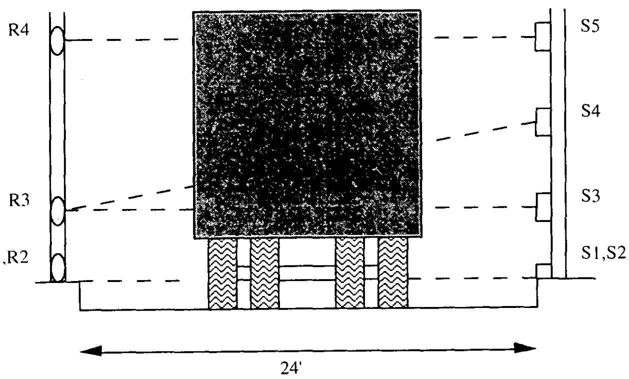

FIGURE 4 Photoelectric sensor system to count and classify vehicles.

receiver and transmitter located in the sensor head. The beam, when interrupted, generated a signal to detect the presence of the vehicle body.

Two pavement-level sensors (S1 and S2), which were spaced 2 ft apart, were used to count the number of axles per vehicle. This also enabled calculation of the speed of the vehicles by dividing the distance between sensors by the time between successive beam interruptions. The speed data were then used to find the length of the containers. To determine the overall vehicle length, two sensors (S3 and S4) were mounted about 2.5 and 6 ft above the road level and placed at such an angle that all of the vehicle presence time was detected. To differentiate trucks from passenger cars and pickups, a sensor (S5) was mounted approximately 10 ft above the roadway at the roadside. This also provided information pertinent to determining the length of the containers.

Traffic Volume Counts

A detailed trip generation study was conducted at the Barbours Cut facility to estimate the vehicle trips generated at or attracted to the site. Automatic counters (photoelectric sensors) as described in the previous section were used to collect traffic data. The equipment was designed and deployed at the site in such a way that vehicles passing the sensors were divided into those entering and those exiting the port. The data were collected for 15-min intervals over 7 days. Manual counts were conducted at the site during the peak hours to test the accuracy of the sensor equipment. Table 1 summarizes the vehicle trip ends, which are the sum of entering and exiting vehicles for weekdays and peak hours of the generator as collected at the site.

Independent Variables

Another part of the data collection phase of trip generation calculations involved compiling data on independent variables of the site. For this study, information was gathered on total acreage of the site, revenue-tons of cargo throughput, number of ship berths, and container throughput (TEUs). These data were provided by the terminal manager. Land area in acres, revenue-tons, and number of ship berths were chosen for this analysis because these variables have been used previously as input into trip generation calculation *(14)*. In actual practice, data for all these variables may not be readily available; therefore, it is helpful to have the ability to estimate vehicle trips based on more than one variable. Most container terminals have TEUs instead of revenue-tons of cargo as their productivity unit. Therefore, the TEU was established as another independent variable for use in calculating trip rates. Table 2 is a compilation of the land use characteristics.

Vehicle Classification

In trip generation studies, information about the types of vehicles that constitute the total traffic is valuable. Because of increases in container traffic, there has been an increase in the number of trucks to and from these facilities. The typical vehicular unit is a five-axle truck with a 20- or 40-ft container. There are also four-, six-, seven-, and occasionally eight-axle trucks. Other than these trucks, two- and three-axle vehicles enter and exit the port for a variety of purposes. The two-axle vehicles are usually service vehicles, employees' personal vehicles, or other purpose vehicles and are typically pickups, single-unit trucks, or passenger cars. The three-axle traffic is mainly bobtails (a truck without a trailer). The variety of vehicle types entering and exiting a container port suggested that it was important to consider all traffic related to the facility. Data were collected at the site to document the types of vehicles that entered and exited the facility.

TABLE 2 Independent Variables

Independent Variables	Barbours Cut Facility
LandArea(acre)	230
Revenue-Tons(per week)	83333
Twenty Foot Equivalents(per week)	4413
Ship Berths	4

TABLE 1 Total Vehicle Trip Ends at Site

DAYS	24 hour vehicle trip ends			A.M. peak hour vehicle trip ends			P.M. peak hour vehicle trip ends		
	IN	OUT	TOTAL	IN	OUT	TOTAL	IN	OUT	TOTAL
MONDAY	1453	1776	3229	160	180	340	170	200	370
TUESDAY	1734	2071	3805	170	192	362	178	168	346
WEDNESDAY	1864	2325	4189	166	246	412	176	215	391
THURSDAY	1785	2367	4152	166	273	439	180	222	402
FRIDAY	1703	2122	3825	155	252	407	156	182	338
SATURDAY	499	555	1054	31	35	66	43	53	96
SUNDAY	672	792	1464	33	34	67	90	72	162

DATA EVALUATION

Trip Generation Analysis

Actual trip generation rates of the sites were computed by developing mathematical relationships between measured traffic volumes and the independent variables. Trip rates are expressed in terms of independent variables. Depending on the duration of the data collected, trip rates are calculated for average weekday trip ends, a.m. and p.m. peak hour of generator trips.

After collecting the data, trip generation rates were calculated. With the above data, average weekday trip rates were calculated for the site with respect to land area (per acre), ship berth (per berth), and revenue-ton throughput (per ton). In the calculation of average weekday trip rates, an average of the trip ends over a period of 5 days was calculated and then divided by the independent variable unit. Since data were collected over a period of 7 days and information about the independent variable TEU was also available for this period, weighted average weekday trip rates were calculated by summing all trip ends and all independent variables and then dividing the sum of trip ends by the sum of the independent variable units for Monday through Friday. Tables 3 and 4 present examples of the procedures performed to calculate average weekday trip rates and weighted average weekday trip rates, respectively. Data were collected for 15-min intervals and were tabulated to determine the peak-hour traffic volume for each day at the site. After identifying the peak hours of operation, a.m. and p.m. rates were calculated. Peak hour of the generator rates for a.m. and p.m. and weighted average weekday trip rates are summarized in Tables 5 and 6, respectively.

TABLE 3 Peak Hour of Generator Trip Rates per Berth (Sample Calculation)

TOTAL TRIPS:	
PEAK HOUR OF GENERATOR (11:00 A.M.-12:00 P.M.)	
	TOTAL
Vehicles Entering:	166
Vehicles Exiting:	273
	439
Percent of Vehicles Entering:	166/439 = 38%
Percent of Vehicles Exiting:	273/439 = 62%
Trip Rate:	439/4 = 109.75 Trips per Berth

TABLE 4 Average Weekday Trip Rate per TEU (Sample Calculation)

TOTAL TRIPS	
Trip Ends:	19200
Total TEU's:	4413
Percent of Vehicles Entering	48%
Percent of Vehicles Exiting	52%
Average Weekday Trip Rate:	19200/4413 = 4.35 Trips per TEU

Vehicle Classification

Considerable effort was made to record the vehicular volume and class for the study site. The data were collected over a period of 7 days and checked for accuracy before being used in the analysis. After the equipment was installed, 15-min manual counts were made to validate the automatic counts.

During a validation check it was observed that the equipment was recording more vehicles with six or more axles and too few five-axle vehicles, although the total number of vehicles was correctly recorded. It was found that some trucks had mud flaps behind the front and rear wheels that were hanging so low that they were almost touching the surface of the road and would on some passes be registered as another axle. The sensors were placed as low as possible to eliminate the error, but without complete success. To adjust for this error, manual classification counts were performed to get a percentage distribution of five-axle vehicles that were erroneously registered by the equipment as having six or more axles. It was found that about 73 percent of those vehicles placed in the class of six or more axles were actually five-axle vehicles. This facilitated a calibration of the classification distribution.

TABLE 5 Peak Hour of the Generator Trip Rates

DAYS	Average Trip Rate for Peak Hour of the Generator							
	Per Acre		Per Berth		Per Revenue-Ton		Per TEU	
	A.M.	P.M.	A.M.	P.M.	A.M.	P.M.	A.M.	P.M.
MONDAY	1.47	1.6	85	92.5	0.02	0.02	0.34	0.37
TUESDAY	1.57	1.5	90.5	86.5	0.02	0.02	0.44	0.42
WEDNESDAY	1.79	1.7	103	97.75	0.02	0.02	0.51	0.48
THURSDAY	1.9	1.74	109.8	100.5	0.02	0.02	0.45	0.42
FRIDAY	1.74	1.46	100.5	84.5	0.02	0.02	0.47	0.39
SATURDAY	0.28	0.41	16.5	24	0	0	0	0
SUNDAY	0.29	0.7	16.75	40.5	0	0	7.44	18

TABLE 6 Weighted Average Weekday Trip Rates

Average Week Day Trip Rate			
Per Acre	Per Berth	Per Revenue-Ton	Per TEU
16.69	960	0.23	4.35

The results of the field survey indicated that 30 percent of total traffic was container truck traffic. The rest consisted of passenger cars, pickup trucks, and truck-tractors (bobtails). Table 7 presents the percentage variation of each vehicle class for each day. As expected, vehicles with five or six or more axles were negligible on weekend days because of the closure of the terminal on those days.

SUMMARY AND CONCLUSION

This paper presents the results of a case study of a single container port, the Barbours Cut Terminal in the Port of Houston. The case study focused on obtaining primary data in an effort to characterize the trip production and attraction associated with the container facility and its operation.

It is recognized that the observations may not be transferable to other container ports; however, the methodology and data collection techniques may lead to other efforts that will enrich our appreciation of landside traffic characteristics. A search of the published literature and reference material suggested that limited data are available for similar efforts. However, the growth in containerization and forecasts for increasing activity suggested that landside access will in all likelihood become a much higher priority issue among state and local transportation and port management officials. To appreciate the relative impact of container port operation on landside traffic conditions, more complete information must be available to guide investment decision and evaluate alternative recommendations.

It is recognized that there are seasonal variation in commodity flow, variance in vessel calls at respective ports, changes in intermodal transshipments, and directional splits that represent only some of the traits affecting container ports. This effort begins the documentation of such activities.

FINDINGS

Trip generation rates for the peak hour and for average weekday were calculated from the data collected for the Barbours Cut Terminal in the Port of Houston. These rates, using a set of newly defined independent variables, are total values that include automobile trips. Although the rates may vary by season and other factors affecting port operations, the TEU was found to be a significant variable in explaining trips for the container port facility and may be important in studies of other container facilities.

Average weekday trip rates for total vehicles (trucks and automobiles) as calculated in the analysis section were 16.69 trips/acre, 960 trips/berth, 4.35 trips/TEU, and 0.23 trips/ton. An effort was made to calculate peak hour of generator trip rates, both morning and evening. The directional distribution of traffic entering and exiting the site was measured. The average weekday directional percentages entering and exiting were 53 and 47 percent, respectively. The peak hour differed for each day, as did the directional splits.

Vehicle classification represented a significant effort in this case study. Container terminals do not document the actual percentage of types of vehicles that use the port. This case study provides information on the classes of vehicles that make up port traffic, measured in 15-min intervals over a period of 7 days and grouped by number of axles. The analysis indicated that only 30 percent were trucks, 60 percent were automobiles (cars, pickups, and two-axle trucks), and the remaining 10 percent were three-axle trucks (bobtails).

Similar studies of different container facilities in the United States are needed to develop a more comprehensive understanding of container port characteristics. Because of steady increases and anticipated growth in container tonnage through U.S. ports, further studies are needed to guide future investments to improve landside access. Studies should also focus on negative consequences of container growth, such as the contribution of truck traffic to traffic congestion and related air quality issues. This case study represents a limited initiative in this larger vision.

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TABLE 7 Percent Variation of Vehicle Classes (Monday–Sunday)

DAYS	2 AXLE	3 AXLE	4 AXLE	5 AXLE	6/MORE AXLE
MONDAY	58	11	5	16	10
TUESDAY	58	11	4	19	8
WEDNESDAY	63	10	5	15	7
THURSDAY	63	10	4	16	7
FRIDAY	60	10	5	18	7
SATURDAY	82	10	4	3	1
SUNDAY	80	11	6	2	1

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Time-Motion Analysis of Wharf Crane Operations

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Numerous queueing models are available that are appropriate for modeling wharf crane operations. When used correctly, the models provide an excellent way to assess the efficiency of container port operations. The majority of queueing theory applications assume that exponential distributions adequately describe the service and arrival processes, primarily because of the tractable solutions that result. Regardless of the assumption's simplifying effect, its suitability should be questioned before applying it to any analysis. The appropriateness of the exponential distribution for analyzing service, interarrival, and backcycle processes at container port wharf cranes is determined, and suitable distributions should the exponential distribution prove inappropriate are investigated. Interarrival and service times were recorded for all tractors servicing wharf cranes for a total of more than 30 hr at two United States ports. The formation of the data set used for the analysis, the testing procedure used to determine the most appropriate distribution, and the results of the analysis are described. It is shown that service times, interarrival times, and backcycle times used in queueing analysis should not always be modeled as exponential distributions, contrary to popular belief.

In today's competitive freight industry, where speed is required or at least desired, the ability to efficiently move freight can control how successful ports, freight forwarders, and shippers are in business. Since total transport time can be substantially increased by a breakdown in a single link, each leg of the journey must operate efficiently to ensure expeditious freight transportation. This becomes increasingly difficult in intermodal transportation where freight travels through any number of freight terminals—the primary source of excessive delays. Since terminals are the only segment of a journey in which freight is not moving toward its destination, the time spent in the terminal can make or break an efficient journey. Unfortunately, container ports are more often than not the source of long delays relative to total transport time.

Simply stated, container ports are critical interfaces in the efficient movement of international containerized freight from the viewpoint of both the customer and the shipper. A manifestation of this demand for speed is an increase in the research on container port operations, the primary goal of which is to develop and implement techniques to streamline operations and improve efficiency. In 1990, researchers at the University of Texas at Austin embarked on a series of such studies. This paper focuses on one component of these studies.

Much of the research at the University of Texas relied heavily on queueing theory to evaluate operations surrounding the wharf crane. Kiesling (*1*) analyzed wharf crane productivity at two major container ports in a three-step process. First, several statistically significant factors affecting wharf crane productivity were identified. Second, several queueing models were applied to the loading and unloading cycle associated with wharf cranes and storage yards. Third, computer simulations were developed to determine the benefits of modifying operations. This paper deals primarily with step two of the research effort and provides insight into arrival and service processes associated with wharf crane operations. Ultimately, this enables researchers to more accurately specify queueing models commonly used in analyses of port operations. This, in turn, leads to improvements in the management of container port operations by specifying improved wharf crane service configurations (such as specifying optimal number of tractors in system and their service protocol toward wharf cranes).

Most queueing theory applications are built on the assumption that exponential distributions correctly describe the service and arrival processes of the system. One reason for the exponential assumption is that the resulting models are mathematically tractable and typically result in closed-form solutions for single server and cyclic queues. Regardless of the exponential distribution's elegance, its suitability in any queueing application should be validated. (To the authors' knowledge, there have been no published works validating the assumption of exponential arrival and service processes of tractors at the wharf crane.)

Existing wharf crane performance studies generally assume exponential interarrival and service time distributions without validation. The objective of this paper is to assess the validity of that assumption. The most effective way to assess the suitability is through a time-motion study of the service facility in question. If the assumption is not suitable, it is necessary to determine what distributions can be used to accurately describe the system. Knowing this will improve the accuracy of container port operational models. In turn, it will be possible to more accurately specify the number of cranes and tractors and an operational configuration that maximizes the efficiency of ship loading and unloading.

Toward the goal of specifying correct distributions, arrival and service times were recorded for all tractors servicing wharf cranes at two major United States container ports. For anonymity, the ports will be referred to as Port 1 and Port 2, and ships will be assigned letter names (A-G). The remainder of this report documents the data collection procedure, the analysis of the data, and the conclusions that can be drawn from the analysis.

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EXPERIMENTAL ENVIRONMENT

Loading and unloading procedures at most container ports are conceptually similar. While unloading a containership, a cycle is formed that involves a tractor and chassis accepting a container from a wharf crane, carrying it to the storage yard where it is removed and stacked, and returning to the wharf crane where another container is received. (In the event that containers are stored in the yard on the chassis, a bobtailed tractor picks up another chassis before returning to the wharf crane.) This cycle is reversed for the loading of a containership. In general, six or seven tractors serve one wharf crane during this process. Atkins (*2*) provides an excellent description of the containership loading/unloading process.

Three elements of the cyclic queue are examined in this paper: the service process, the arrival process, and the total cycle of tractors. At the container port, the service facility is the wharf crane, and customers are the tractors serving the crane. The service provided by the single server facility is the removal of a container from the chassis of the tractor or the placement of a container onto the chassis. The service time is defined as the difference between service completions of succeeding tractors. Thus, the first tractor in queue (if a queue is present) begins service immediately after the preceding tractor completes service. The service time includes the move-up time [see Carmichael (*3*)]. Similarly, the interarrival time is the time between consecutive arrivals of tractors into a queue or at the wharf crane if no queue exists. The backcycle time is the time to complete a full cycle through the storage yard (in other words, the difference between the departure from the service facility and the arrival at the crane or queue). To identify the correct time distribution, we record the service, interarrival, and backcycle times for a large number of tractors. Given a sample of such measurements, we then test what theoretical distribution best describes the empirical distribution. This process is described in the following sections.

CREATION OF THE DATA SET AND INITIAL DATA ANALYSIS

Data for this research effort were collected at two United States container ports. Four different operating entities were represented. Two ports are privately operated and two are publicly operated. Two of the ports use chassis storage as opposed to container stacking. In each case, wharf cranes were rail-mounted, single-pick cranes with adjustable spreader bars and adequate clearance to move 48-ft containers. Yard cranes were rubber-tired cranes with clearance for stacking containers four deep and up to five container widths, or top-pick loaders capable of stacking containers three deep. The type of yard crane associated with each data file is identified later in this report.

The time-motion experiment was based on the coded events described in Table 1. The code "999" was included in the list to permit recording any nonstandard tractor or crane operations, including tractors balking from queues, hatch cover removals, lashing, movement between bays, and spreader adjustments. Such nonstandard operations were noted in the field through the use of microcassette recorders and later corrected in the actual data files. The tractor number was also recorded to permit tracking gang members through the cycle.

The exact time of events was recorded with programmable Hewlett-Packard calculators. A simple program prompted first for the tractor or crane number, then for a predefined event code. Event times were recorded to the nearest second, more accuracy than necessary since tractors and cranes often "inch" forward at the beginning or end of an event. Data were then uploaded to desktop computers and immediately transferred to spreadsheets, minimizing the potential for human error. Multiple port visits resulted in a total of 16 data files. Each filename identifies the date and time of day it was created (e.g., Feb11a.1, the first file created on February 11 in the morning). Data files created in March are associated with top-

TABLE 1 Data File Code Description

Code	Description of Event
1	Tractor enters queue. (wheels of tractor stop rotating)
2	Tractor completes move-up procedure. (wheels of tractor stop rotating)
3	Tractor departs service. (wheels of tractor begin rotating)
3.1	Placement of first container during double container moves. (tractor remains in service position)
3.2	Service completion of double container move. (wheels of tractor begin rotating)
4	Beginning of crane movement from one bay to another. (wheels begin rotating)
5	Completion of crane movement from one bay to another. (wheels stop rotating)
6.0 (6.1)	Beginning of crane idle period with zero (one) container.
7.0 (7.1)	End of crane idle period with zero (one) container.
8	A tractor that was in queue, balks.
999	Special event or comment about crane or tractor operations.

pick loaders operating in the storage yard. Table 2 provides a sample of the Jan7p.1 data file.

The 16 data files represent 31 hr 10 min of data collection. The individual data files cover time periods ranging from only 30 consecutive min to more than 5 hr. Short observation periods were caused by service interruptions such as lashing/unlashing, hatch cover removal, crane movements, mechanical failure, equipment changes, or other unexpected operational problems. Table 3 summarizes the results of the data collection effort. Seven ships are represented in the 16 data files, all of which are cellularized vessels. The crane productivity averaged 28.6 container moves per hour with a standard deviation of 6.1 moves per hour. Maximum productivity achieved was 37.1 moves per hour for the observation period of 1 hr 20 min, a substantial period of time to maintain exceptionally high productivity. Minimum productivity was only 13.3 moves per hour over a span of 1 hr 7 min. This includes at least one significant delay, which deflates the reported crane productivity (the same crane provided the fastest average service time of 40 sec/tractor).

There is a high variance of service, backcycle, and interarrival times between and within individual files. Reasons for this are as follows. First, the stowage location of the container on the ship significantly affects how quickly a container can be placed or removed. Restows on the ship can also inflate average service times. Other factors that delay service times have already been discussed. Backcycle times are controlled primarily by the distance from the ship to the yard storage location and the speed at which the container can be transferred in the yard. This will vary between ships, as well as throughout the ships' loading/unloading plan. Thus, if yard delivery locations change within the time frame of a data file, the backcycle times will also change, increasing its variance. Ideally, then, there should be more than one distribution assigned to describe backcycle times throughout the loading/unloading process. The same argument applies to service and interarrival times. It may seem most appropriate to specify several different distributions for service, interarrival, and backcycle times to describe various stages of the loading/unloading process. The result would be the ability to optimize the number of tractors in a gang for each phase in the loading/unloading process. Obviously, decisions are not made this way in practice—the same number of gang members serve a crane from start to finish. To coincide with this practice, we will focus on specifying a single distribution for service, interarrival, and backcycle times through the duration of servicing a ship. In other words, we will not try to specify different distributions for the movement of containers only on top of the hatch covers, or being delivered to one part of the storage yard. The process of testing and specifying various time distributions is presented in the following sections.

TABLE 2 Field Data Extracted from Jan7.p1 Data File

Event	Tractor	HH:MM:SS	Queue	Interarrival Time	Service Time
no event	no event	14:05:14	1		
2	921	14:05:43	0	0:00	
1	952	14:08:26	1	4:51	
1	922	14:09:21	2	0:56	
3	921	14:11:25	2	0:00	5:41
2	953	14:11:46	1	0:00	
1	950	14:12:25	2	3:04	
3	953	14:13:35	2	0:00	2:10
2	952	14:14:03	1	0:00	

ERLANG DISTRIBUTION

When the exponential distribution's validity is questioned, a common alternative to consider is the Erlang distribution. The Erlang distribution is very flexible and, depending on the selection of parameters, transforms into the exponential, normal, and constant distributions, as well as many distributions "in between" [see Winston (4)]. The density of the Erlang distribution is specified by two parameters: a rate parameter R and a positive shape parameter k. The rate parameter is the inverse of the mean of the sample under consideration. The Erlang probability density function is

$$f(t) = \frac{R(Rt)^{k-1}e^{-Rt}}{(k - 1)!} \tag{1}$$

where $E(T) = k/R$ and $\text{var}(T) = k/R^2$.

Inspection of the Erlang probability density function (pdf) reveals that when $k = 1$, the Erlang reduces to the exponential density. As the shape parameter k increases, the variance of

TABLE 3 Initial Data Analysis

File	Moves per hr	Service Times # Obs	Mean	St Dev	Interarrival Times # Obs	Mean	St Dev	Backcycle Times # Obs	Mean	St Dev
Jan7p.1	26.2	60	1:40	1:20	59	2:36	2:05	50	12:39	8:57
Jan7p.2	28.7	37	1:17	1:11	39	2:05	1:49	26	11:13	3:23
Feb11a.1	30.5	41	1:44	0:42	44	1:50	1:05	34	5:13	1:43
Feb11a.2	27.9	37	1:09	0:45	38	2:10	1:40	21	9:34	10:26
Feb11p.1	28.0	74	1:40	1:31	74	2:37	2:21	62	12:02	7:58
Feb12a.1	23.8	27	1:23	1:22	29	2:35	2:09	6	16:36	2:47
Feb12a.2	13.25	15	0:40	0:25	16	3:53	5:44	11	17:49	11:35
Feb12a.3	36.3	22	1:40	0:34	22	1:36	1:12	16	6:22	1:22
Feb12p.1	33.3	53	1:33	1:03	48	1:51	2:27	39	6:35	1:35
Mar7p.1	36.2	30	0:48	0:21	27	1:49	2:02	17	9:24	6:21
Mar7p.2	37.1	47	1:00	0:26	43	1:49	2:45	43	5:00	2:58
Mar8a.1	24.1	25	1:32	0:41	21	2:03	1:36	21	8:09	4:51
Mar8a.2	33.2	17	1:50	0:49	14	2:00	1:09	14	3:44	0:30
Mar8p.1	24.1	61	1:25	1:02	65	2:19	2:41	47	6:27	4:46
Mar9p.1	25.1	118	2:09	1:22	97	2:15	1:44	89	6:31	2:04
Mar9p.2	29.7	128	1:36	1:12	136	1:57	1:54	133	7:20	4:48

the pdf decreases, causing the density to behave more like a normal density function. For extremely large values of k, the Erlang density approaches a constant density (zero variance).

The shape parameter of the Erlang distribution has a powerful yet simple interpretation. Consider a process that is described by an Erlang distribution with parameter k. The process is actually composed of k exponential service phases that occur in series. Each of the k phases follows independent and identically distributed exponential random variables, each with a mean of $(1/\mu k)$, where μ is the mean service rate. Only one customer at a time is allowed in the system of phases, and each customer must complete all k phases of the system.

TESTING METHODOLOGIES AND DISTRIBUTION TEST RESULTS

The individual data files were tested two ways. Initially, the chi-square test was used to determine whether the exponential distribution was appropriate. Initial analyses indicated that this was seldom the case. The Kolmogorov-Smirnov (K-S) statistical test was used extensively to further test the distributions. The K-S test has several inherent advantages over the commonly used chi-square test for this application, including the ability to compare theoretical and empirical data by considering cumulative distributions instead of categorized data. In the remainder of this paper, the null hypothesis is that data were drawn from the tested distribution. The test is executed by comparing cumulative distribution functions of theoretical and sample distributions. The test statistic, D, is the maximum absolute difference between the two distributions. If the difference between the cumulative distributions is greater than that allowed by the test statistic, the null hypothesis is rejected.

Although the primary objective of the tests is to specify the distribution that best describes the service, interarrival, and backcycle times, other events were tested. For example, whenever double moves were captured within a data file, tests were performed on single, double, and combined service and interarrival times. Also, if two or more data files were created for the same ship, the tallied service and interarrival times were combined and the tests performed again on the new data file.

The test results are presented in Tables 4, 5, and 6, representing service times, interarrival times, and backcycle times, respectively. Each table represents statistical tests for a significance level of $\alpha = 0.05$. Note that the majority of the files tested allow several possible distributions. The best-fit distribution is considered the distribution with the smallest maximum deviation. However, the null hypotheses that the exponential, E(3), and E(4) distributions are the same as the sample distribution cannot be rejected at the $\alpha = 0.05$ significance level. Erlang distributions with shape parameters greater than seven were not considered. Such distributions become extremely laborious to analyze. If there is reason to believe that a distribution should be described by shape parameters higher than seven, a secondary shape parameter estimation procedure exists. Carmichael (*3*) illustrates the simple derivation leading to the following estimation for k:

$$k = (\text{mean})^2/(\text{stdev})^2 \tag{2}$$

TABLE 4 Service Time Distribution Tests

Data File	K-S Statistic	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)
Jan7p.1	0.175	0.144	**0.070**	0.136	0.177	0.207	0.236	0.260
Jan7p.2	0.218	0.164	0.158	**0.149**	0.176	0.205	0.2300	0.251
Feb11a.1	0.212	0.344	0.242	0.195	0.161	0.151	0.143	**0.135**
Feb11a.2	0.218	0.228	0.154	0.134	**0.120**	0.146	0.174	0.196
Feb11p.1	0.158	0.165	**0.114**	0.116	0.147	0.171	0.192	0.206
Feb12a.1	0.254	0.198	**0.178**	0.190	0.234	0.268	0.297	0.321
Feb12a.2	0.338	0.262	**0.152**	0.188	0.222	0.250	0.274	0.295
Feb12a.3	0.251	0.458	0.362	0.305	0.262	0.229	0.202	**0.198**
Feb12p.1	0.186	0.352	0.245	0.236	0.234	0.230	0.227	0.222
Mar7p.1	0.242	0.264	0.198	0.166	0.143	0.126	**0.116**	0.130
Mar7p.2	0.198	0.339	0.252	0.201	0.164	0.134	0.108	**0.087**
Mar8a.1	0.264	0.300	0.168	**0.094**	0.095	0.099	0.105	0.111
Mar8a.2	0.318	0.427	0.325	0.263	0.218	0.183	0.169	**0.165**
Mar8p.1	0.174	0.154	**0.070**	0.119	0.156	0.187	0.214	0.236
Mar9p.1-single	0.132	0.379	0.254	0.181	0.191	0.203	0.214	0.222
Mar9p.1-double	0.361	0.437	0.346	0.293	0.263	0.238	0.218	**0.200**
Mar9p.1-all	0.125	0.364	0.234	0.161	0.159	0.176	0.191	0.205
Mar9p.2-single	0.136	0.211	**0.107**	0.129	0.149	0.171	0.191	0.208
Mar9p.2-double	0.246	0.398	0.279	0.208	0.160	0.124	**0.114**	0.125
Mar9p.2-all	0.120	0.175	**0.078**	0.134	0.176	0.211	0.240	0.264
Ship A	0.138	0.169	0.165	0.218	0.258	0.289	0.315	0.338
Ship B	0.109	0.187	0.132	0.129	0.124	0.134	0.152	0.166
Ship C	0.217	0.214	**0.121**	0.184	0.232	0.268	0.297	0.321
Ship D	0.154	0.358	0.247	0.204	0.189	0.175	0.162	**0.151**
Ship E	0.154	0.280	0.157	0.086	0.063	**0.059**	0.080	0.104
Ship F	0.132	0.154	0.161	0.198	0.226	0.251	0.280	0.304
Ship G	0.093	0.245	0.106	0.101	0.111	0.125	0.138	0.162

* Boxes identify the minimum deviation between the theoretical and sample distributions.

TABLE 5 Interarrival Time Distribution Tests

Data File	K-S Statistic	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)
Jan7p.1	0.177	0.089	0.100	0.173	0.222	0.256	0.282	0.301
Jan7p.2	0.213	0.110	0.100	0.148	0.196	0.231	0.258	0.278
Feb11a.1	0.205	0.238	0.116	0.074	0.118	0.152	0.181	0.205
Feb11a.2	0.215	0.156	0.118	0.118	0.154	0.175	0.191	0.204
Feb11p.1	0.158	0.144	0.111	0.134	0.181	0.216	0.242	0.264
Feb12a.1	0.246	0.126	0.125	0.158	0.192	0.222	0.249	0.272
Feb12a.2	0.327	0.281	0.355	0.403	0.439	0.467	0.491	0.512
Feb12a.3	0.281	0.147	0.088	0.152	0.198	0.234	0.263	0.287
Feb12p.1	0.196	0.097	0.116	0.183	0.226	0.254	0.272	0.290
Mar7p.1	0.254	0.156	0.200	0.246	0.288	0.323	0.352	0.376
Mar7p.2	0.207	0.243	0.278	0.292	0.335	0.371	0.400	0.424
Mar8a.1	0.287	0.172	0.117	0.133	0.160	0.195	0.224	0.248
Mar8a.2	0.349	0.188	0.117	0.128	0.138	0.141	0.158	0.180
Mar8p.1	0.168	0.092	0.127	0.201	0.248	0.280	0.303	0.322
Mar9p.1-single	0.152	0.128	0.085	0.119	0.154	0.181	0.204	0.227
Mar9p.1-double	0.318	0.064	0.174	0.232	0.261	0.296	0.325	0.348
Mar9p.1-all	0.138	0.109	0.074	0.134	0.173	0.206	0.232	0.252
Mar9p.2-single	0.130	0.052	0.112	0.179	0.218	0.254	0.282	0.304
Mar9p.2-double	0.250	0.180	0.195	0.232	0.258	0.271	0.286	0.307
Mar9p.2-all	0.116	0.055	0.126	0.189	0.225	0.252	0.280	0.301
Ship A	0.137	0.088	0.095	0.155	0.199	0.233	0.262	0.285
Ship B	0.108	0.155	0.089	0.095	0.144	0.179	0.208	0.231
Ship C	0.202	0.158	0.145	0.165	0.213	0.249	0.278	0.302
Ship D	0.162	0.092	0.091	0.149	0.198	0.234	0.262	0.284
Ship E	0.162	0.176	0.208	0.248	0.295	0.332	0.361	0.384
Ship F	0.136	0.105	0.070	0.143	0.192	0.226	0.252	0.271
Ship G	0.099	0.081	0.084	0.149	0.185	0.214	0.242	0.265

* Boxes identify the minimum deviation between the theoretical and sample distributions.

TABLE 6 Backcycle Time Distribution Tests

Data File	K-S Statistic	E(1)	E(2)	E(3)	E(4)	E(5)	E(6)	E(7)
Jan7p.1	0.192	0.208	0.118	0.157	0.185	0.207	0.229	0.243
Jan7p.2	0.259	0.358	0.266	0.210	0.169	0.137	0.109	0.104
Feb11a.1	0.227	0.412	0.305	0.244	0.200	0.165	0.144	0.156
Feb11a.2	0.287	0.232	0.339	0.408	0.456	0.492	0.521	0.544
Feb11p.1	0.172	0.284	0.151	0.158	0.159	0.160	0.189	0.212
Feb12a.1			no test					
Feb12a.2			no test					
Feb12a.3	0.327	0.232	0.339	0.408	0.456	0.492	0.521	0.544
Feb12p.1	0.213	0.426	0.331	0.273	0.231	0.197	0.169	0.146
Mar7p.1	0.318	0.211	0.133	0.201	0.249	0.285	0.314	0.338
Mar7p.2	0.207	0.386	0.261	0.227	0.259	0.285	0.308	0.328
Mar8a.1	0.287	0.250	0.110	0.145	0.193	0.226	0.251	0.270
Mar8a.2	0.349	0.473	0.394	0.348	0.313	0.286	0.263	0.243
Mar8p.1	0.198	0.236	0.106	0.108	0.130	0.166	0.194	0.216
Mar9p.1	0.144	0.447	0.343	0.280	0.235	0.200	0.173	0.162
Mar9p.2	0.117	0.379	0.258	0.187	0.190	0.200	0.208	0.217

* Boxes identify the minimum deviation between the theoretical and sample distributions.

There are two disadvantages to estimating the shape parameter in this fashion. First, there must be prior knowledge that the process can be described by the Erlang distribution. Second, when k is estimated by the mean and variance of the sample, it is more sensitive to outliers in the sample data file. The K-S methodology, on the other hand, is based on the cumulative distribution of the sample and is less sensitive to extreme values.

Service Time Distributions

Inspection of the service time distributions indicates that there is no consistency in the shape parameters of the Erlang distributions not rejected by the K-S test. Put another way, there is no indication that the service times at wharf cranes can be predicted or modeled as one distribution. This is verified by the fact that every single distribution was rejected by at least five of the data files. More specifically, the 16 original data files indicate that the E(1)–E(7) distributions were deemed most appropriate 0, 6, 2, 1, 0, 1, and 4 times, respectively. On two occasions, no distribution tested successfully.

Two of the four files that tested successfully as E(7) distributions represented the operations of ports using chassis storage systems. It was expected a priori that these operations would result in more efficient (lower variance) distributions because of the chassis storage system. On the basis of the observed data, this is the case. The reason is that yard crane operations are avoided, reducing the opportunity for delays in queue or yard crane maneuvering. This is not to say that backcycle times are necessarily shorter; they are merely more consistent for chassis storage systems.

The data files created at Port 2 (Mar9p.1 and Mar9p.2) were categorized into single and double moves to determine whether they follow different distributions. On the basis of the differences found in the Mar9p.2 distributions, this is the case, suggesting that single and double moves should be modeled separately. It was previously mentioned that several distributions test "acceptable" for each data file in addition to the actual best-fit distribution. Note, however, that 11 of the 16 data files indicate that the null hypothesis can be rejected, since the deviation for the exponential distribution is greater than the test statistic.

To determine whether specific ships followed specific service distributions, all data files associated with the same ship were combined and tested. The results indicate that of the seven ships represented (Ships A–G), only three tested successfully with E(2), E(7), and E(5) service time distributions. The premise that service times are not necessarily exponentially distributed is supported by these tests for two reasons. First, four of the seven ships did not test successfully with any of the seven distributions. Second, the ships that did successfully test (for any distribution) did not test as exponentially distributed service times.

The last test performed was on a data set that contained all service time observations. The test was inconclusive, because no distribution was accepted as statistically similar to the sample distribution. It is possible that a hyperexponential distribution would be applicable. However, the variability in the mean service times suggests that the service time is too general of a process to be modeled with only one distribution (i.e., it is very unlikely that a single distribution could be specified that accurately describes the service process for any ship).

The major conclusion that may be drawn from the service time distribution tests is that the process is not necessarily exponentially distributed as assumed in most studies. The test results indicate that more efficient distributions (high k) or very broad distributions [exponential or E(2)] are generally appropriate to model the process. It is likely that there is a relationship between the level of congestion in the port and the service time distribution, explaining the different "groups" of distributions. Because of the inadequacy of the data to accurately quantify the congestion (*1*, Chapter 3), it is not possible to explore this hypothesis in this study. The point remains, however, that the service times are often not accurately described by the exponential distribution.

Interarrival Time Distributions

Interarrival time distribution tests were performed for the same data files as the service time distributions. The results, however, were much more consistent for the interarrival time distributions. The E(1) distribution was selected seven times, the E(2) was selected seven times, and the E(3) distribution was selected twice. No other distributions accurately modeled the empirical interarrival time distribution.

All files that were tested for interarrival time distributions tested successfully, including the two data files that did not test successfully for the service times because of the presence of single and double moves. Even when the interarrival times for single and double moves were tested separately, the same distribution as the combined times was specified. In other words, single and double moves did not have the same effect on interarrival times that they did on service times. The trend that exponential interarrival times are more appropriate than exponential service times is supported by the fact that only two of the data files that were tested can reject the exponential distribution as statistically similar to the sample distribution.

The last data file tested for interarrival time distributions combined all individual files. The test was again inconclusive; no distribution was accepted as statistically similar to the combined sample distribution. The distribution tests on individual files indicate that exponential distribution of interarrival times is a much more solid assumption than exponential distribution of service times.

Backcycle Time Distributions

Backcycle time distributions appear to be less consistent than the interarrival distributions yet more consistent than the service time distributions. Specifically, each distribution tested successfully with the following frequencies: E(1) two times, E(2) five times, E(3) zero times, E(4) zero times, E(5) zero times, E(6) one time, E(7) three times, and no distribution three times. The actual test results are given in Table 4. (Only 14 data files are included in the test results because two data files had too few observations to produce strong results.)

The three unknown distributions correspond to the files Mar7p.2, Mar9p.1, and Mar9p.2. The first of the files represents stacking operations using top-pick loaders, and the last two files are associated with chassis storage operations. However, it does not appear that there is any correlation between container storage techniques and backcycle time distributions. Inspection of the test results of these three files indicates that the Mar7p.2 and Mar9p.2 files do not correspond to any of the Erlang distributions considered in the testing procedure. However, it appears that the Mar9p.1 data file is converging toward an acceptable Erlang distribution with a high shape parameter. The shape parameter is estimated as $k \approx 10.0$.

It is somewhat surprising that several data files tested successfully for distributions other than exponential or E(2). It was expected that the backcycle times would be consistently exponential or E(2) because of the wide range of mean backcycle times given in Table 1. This wide range verifies that the backcycle time is dependent on the operations within the storage yard. Specifically, if containers are being delivered to a point in the yard that is near the wharf crane, the mean backcycle time is expected to be considerably less. The variance of the backcycle time is also expected to decrease as the point of delivery in the storage yard draws nearer to the wharf crane. This would have the effect of increasing the shape parameter of the Erlang distribution.

Visual inspection of the test results does not indicate that such trends exist. The four data files that produced the highest-parameter Erlang distributions are associated with mean backcycle times ranging from the smallest to the third largest. Mar8a.2 resulted in an E(7) distribution and is associated with a mean backcycle time of only 3 min 44 sec. Jan7p.2 also resulted in an E(7) distribution but is associated with a mean backcycle time of 11 min 13 sec. This wide range suggests that there may not be a relationship between the Erlang shape parameter and the location of storage yard deliveries, contrary to prior expectations. Obviously, there is not enough information to quantify such relationships.

It is very difficult to make any assumptions or predictions about the backcycle time distributions. It appears that the best-fit distribution may be as file specific as the service time distributions. This makes it increasingly difficult to form general models that are applicable to more than one ship.

CRITICISM OF DATA COLLECTION EXPERIMENT

The actual process of collecting, processing, and testing field data for this experiment was successful. The required information was captured, and all test results are appropriate and significant. However, the experiment could be improved in several ways.

First, this data collection effort produced time-motion studies of cellularized vessels only. As yet, the implications of noncellular vessels for time distributions have not been quantified. We can safely assume that the mean service time is larger but cannot safely assume what distribution best describes any element of the process. The only way to quantify the effects is to repeat the data collection on noncellularized vessels.

Second, it is unfortunate that visibility, logistics, and safety concerns precluded the collection of data from yard cranes where container stacking is used. Such information could be used to further analyze the variability of backcycle time distributions. It would also open the door to further decompose the cyclic queue so that transit times could be analyzed as another stage in the cycle. The collection of data in the storage yard would also allow researchers to study the impact of various storage container techniques on operational efficiency.

Third, not all events that affect service, backcycle, and interarrival time distributions could be recorded in this time-motion analysis. It would have been beneficial to have information on where containers are located in the ship, exactly where containers are placed in the yard, the reason for all crane delays, and other miscellaneous operating characteristics. Having such information would have equipped us to analyze the data more effectively and quantify the effect of such information on time distributions. Similarly, if this type of data collection effort is repeated, an account of how far a container is stored from the wharf crane should be kept during the data collection effort. This could be as basic as counting the number of bays between the storage location and the ship. Such information would help explain the variability of the backcycle time distributions and may provide an explanation for the division in the service time distribution results.

Fourth, the data collection experiment is port specific. Conducting similar experiments at other ports could yield different results, since operating technologies and strategies differ at each port. Thus, the results presented in this paper should not be blindly assumed appropriate for all ports. To investigate this issue, similar studies should be conducted at numerous other ports.

These inadequacies do not render the experiment unsuccessful or unimportant. The experiment would benefit greatly from repetition at other ports and from having full cooperation from port operators in viewing activities and obtaining valuable documentation. However, valuable and reliable information was obtained that, to our knowledge, has not been collected in the past. The experiment successfully indicated that exponential distributions are not always appropriate to describe service times (and perhaps backcycle and interarrival times), contrary to popular belief. It also provides a framework for similar experiments at other ports.

SUMMARY

This paper outlined the collection of data describing the efficiency of operations at container port wharf cranes. The data collected constitute a time-motion study of the service, arrival, and cycling processes surrounding the wharf gantry crane. Kolmogorov-Smirnov tests were used as goodness-of-fit tests to determine which theoretical distributions can or cannot be used to describe individual samples of the time-motion study. The distributions considered in the testing procedure were the exponential distribution and the Erlang(2) through Erlang(7) distributions. The range of distributions was appropriate for the majority of the samples tested.

On the basis of the results of testing 16 individual data files, this research showed that the service and backcycle time distributions are the most difficult to predict. Most important, this research showed that the service time distribution at the wharf crane is not always exponential. The arrival process, on the other hand, appears to be properly represented by the Poisson distribution.

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Multimodal Transportation and Impacts of Policy: Grain Transportation Model

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Multimodal systems offer efficiencies from complementary and competitive interactions. A least cost spatial equilibrium model is used to determine how alternative policies and firm decisions affect the performance of a multimodal grain transportation system. The system is found to be extremely competitive, and much of the competitive structure comes from intermodal movement via truck-barge. It is also found that the operating structure of the shipping firm using the system directly affects the performance.

The availability of a multimodal transportation system brings with it many benefits for shippers. The obvious benefit is the efficiencies achieved by allowing each mode to be used for the type of movement for which it is specifically suited. This is particularly evident in an intermodal movement where different segments or functions of the overall movement are performed by that mode with the comparative advantage for each segment. These efficiencies and system approach have led to TOFC, double-stack railcars, RoadRailer, truck-barge, truck-rail, and rail-barge intermodal movements throughout the United States and the world.

An additional benefit of a "complete" intermodal system, meaning availability of rail, truck, and barge modes, has been the competition among these modes. Competitively induced rates and competitively induced cost innovations and reductions have been the impetus for much of the economic development of the United States and have been the sustaining force in the competition for U.S. markets. Competition between the rail industry and truck-barge movements has left rail rates, as late as 1991, at 1936 levels.

The historical policies toward aiding each mode to develop, regulating each mode's economic decision making, and the shippers' use of the modes are currently undergoing significant change. Critical issues of rail line abandonment, potential rural road deterioration, and loss of barge movement due to salmon preservation efforts have received considerable attention from researchers and policymakers (*1–9*). The Pacific Northwest grain transportation serves as a good laboratory in which to evaluate the probable impacts of such changes on a multimodal system. It has a complete multimodal system with alternative management structures in shipping firms and a history of active rate and service competition as well as complementary activity among modes.

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OBJECTIVES

The overall purpose of this study is to determine how alternative marketing strategies and transportation policies affect the efficiency and performance of a multimodal transportation system. Specific objectives are to

1. Select a case study area where the modal competitive environment has affected the grain industry,
2. Determine modal use and marketing characteristics of farm producers and grain elevators,
3. Develop a conceptual and mathematical spatial equilibrium model capable of reflecting commodity flows,
4. Construct alternative model scenarios reflecting current or potential shipper marketing strategies and transportation policy changes, and
5. Determine multimodal response and system performance under the alternative models.

STUDY APPROACH

The primary tool of analysis for this study was a least cost spatial equilibrium model, developed to evaluate intermodal competitiveness in the transportation system in eastern Washington. Supporting the mathematical model and providing realistic borders for the analysis were two comprehensive surveys of grain producers and grain elevators in the study region. Transportation rates and other coefficients were obtained from shippers, carriers, and elevator firms currently participating in grain marketing.

An area including southern Spokane and northern Whitman counties in eastern Washington was chosen for this study (Figure 1). Wheat and barley are the major crops in this area, with natural geographic and political boundaries serving as effective barriers and minimizing grain inflows into the region. The area has 25/26-car rates available to it from the Burlington Northern and the Union Pacific railroads, as well as single- and 3-car rates. Proximity to the Snake River is an important

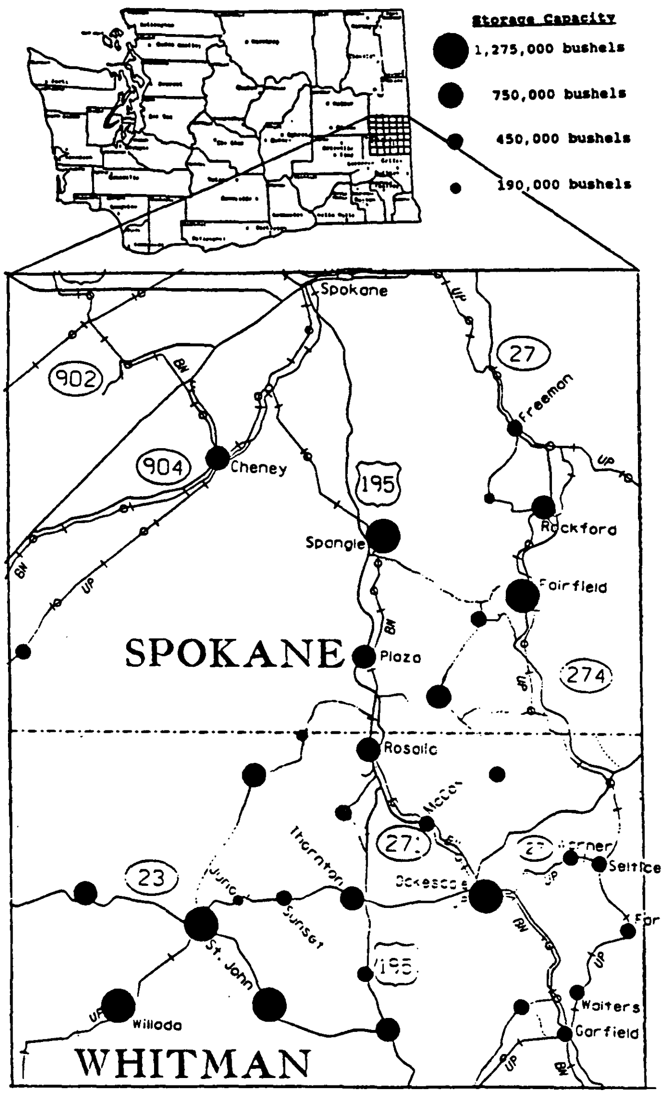

FIGURE 1 Location of the study area and the 33 county elevators identified for the development of a grain transportation cost minimization model for southern Spokane and northern Whitman counties in Washington State (adapted from *Washington Agricultural Statistics 1989–1990* and the U.S. Geological Survey, 1965).

determinant of whether grain is shipped by truck to river barges or sent by rail (*10*).

It has been hypothesized that the introduction of multiple-car rail rates will hasten the demise of smaller country elevators (*4*). To test the potential effect of such impacts from multimodal competition, the study area chosen had to have a representative size distribution of elevators by licensed capacity. The 33 elevators, belonging to 12 firms existing in the study area, represent that desired size distribution (Figure 1).

The difficulty of allocating accounting costs to programming cost coefficients was reduced using information provided by two sources. The first was a seminal work conducted in a similar geographic area by Dooley in 1986 (*4*), where cost coefficients were approximated by nonlinear cost functions using mixed integer programming. Second, estimates were developed from the two surveys and from direct telephone consultation with the elevator managers and personnel of Burlington Northern and Union Pacific railroad companies.

SURVEY RESPONSES IN STUDY AREA

Producers were surveyed to develop an appropriate operating framework and coefficients for the analytical model. [An in-depth review of survey findings and a copy of the survey forms are given elsewhere (*11*).] Agricultural producers had various marketing alternatives available to them. Depending on location and size of farm, considerable differences were found in what producers did with their grain. Almost half of producers moved their grain first to local elevators, with country elevators being the most important form of wheat storage. On-farm storage was used by fewer than 20 percent of the surveyed farms, but more frequently by larger producers.

Farm size and seasonal timing of marketing activity influenced perceived road conditions. Larger farms moving grain during the winter months on local roads more frequently reported problems with roads. For all producers in the area, the dominant perception was that road conditions were good but deteriorating.

More than half of the farm-to-elevator movement occurred just after the harvest period. These findings were used to define realistic coefficients for the model. Most of the grain was moved to elevators during the 4 months following harvest (July through October). Shipments from elevators to markets occurred throughout the year.

Since decisions made by grain elevators have a direct impact on the transportation system, such analysis was of primary importance. The breakdown of wheat and barley handled by the elevators is consistent with proportions reported by grain producers (an approximately 7:3 wheat:barley relation). Wheat is shipped almost exclusively (98 percent) to Portland. Three-car and 25/26-car are the common railroad methods used. Direct truck-to-market shipments were not used by the producers or elevators surveyed. Transshipments go from elevators without direct railroad access to the 25/26 multiple-car loading facilities within the same firm.

Because barley is not a homogeneous product like wheat, its transport is more specialized. Malting barley was transported by rail to Vancouver. Barley went to in-state feedlots by truck. Barley for export was moved by train and truck-barge.

MATHEMATICAL MODEL

A traditional linear programming model was used to find the least cost optimal solution to the transportation cost problem. The model considered the following costs: (*a*) assembly costs, the costs of moving 1 bushel of grain from the supply regions (farms) to the elevators; (*b*) elevation costs, cents per bushel elevator operating costs; and (*c*) shipment costs, cents per bushel transportation and handling costs from the elevator to the final destination.

The mathematical model took into account the total cost of assembly, elevation, shipping, and transshipment, subject to specified constraints imposed on the grain marketing industry of the area. The specified objective function was as follows:

$$\text{Minimize } z = \sum_j \sum_i \sum_n \sum_t (c_g)_{ij}^{tn} G_{ij}^{tn} + \sum_j \sum_n \sum_t (c_e)_j^{tn} E_j^{tn} + \sum_{j'} \sum_j \sum_t (c_t)_{jj'}^{t1} T_{jj'}^{t1} + \sum_p \sum_j \sum_n \sum_t (c_s)_{jp}^{tn} S_{jp}^{tn} \quad (1)$$

The c coefficients in parentheses in Equation 1 indicate the cost per unit of the variable they precede. The superscripts, subscripts, and activities in this objective function are defined as follows:

- t = time period (1 for July–August, 2 for September–October, 3 for November–February, and 4 for March–June).
- n = type of grain (1 for wheat and 2 for barley).
- i = crop origin supply point; each origin supply point is a township ($i = 1, 2, \ldots, 40$).
- j = elevator ($j = 1, 2, \ldots, 33$).
- j' = elevator with multiple-car loading facilities (the j''s are a subset of the j's; $j' = 1, 2, \ldots, 17$).
- p = mode used to transport the grain from elevators to final market [1 for truck-barge of wheat and barley to Portland, 2 for three-car unit trains of wheat to Portland and for barley to Portland or Vancouver (since the rates are the same), 3 for 25/26-car unit trains of wheat to Portland, and 4 to indicate that barley goes to in-state feedlots].
- G_{ij}^{tn} = is the quantity of the nth grain assembled from origin supply point i to elevator j in time period t.
- E_j^{tn} = quantity of the nth grain received at the j elevator during time period t, stored, and subsequently shipped.
- $T_{jj'}^{t1}$ = level of wheat transshipment activities, shipping wheat from elevator j to an elevator with multiple-car loading facilities j' in time period t ($j \neq j'$).
- S_{jp}^{tn} = quantity of the nth grain shipped from elevator j by the mode and destination p in time period t.

The equation is minimized subject to empirical conditions relating to grain production, assembly coefficients, elevator capacities, shipping coefficients, and minimum storage use of elevator's capacity.

Four elevator capacities were used in a multiplant grain firm structure. Multiple-car loading facilities were identified as central gathering points for subsequent lower-cost outbound shipments. The base model outlined below is a close approximation, compared with survey results, of what actually happens in the grain marketing system in the study region.

Linear programming models, as used in this study, are constrained representations of the actual marketing system. Competitive reaction to price changes, handling costs related to volume put through an elevator, and capacity changes over time are the types of changes that are held constant in this type of model.

MODEL SCENARIOS

Seven models were evaluated; each model tested a marketing strategy or policy change within the multimodal transportation system. The first four models evaluated alternative shipper marketing strategies of grain firms, and the final three deal specifically with potential carrier policy changes in the transportation sector. The base model reflects the existing grain transportation system and actual usage of that system in eastern Washington. Elevators are organized into multiplant firms, as in the actual situation, where an average cost of operation for the entire firm, rather than for each elevator, is charged per bushel handled. A critical feature of this base model is the minimum amount of grain forced into each elevator, determined by the elevator survey.

The shipping of grain from the elevator to final market is a function of the type of grain and the transportation modes available. Two general transportation modes compete for wheat shipping to this port: railroad, which offers 3-car and 25/26-car rates, and truck-barge, which takes the wheat by truck to the Central Ferry Port on the Snake River and then to Portland by barge. Wheat is also transshipped from elevators without access to those with access to 25/26-car rates, but only within the same firm. No seasonal variation in rates occurs in the study area.

The second model, the least cost model, relaxes the assumption of minimum storage constraint. Thus, grain was allowed to flow without any restriction of using all elevators through the path with the lowest total transportation cost.

The third and fourth models were run on a single firm basis with every elevator operating as an independent firm; there were no multiplant firms. Single Firm Model A allowed no transshipments, and 25/26-car rates were only available to multiple-car loading facilities. Single Firm Model B eliminated 25/26-car rates by assuming that even elevators with multiple-car loading facilities could not put together enough grain to meet the requirements of filling 25/26-car trains in 24 hr.

A virtue of linear programming is the flexibility it offers to change specific parameters, maintaining the rest of the economical setting unchanged, and predicting the effects of the changes made. This allowed the last three models to evaluate the impact of actual issues confronting eastern Washington shippers.

The first policy model examined the impact on grain flow of closing the Snake River during the early summer in an attempt to save the salmon recently listed under the Endangered Species Act. This was accomplished by closing the time period in the base model from March to June (time period 4).

A second policy model sought to examine the effect on wheat movement and rail revenue if the Burlington Northern were to adopt a competitive or aggressive rate policy. Burlington Northern rail lines cross the study area as a vertical column from south to north, with 3 elevators on its lines being multiple-car loading facilities and 11 other elevators having transshipment connections to multiple-car loading facilities.

The final policy model evaluated the potential result if a recently abandoned (but not yet salvaged) line (the Arrow Line) were to be purchased and operated as a regional or short line railroad. If this line were to be successfully resurrected, it would have to offer lower rates to draw traffic. To test the effect of such changes, both Burlington Northern and Union Pacific rates were decreased to determine the impact on rail movement. Several other permutations of the rates gave information on the elasticities of demand for transportation modes.

ANALYTICAL RESULTS

The results of the first model are indicated in Table 1. It is evident that many of the smaller elevators, as forced by the assumptions, collect grain, but then quickly transship the grain to multiple-car loading elevators. Since these elevators fill only about 40 percent of their capacity, their long-term life is suspect.

Three factors explain these results and give a better understanding of the industry's use of the multimodal system. First is the organization of elevators into multiplant firms and the average firm cost scheme they use. Essentially, a firm's share of the grain market is more important than any one elevator's share. Therefore, small elevators serve as grain collection units into the overall firm volume.

Dooley (*4*) found that larger elevators could increase their market share if they could build additional storage capacity when individual elevators are operating as firms. Another fact favoring the association of individual firms into multiplant firms, rather than the buildup of large individual elevators, was discussed by Hays (*12*). He found that because of severe time constraints, especially during harvest, grain producers choose the closest elevator available.

The modal split of the grain shipments for the base model indicates that wheat is moved by truck-barge only if the elevator does not have access to multiple-car loading facilities (12 percent of total wheat transported) or if the distance to the Snake River port is short enough to allow competition between truck-barge and rail rates.

Three-car rates were used by elevators with access to them except in the case of the elevators with on-site multiple-car loading facilities. This option is well suited to firms that do not have the operational volume required for the implementation of multiple-car loading facilities (21 percent).

There are five multiple-car loading facilities in the model, each belonging to a different multiplant firm and being located at the largest elevator of the firm. All the multiple-car loading facilities have transshipment connections with the other elevators within the firm. For the base model, 67 percent of the wheat delivered to Portland was shipped by this means. Of the 67 percent, 41 percent came directly into elevators from farms, and 26 percent was the product of transshipments.

System costs for the base model are presented in Table 2. The total bill for transportation of 12.184 million bushels of wheat and 5.733 million bushels of barley from the producing areas of southern Spokane and northern Whitman counties

TABLE 1 Modal Split of Grain Transportation for Base Model

Elevator	Wheat							Barley			
			MCLF (25/26-Car Rail)								
	Truck-Barge	3-Car Rail	At Elevator	Transship From	Transship To	Total 25/26-Car	Total Shipped	Truck-Barge	3-Car Rail	Truck to Feedlots	Total Shipped
	000 Bushels										
Cheney	0	391					391	0	261	0	261
Rodna	100						100	0		50	50
Fairfield	0	0	845		88	933	933	0	585	0	585
Waverly	0			88	Fairfield		0	0		83	83
Rockford	0	600					600	0	50	0	50
Freeman	0	333					333	0	81	0	81
Mt. Hope	150						150	0		9	9
Spangle I	0		891			891	891		523	0	523
Plaza	0	0	473		1,070	1,543	1,543	0	202	0	202
Spangle II	0	268		0	Plaza		268	0	114	0	114
Spring Valley	0			268	Plaza		0	0		115	115
Rosalia	0	472		0	Plaza		472	0	203	0	203
Balder	0			266	Plaza		0	0		116	116
McCoy	0	240		0	Plaza		240	0	100	0	100
Pine City	0			472	Plaza		0	0		203	203
Squaw Canyon	0			64	Plaza		0	0		28	28
Thornton	0	303					303	0	477	0	477
Cashup	120						120	0		51	51
Steptoe	380						380	0		237	237
Garfield	200						200	0		20	20
Walters	75						75	0		8	8
Crabtree	60						60	0		15	15
Oakesdale	0		1,543		669	2,212	2,212	0	200	0	200
Farmington	0			200	Oakesdale		0	0		100	100
Seltice	0			114	Oakesdale		0	0		57	57
Warner	0			100	Oakesdale		0	0		60	60
Fairbanks	0			255	Oakesdale		0	10		118	128
St. John	37			412	Willada		37	221		229	450
Ewan	56			381	Willada		56	238		0	238
Willada	0		1,225		1,367	2,592	2,592	0	400	0	400
Juno	88			14	Willada		88	4		64	68
Sunset	59			141	Willada		59	150		0	150
Pleasant Valley	82			418	Willada		82	195		155	350
Total	1,407	2,606	4,977		3,193	8,171	12,184	818	3,196	1,719	5,733
Percent	12	21	41		26	67	100	14	56	30	100

TABLE 2 Transportation System Costs for Base Model

Item	Wheat	Barley	Total	Percent	Grain Shipped
	---------- 000 Dollars	---------			---- 000 Bu ----
Assembly	297	148	445	5	
Elevation	2,453	1,138	3,591	40	
Shipping	3,705	1,215	4,920	55	
Wheat	3,705		3,705	0.41	12,184
Truck-Barge	492				1,407
3-Car Rates	857				2,606
25-Car Rates	2,196				8,171
Transshipments	160				3,193
Barley		1,215	1,215	0.14	5,733
To Portland-Vancouver		1,001			4,014
Truck-Barge		275			818
3-Car Rates		726			3,196
To Feedlots		214			1,719
Total Costs			8,956	100	

TABLE 3 Modal Split of Grain Transportation for Least Cost Model

Elevator	Wheat							Barley			
			MCLF (25/26-Car Rail)								
	Truck-Barge	3-Car Rail	At Elevator	Transship From	Transship To	Total 25/26-Car	Total Shipped	Truck-Barge	3-Car Rail	Truck to Feedlots	Total Shipped
	-----	-----	-----	-----	-----	----- 000 Bushels	-----	-----	-----	-----	-----
Cheney	0	491					491	0	313	0	313
Rodna	0						0	0		92	92
Fairfield	0	0	1,418		0	1,418	1,418	0	760	0	760
Waverly	0			0	Fairfield		0	0		0	0
Rockford	0	0					0	0	0	0	0
Freeman	0	0					0	0	81	0	81
Mt. Hope	0						0	0		0	0
Spangle I	0		1,898			1,898	1,898		545	0	545
Plaza	0	0	599		430	1,029	1,029	0	282	0	282
Spangle II	0	0		0	Plaza		0	0	0	0	0
Spring Valley	0			0	Plaza		0	0		0	0
Rosalia	0	582		0	Plaza		582	0	193	0	193
Balder	0			0	Plaza		0	0		0	0
McCoy	0	633		0	Plaza		633	0	93	0	93
Pine City	0			430	Plaza		0	0		0	0
Squaw Canyon	0			0	Plaza		0	0		0	0
Thornton	0	0					0	0	1,539	0	1,539
Cashup	373						373	0		0	0
Steptoe	219						219	0		0	0
Garfield	0						0	0		0	0
Walters	0						0	0		0	0
Crabtree	0						0	0		0	0
Oakesdale	0		2,550		0	2,550	2,550	0	78	0	78
Farmington	0			0	Oakesdale		0	0		224	224
Seltice	0			0	Oakesdale		0	0		135	135
Warner	0			0	Oakesdale		0	0		138	138
Fairbanks	0			0	Oakesdale		0	0		52	52
St. John	0			0	Willada		0	0		142	142
Ewan	110			314	Willada		110	0		571	571
Willada	0		2,064		613	2,677	2,677	0	130	0	130
Juno	0			23	Willada		0	0		157	157
Sunset	205			245	Willada		205	0		0	0
Pleasant Valley	0			31	Willada		0	0		208	208
Total	906	1,705	8,530		1,042	9,573	12,184	0	4,014	1,719	5,733
Percent	7	14	70		9	79	100	0	70	30	100

to the final markets was $8.956 million. This compares closely with a total estimated transportation bill of $9.200 million developed from the elevator surveys.

LEAST COST MODEL

In this model, the assumption of minimum storage constraint was relaxed. Thus, grain was allowed to flow, without any restriction, through the path with the lowest cost of assembly, elevation, and shipping to the market.

This environment of greater competition with no minimum storage constraints would result in the complete elimination of 10 elevators from the system (Table 3). The underused elevators identified in the base model are, in fact, now forced to exit the industry under the competitive conditions of this model. Grain would be concentrated around the multiple-car loading facilities and transshipments would be almost completely eliminated. Truck-barge would be completely eliminated as a barley transportation mode, and only four elevators would use truck-barge for wheat.

Compared with the base model, total transportation costs in the least cost model decreased from $8.956 million to $8.643 million (approximately 3.6 percent; see Table 4). This savings was realized mainly in the shipment of grain from elevators to the final market.

The increase in use of 25/26-car train units was accompanied by a reduction in transshipments to multiple-car loading facilities. Handling costs of loading and unloading were avoided by directly assembling the grain over longer distances instead of transshipping it as in the base model case.

SINGLE FIRM MODEL A (WITH MULTIPLE-CAR RATES)

The results of this scenario (Table 5) differ little from the base model results in Tables 1 and 2, although a 2 percent increase in the total transport bill occurred. This similarity arises largely because the supply of grain from farms closely matches the storage capacity of the elevators or the minimum amount of grain handled.

Once transshipments are eliminated, all of the wheat, previously transshipped to multiple-car loading facilities for movement by 25/26-car unit trains, makes its way to Portland through the truck-barge mode (Table 6). The truck-barge activity increased from 12 to 38 percent when transshipments were eliminated. However, the three-car rail rates were still a more economically efficient option than truck-barge for moving some wheat to Portland.

SINGLE FIRM MODEL B (NO MULTIPLE-CAR RATES)

With 25/26-car unit trains eliminated, 3-car rail rates remain a more economically efficient option than truck-barge for moving wheat to Portland (Figure 2). Without 25/26-car unit trains, all the rail-moved wheat would be moved by 3-car train units. However, because these rates were not as low as the 25/26-car rates, they did not lead to the pooling of grain from as far as multiple-car loading facilities had done.

Total transportation costs went up by $253,000 when multiple-car loading facilities were eliminated. This represents cost savings from moving almost 5 million bushels of wheat by 25/26-car train units. This comparison underscores the importance of the lower rates for 25/26-car rail.

A comparison of the shipping costs (Table 7) and total cost components (Figure 3) reveals little variation in assembly, elevation, and barley shipping costs. The cost of shipping wheat causes most of the variation.

RIVER CLOSURE MODEL

As previously discussed, one potential impact of salmon being listed under the Endangered Species Act is the drawdown of the river below levels that would allow barge traffic to continue. Results of the analysis indicate that the grain that would normally go by barge in the fourth period, after closure, sim-

TABLE 4 Transportation System Costs for Least Cost Model

Item	Wheat	Barley	Total	Percent	Grain Shipped
	----------- 000 Dollars		----------		---- 000 Bu ----
Assembly	333	152	485	6	
Elevation	2,421	1,137	3,557	41	
Shipping	3,484	1,117	4,601	53	
Wheat	3,484		3,848	0.40	12,184
Truck-Barge	307				906
3-Car Rates	541				1,705
25-Car Rates	2,584				9,573
Transshipments	52				1,042
Barley		1,117	1,117	0.13	5,733
To Portland-Vancouver		902			4,014
Truck-Barge		0			0
3-Car Rates		902			4,014
To Feedlots		214			1,719
Total Costs			8,643	100	

TABLE 5 Modal Split of Grain Transportation for Single Firm Model A

Elevator	Wheat							Barley			
			MCLF (25/26-Car Rail)								
	Truck-Barge	3-Car Rail	At Elevator	Transship From	Transship To	Total 25/26-Car	Total Shipped	Truck-Barge	3-Car Rail	Truck to Feedlots	Total Shipped
	000 Bushels										
Cheney	0	391		NA	NA		391	0	391	0	391
Rodna	100			NA	NA		100	0		50	50
Fairfield	0	0	845	NA	NA	845	845	0	451	0	451
Waverly	88			NA	NA		88	0		83	83
Rockford	0	600		NA	NA		600	0	216	0	216
Freeman	0	333		NA	NA		333	0	50	0	50
Mt. Hope	150			NA	NA		150	0		9	9
Spangle I	0	0	770	NA	NA	770	770	0	310	0	310
Plaza	0	0	594	NA	NA	594	594	0	285	0	285
Spangle II	0	268		NA	NA		268	0	114	0	114
Spring Valley	268			NA	NA		268	0		115	115
Rosalia	0	472		NA	NA		472	0	203	0	203
Balder	266			NA	NA		266	0		116	116
McCoy	0	240		NA	NA		240	0	100	0	100
Pine City	472			NA	NA		472	0		203	203
Squaw Canyon	64			NA	NA		64	0		28	28
Thornton	0	303		NA	NA		303	0	164	0	164
Cashup	120			NA	NA		120	0		51	51
Steptoe	380			NA	NA		380	0		237	237
Garfield	200			NA	NA		200	0		20	20
Walters	75			NA	NA		75	0		8	8
Crabtree	60			NA	NA		60	0		15	15
Oakesdale	0	0	1,049	NA	NA	1,049	1,049	0	513	0	513
Farmington	200			NA	NA		200	0		100	100
Seltice	114			NA	NA		114	0		57	57
Warner	100			NA	NA		100	0		60	60
Fairbanks	255			NA	NA		255	0		128	128
St. John	450			NA	NA		450	370		80	450
Ewan	437			NA	NA		437	238		0	238
Willada	0	0	1,719	NA	NA	1,719	1,719	0	400	0	400
Juno	103			NA	NA		103	0		68	68
Sunset	200			NA	NA		200	0		150	150
Pleasant Valley	500			NA	NA		500	209		141	350
Total	4,601	2,606	4,977			4,977	12,184	818	3,196	1,719	5,733
Percent	38	21	41			41	100	14	56	30	100

TABLE 6 Transportation System Costs for Single Firm Model A

Item	Wheat	Barley	Total	Percent	Grain Shipped
	000 Dollars				-- 000 Bu --
Assembly	306	139	445	5	
Elevation	2,447	1,145	3,593	40	
Shipping	3,801	1,221	5,022	55	
Wheat	3,801		3,801	0.42	12,184
Truck-Barge	1,609				4,601
3-Car Rates	857				2,606
25-Car Rates	1,335				4,977
Transshipments	0				0
Barley		1,221	1,221	0.13	5,733
To Portland-Vancouver		1,006			4,014
Truck-Barge		275			818
3-Car Rates		732			3,196
To Feedlots		214			1,719
Total Costs			9,060	100	

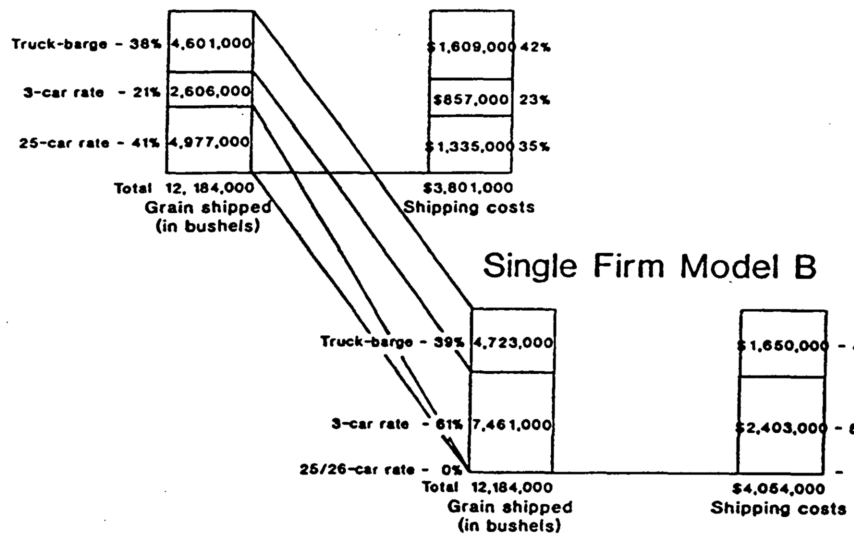

FIGURE 2 Comparison among the three shipping options (25/26-car, 3-car, and truck-barge) used in Single Firm Models A and B to ship wheat produced in southern Spokane and northern Whitman counties to Portland, Oregon.

TABLE 7 Shipping Costs for the Four Broad Base Models

County	Shipping Costs			
	Base Model	Least Cost Model	Single Firm	
			Model A	Model B
	000 Dollars			
Spokane	1,566	1,365	1,385	1,488
Whitman	1,979	2,067	2,416	2,566
Total	3,545	3,432	3,801	4,054

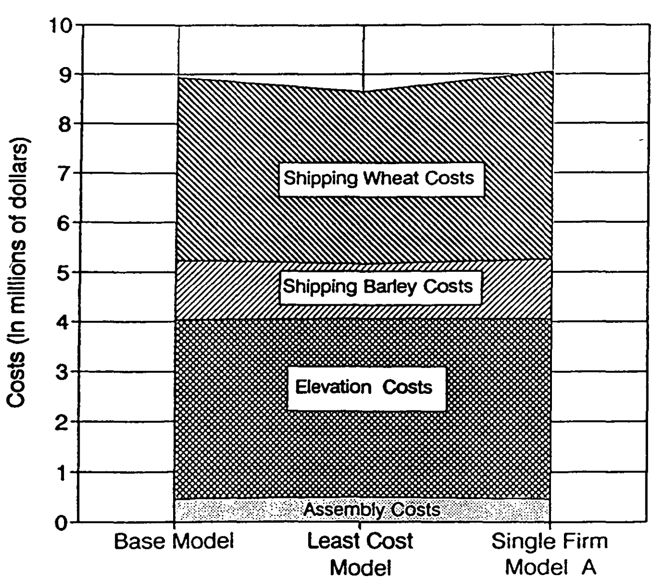

FIGURE 3 Comparison of component and total costs for three models.

ply shifted to another time period. The model did not specifically price the storage and shipping during the fourth period by adding on a storage penalty; thus the mathematical solution was simply another shipping pattern. If such a penalty were assigned, total costs would increase. No change in costs, storage, or modal choice occurred.

The shipper could sell before closure, hold until after the closure period, or sell during closure but move the grain via a different mode. The first alternative saves storage costs but makes shippers dependent on existing market price, the second causes increased storage cost and some price dependency, and the third entails higher transport costs. The actual response by shippers to a river closure would be driven by market demand conditions, financial needs of producers, rate reactions by other modes, and capacity needs in the elevator and storage sector.

BURLINGTON NORTHERN COMPETITIVE MODEL

Results from the base model indicated that almost 50 percent of the 12.184 million bushels of wheat shipped from the study area went to Portland, Oregon, on Burlington Northern cars. Union Pacific moved around 39 percent, and the remaining 11 percent went by truck-barge. Reducing Burlington Northern rates did not have a great effect on the modal share distribution of wheat shipments (Figure 4), suggesting that there is little incentive for Burlington Northern to decrease rates since they do not gain traffic.

If all Burlington Northern rates were increased (the 3-car and 25/26-car rates), the first 6-cent range increase would be critical in changing the modal share for wheat movement to Portland, Oregon. A 4-cent rate increase reduced the Burlington Northern share from almost 50 to 29 percent (almost eliminating three-car rates and transshipments to multiple-car loading facilities), in favor of an increase in the truck-barge share from 10 to 30 percent. Union Pacific gained only 2 percent of the shipping share.

This reduction assumes availability of barge capacity on the river system. In the peak year of grain movement on the river, 1985, almost twice as much moved on the river as the volume used in this analysis; thus, barge capacity appears to be available.

These results reflect the intense competition that exists in the transportation system in eastern Washington since the rates per ton-mile are very similar among model alternatives. Union Pacific did not gain a bigger share because of the proximity of Willada (its busiest station) to the Snake River. Another factor that influenced this result is the loyalty of wheat producers to specific elevators, thus preventing the low Union Pacific rates from drawing more grain to its stations. This loyalty was expressed by the minimum amount of grain handled per elevator that constrained the linear programming model.

ARROW LINE ALTERNATIVE MODEL

The assumed reduction in rates from the new Arrow Line did not have much effect on modal share since in the base model truck-barge rates were already at a rate disadvantage compared with railroad rates. Yet, if the new Arrow rail line configuration were able to offer a 2-cent reduction, an increase of 159,000 bushels would occur; this shift would be captured by wheat that was previously transshipped or moved by 25/26-car units. A further 2 cents per bushel decrease (a total of 4 cents) would move an additional 163,000 bushels by transshipment and 25/26-car movements.

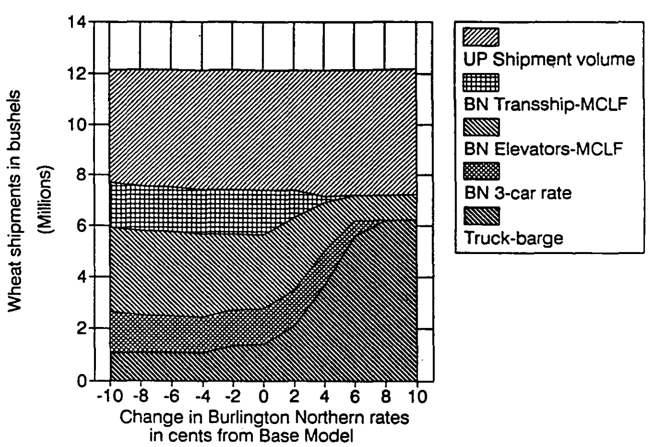

FIGURE 4 Modal share of wheat shipments as a function of Burlington Northern rates.

CONCLUSIONS

The overriding conclusion is that this multimodal system, essentially a duopoly at most shipping points, is quite competitive. Analysis of the modal share shifts in response to rate changes reveals the high elasticity of demand, in economics commonly associated with competition. It is also evident that the competitive environment is made possible by the intermodal complementary relationship of truck and barge in an integrated mode. Any competitive advantage held by the railroads has already been introduced into the market place by multiple-car rates. Little, if any, further monopoly power remains with the railroads.

Any decrease in truck-barge rates, even 2 cents, captures much of the wheat originally transshipped to multiple-car loading facilities. Eight- and 12-cent reductions would eliminate three-car mode and multiple-car shipments, respectively.

A second conclusion is that the multimodal transportation system performance is directly affected by the operating structure of the industry using that system. Maintaining all elevators, even the small, is costly to the transportation system. However, small elevators provide service to local producers during harvest and serve as collection sites whenever transshipments are available. Cooperatives or other multiple-plant firms can take advantage of multiple-car rates using transshipment between elevators in a firm to accumulate the required volume. Costs can then be averaged and spread out among elevators in a firm, allowing the survival of smaller elevators.

It is also evident that a decrease in availability of any mode in the existing complete multimodal system results in increased costs to the shipper, a decrease in the service received by the shipper, and a decrease in the overall mobility of freight and goods. The existing multimodal system seems to offer a competitive and efficient package of rates and service.

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Estimating Annual Waterway Tonnage from Lock Data: Methodology

DONALD LEAVITT

To provide more timely data, the Corps of Engineers has developed advance reports on estimates of commodity tonnage on American waterways since 1989. They are based on correlations between lockage data and operator-reported data over a decade. Experimentation and development of better methods provide more accurate estimates a year before the final published reports. Better methods include regression equations and common sense. Graphical analysis was used. Scattergrams pinpoint outliers due to poor data collection. Line graphs of tonnages by commodity of river locks show which give the maximum waterway tonnage. Time-series graphs of actual tonnage and promising regression estimates show the best estimator and unreported data. Analysis of the past flow of commodities shows which locks are more logical predictors. Graphs can show patterns in past tonnage relationships to justify estimation. Unreliable data must be identified and dropped from the analysis. The temptation to be mechanistic in the methodology must be avoided, and common sense must be used to overcome spuriousness and multicollinearity errors. These precautions can overcome the pitfalls of automatic computer-generated methods. Methods that improved accuracy included graphical analysis, adjusted regression equations, commonsense methods, and adjusted R-square. Analysis of errors improves methods. Advance data for 1990 showed improvement. Validity measures were developed that prove the model valid. Reliability can be predicted, and factors that increase reliability are known.

To provide more timely statistics, the Waterborne Commerce Statistics Center (WCSC) decided to develop annual estimates of waterway tonnage based on the data of prior years. The goal was to estimate timely WCSC tonnages for the previous year with reasonable accuracy. Annual lock tonnages on those waterways were used. Estimates were made for seven categories of commodities for 17 American rivers and waterways, by direction. Estimates were computed for 1988, 1989, 1990, and 1991. Data users indicate satisfaction with the more timely figures.

Actual WCSC annual tonnages were determined for each past year for each waterway and transferred into a Lotus 4.0 spreadsheet. The commodity groups are coal, petroleum, chemicals, metals, farm products, nonmetals, and miscellaneous. Commodity tonnages were obtained from the Corps of Engineers' Lock Performance Monitoring System (LPMS) for each lock and direction on the waterway and nearby locks on associated rivers. Each variable included annual data from 1982 to 1989 with a usual N of 8.

A correlation matrix was calculated for the variables for each commodity group in the spreadsheet. WCSC figures were correlated with all lock variables. The correlations showed which locks were most likely to accurately predict the WCSC tonnage for that commodity group and direction. In 1991, the 1990 tonnages were also checked by a tonnage-flow analysis to determine whether locks carried a significant proportion of the WCSC tonnage.

The best predictor locks were selected on the basis of higher correlations and higher tonnages flowing through the locks. Initially the percentage change from last year for the predictor lock was used to estimate the percentage change for the waterway.

Another method was to develop regression equations by using the best predictor lock. The equations were based on annual data from 1982 to the current year. The new lock figures (1990) were substituted in the equation to get the 1990 WCSC estimate. We regarded the estimation methodology as an iterative process. Minor modifications of our methods were tried each succeeding year to improve the accuracy of the estimates.

The percentage change method was found empirically to be less accurate than the regression equation method, so it was dropped. Various criteria were used to select the "best equation." Some were found to be associated with greater accuracy and were thus relied on more strongly later in the study.

The problem of faulty data was dealt with as experience was gained. Some years, some locks, and some commodities were inaccurate without obvious cause or regularity. Thus we relied on the more reliable post-1981 period for our data. (Several technical problems and a new system made the inclusion of pre-1982 data infeasible.) Even then, for some waterways only more recent data are accurate. An attempt to use quarterly data for a larger N was soon scrapped, since it not only seemed to increase the rate of faulty data but also added the problem of correction for seasonal variation.

Several regression equations were tried for each estimate, and the one that best met our criteria was selected. Alternate locks were used; several locks were used as variables in the equation; the variable of year was used; sums or differences of locks were tried; when justified, the constant was dropped. The question was asked, Does the predictive regression equation make sense in terms of the real world and all the information we have about the process?

The basic mathematical model is

$$\text{Estimate of WCSC tonnage} = \text{constant} + \text{coefficient} * (\text{tonnage through the best predictor lock}) \quad (1)$$

Waterborne Commerce Statistics Center, U.S. Army Corps of Engineers, P.O. Box 61280, New Orleans, La. 70161-1280.

Estimate (metal products for upbound Mississippi, 1991)

= 500,000 + 1.24 * (upbound metal in Ohio Lock 52)

+ 1.88 * (upbound metal in Mississippi Lock 27, Chain of Locks)

= 500,000 + (1.24 * 5,300,000) + (1.88 * 1,500,000)

= 9,900,000

See Figure 1 for more examples of actual equations. This may vary by adding more variables, including year.

Use of a dynamic rather than a static methodology and other experiments violated "taboos," for which we may be criticized. However, accuracy seems preferable to orthodoxy.

Various criteria used to select the best equation included correlation of the variables with the dependent variable, logic, a measure of fit called average error (which is a modification of the Klein ex post forecast), and proportion of waterway tonnage actually going through the lock.

A measure of fit was developed to test the equations. It uses the absolute difference between the estimate and the annual WCSC data for each year, subtracted from 1. The average of those hypothetical errors was used as the probable best measure of fit for an estimate. (However, no error was allowed to exceed 100 percent.) This measure is called "average error": it is the average error between the actual data and the equation-estimated data for each year. It is similar to using half the data to predict the other half. Equations were selected that minimized this error. Subsequent analysis showed this to be the best predictor of the reliability of the estimate.

The multiple correlation of the equation with the WCSC variable and the adjusted multiple correlation were additional criteria.

THEORY

The theory behind this study is that the tonnage through each lock may be a "sample" of the whole tonnage for the waterway. The problem is to get the most reliable sample: as close to a 100 percent sample as possible. This is actually an estimate, like estimating a vote from a preelection poll. However, in some respects, it is like a forecast.

A monograph on forecasting (*1*) discusses and supports methods that influenced the shift in emphasis explained below. A forecast (or estimation) is "the attempt to make scientific statements about non-sample situations on the basis of relationships determined from sample observations" (*1*,p.76; *2*,p.10). Thus data from the past (sample observations of lock and WCSC tonnage) are used to estimate the future (nonsample observations). Ostrom suggests leaving out certain sample points to determine whether the equation can predict these with sufficient accuracy. This was tried at the start, but with single-digit sample sizes (a maximum of 8 years), soon abandoned. Instead the average error criterion was developed.

According to Ostrom (*1*), the forecast error will be smaller with larger samples, explanatory variables with a larger dispersion, and smaller distances between the nonsample observation and the mean of past, sample observations. Thus, future estimates should be more accurate with more years of data. A large variation in past LPMS data should give better results (e.g., 1 million tons some years and none in others). For a new LPMS figure that is quite different from past figures, the estimate is likely to be less accurate. If the new lock figures are much larger or smaller than the past, we can expect less accuracy. This is consistent with the "contention that we are better able to forecast within our range of experience than outside of it" (*1*,p.78; *3*,p.250). Along these lines, it is also easier to estimate the past than predict the future (by excessive curve-fitting). Economic change and other unpredictables are

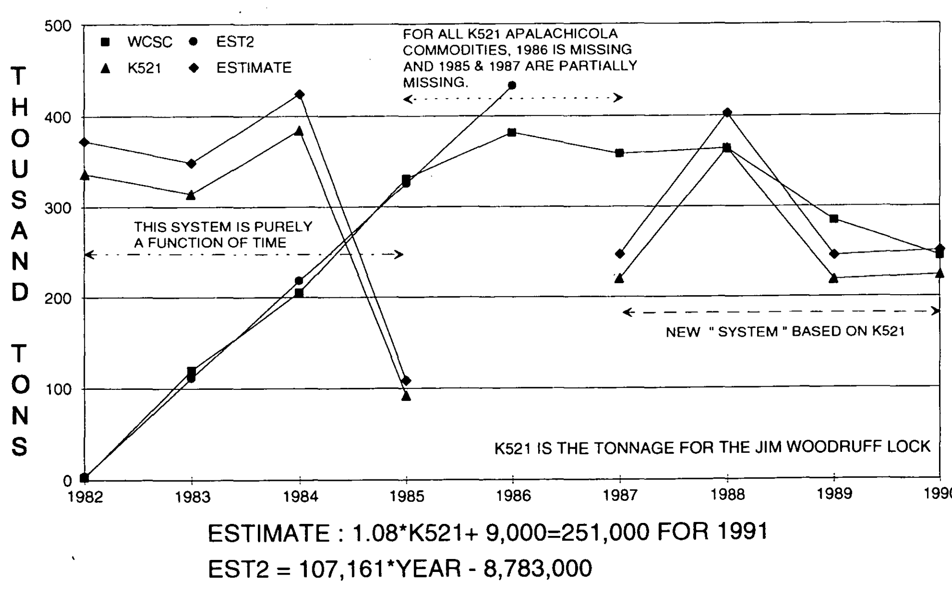

FIGURE 1 Apalachicola River, downbound, nonmetals (1982–1990).

constantly and dynamically changing past relationships. The best solution might be to keep our methods equally dynamic because our past computer models will soon be outmoded.

MIND OVER AUTOMATION

Much emphasis has recently been placed on picking the "best" regression equation by using a particular criterion, formula, strategy, or computer-derived method: stepwise, forward, backward, or chunkwise (*4,5*). However, I have begun to believe that human, nonmechanical techniques are better than automatic, computer-generated ones. The mind can take into consideration available information in a more complex way than do present computer methods.

Ostrom (*1*) says that "there may be times when we wish to be a bit less mechanical in our approach to forecast generation [quoting Klein (*6*,pp.278–279)] . . . (T)here is considerable room for judgment and insight in the generation of forecasts . . . (P)urely numerical methods cannot be used, but must be supplemented by special information and personal judgment . . . (A)ttempts at pure push button mechanistic uses are sure to fail and prove inferior to methods that combine a formal estimated model with a priori information and judgment" (*2*,pp.81–82).

This suggests that when statistical methods result in an estimation that seems suspect, we are allowed to modify it (the fudge factor). Even Einstein added a "universal constant," and it resulted in a model with great predictive value. A similar but computerized method of "fudging" might be to use dummy variables. This, however, brings the disadvantage of adding spuriously to the multiple correlation, just as adding spurious or random variables also appears to give a better prediction by raising the unadjusted multiple correlation. Whether a computer or the human mind should do this "fine tuning" is a question for debate among methodologists. It seems likely that the addition of dummy variables will add misleading spurious variance to a regression equation. The increased multiple correlation may be illusory.

Examples of fallacious results from the overuse of computers in our study include an estimate of negative tonnage, a number that may be quite out of line with the maximum number of tons of a commodity in locks in the waterway, and a negative relationship (lock tonnage goes up but the estimate goes down). Also, when the sum of commodities estimated is out of line with the estimated total, adjustments were made.

We may revise the total equation or the least sound and reliable commodity estimates. Correlation analysis showed that the true figure lies somewhere between the sum of the estimated commodities and the estimate of the total.

Regression equations that multiply a lock tonnage by several times were questioned. Also suspect is a lock that is the sole measure of the WCSC estimate multiplied by a small fractional coefficient. The actual WCSC river tonnage could be more (if some does not go through that lock), but it is unlikely to be significantly less.

Previously, the computer "drew the regression line" and computed the formula. For the 1990 estimates, I sometimes redrew the line that I thought to give the best prediction (judged by a visual scan of the graph). This may involve adding a time factor, combining several locks, or omitting a constant. This was often done when combining several of the larger commodity lock variables to get an accurate estimate of the total. A goal was the closest relationship of the estimation equation with more recent lock data, so the line was drawn to more closely fit the last few data points.

Human judgment, rather than raw computer power or standard programmed formulas or software, seemed most likely to reduce past error levels in our estimates. "Variable selection is a mixture of art and science, and . . . the analyst should be guided by a combination of theory, intuition, and common sense" (*7*).

In sum, we should use all the information available in our estimate, even if it cannot be stated in a precise mathematical form.

In this project, information about lock data is available that can improve the technique beyond a blind adherence to mathematical criteria. Most scientists also have a theory to guide their understanding of a process. A 20-variable correlation matrix without a hypothesis as to which variables should correlate and which should not is a fishing expedition (made easy by computers), not a scientific study. Yet, Bowerman and O'Connell (*4*, chapter 8) recommend putting in all possible variables (like a gumbo) and using statistics to pick out the "best" regression equation. However, I have found that one must discriminate to avoid spurious correlations. A plot or visual scan will reveal outliers and improve judgment for further analysis.

Spuriousness

If we run a 14 by 14 matrix of variables, accepting a .05 error level, we could get five spurious correlations purely by chance. It is easy to get a high correlation where there is no real relationship. Often by pure chance we may discover (for example) that the LPMS tonnage of oil from a lock correlates with the tonnage of metal from WCSC. Sometimes upbound lock figures correlate with downbound WCSC figures. A small-tonnage lock may correlate highly with much larger WCSC totals. Many of these were pure accidents, not reliable relationships. If we use them to predict next year's tonnage, we may be lucky, but we are most likely to be inaccurate.

Thus, when logic tells us that no connection is reasonable, even high correlations should be used only with caution when there are other, more logical candidates.

Here are some techniques based on commonsense information: Lock tonnages were only used to estimate same-direction WCSC tonnages. More tonnage in a lock is logically likely to be related to more tonnage in the WCSC figure (so we omit variables with negative correlations). The total of all commodities should be equal to the sum of each commodity group estimated. The lock on the waterway with the most tonnage for a direction is likely to contain the best "sample" of tonnage for the waterway. We prefer bigger samples to measures with larger correlations.

This method can also be used to determine which locks give tonnage consistent with the WCSC figures. If all the river tonnage goes through a lock, the lock tonnage should equal the WCSC tonnage. From a graph of several locks, the one closest to the WCSC tonnage or the nearest pattern in recent years can be selected. In this case, we may omit the constant in the regression equation.

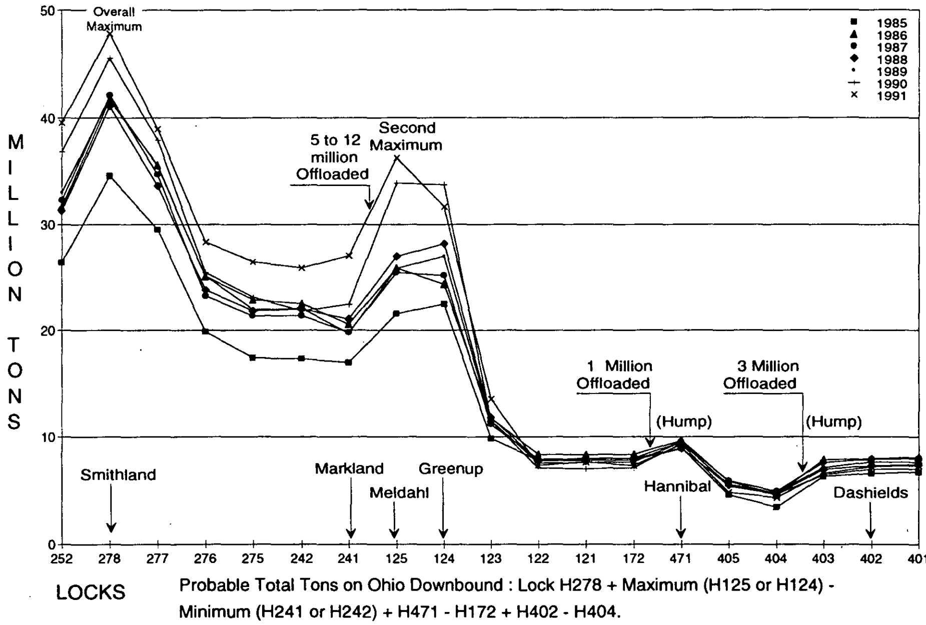

FIGURE 2 Ohio River, downbound, coal (1985–1991).

Multicollinearity

We should expect high correlations of locks with WCSC data, since they are from the same river. Often we find them.

When we find many correlations, the problem of multicollinearity presents itself. This involves multiple regression analysis with explanatory variables that correlate highly with each other, leading to unstable regression coefficients and erroneous inferences about the model (*7,8*). For example, another variable may be added that makes a variable coefficient flip over to negative (contrary to the logic of the analysis). Another highly significant variable may then be reduced to insignificance. At times, regression analysis seems to be a matter of chance rather than science. We were unsuccessful in using factor analysis, first differences, or two-stage least-squares regression to solve the problem. Eventually common sense and graphical techniques were applied for more satisfying equations.

CHARTING THE FLOW OF COMMODITIES

High correlations and regression equations can suggest candidates for estimates, but we must guard against spurious correlations. We can use the WCSC data file for the latest year to document the flow of a commodity within a waterway or system of waterways. This is an empirical method to find how much tonnage actually went through the various locks under consideration in a recent year.

Initially we found high correlations with WCSC tonnages for river locks or for the lock of a nearby waterway (e.g., an Ohio lock for the Tennessee River). Later flow analysis gave empirical evidence that relationships were justified (in addition to probabilistic deduction). Sometimes we found that it was not. Sometimes most of the river's tonnage does not go through a reporting lock. The Alabama River is an example.

The flow of commodities can show which locks are the best estimators that have the most tonnage flowing through the river studied. Figure 2 is an example of a graph of the flow chart of the river with the locks in geographical order. This method shows which locks have the most tonnage. A river with several maximums (humps) indicates that there are short hauls or local tonnage, and the total may be estimated by summing the locks giving the maximum for each hump (and perhaps subtracting the locks with the minimum between them). An example was nonmetals in the downbound Allegheny. This hypothesis was tested by calculating the error level and correlation for each likely combination. If a higher correlation is the result of such a combination, greater confidence in our final estimate is justified. However, adding variables also means adding to the error factor.

CONSISTENT AND STABLE PATTERN

Estimation is based on the assumption that the system dynamics will remain stable so that the future will be like the past (*1*,p.82; *4*,p.3). Reliable estimates will then be possible.

However, the process for the year studied may not be typical of previous years. Changes in extent of usage or operation (such as the Tennessee-Tombigbee), a drought, or shifting patterns of economics may change the underlying process of flow of commodities. Graphing the processes can reveal when the recent system is different from the past. Flow analysis revealed changes in patterns. Only the years reflecting the present system ideally should be used for the regression equation. Sometimes only 1 or 2 years define the current system. Unfortunately, this bases the estimates on few data with a low level of reliability. However, the ideal method should involve understanding the system and trying to use all useful available information.

Thus, forecasting works when the same structure operating in the sample period is still in force in the postsample period. A correction for trends over time ("year") may aid the process. The lock or WCSC tonnage may be increasing in the accuracy of reporting. The tonnage of a commodity may be steadily increasing or decreasing over time for shipments that do not go through the best lock measure. "Year" alone was used in the equation if the best lock gave an unreliable estimate according to "average error" or no lock correlated with WCSC tonnage.

GRAPHICAL ANALYSIS

The stability of the pattern may not be reflected by a simple correlation. It can, however, be tested by a graphical analysis of the relationship between the data points over time. A change in system dynamics can be identified and only the more recent system data used in the regression analysis (Figure 1).

Present software makes it much easier to draw graphs quickly. Recent books and statistics courses include techniques of data analysis through graphing (*7,9*). "Look closely at the raw data . . . before carrying out a multiple regression analysis . . . since computer programs are blind to many anomalies in the data" (*7*,p.6). The estimate of 1990 data involved line graphs of tonnages with time and also geography and some scattergrams. Lotus 4 drew the graphs. Line graphs of lock tonnages over time were constructed along with the variable of WCSC tons to determine which years did not show a consistent relationship between locks and WCSC tons. Outliers can be spotted and dropped from inclusion in a regression equation (inferring that they are bad data).

THE PROBLEM OF BAD DATA: OUTLIERS

In 1929 the British economist Josiah Stamp said, "Government(s) are very keen on amassing statistics—they collect them, add them, raise them to the nth power, take the cube root, and prepare wonderful diagrams. But what you must never forget is that everyone of those figures comes . . . from the village watchman, who just puts down what he damn pleases" (*10*).

The most logical predictor to estimate the WCSC river tonnage for each direction and commodity should be the largest commodity tonnage of any lock. If the correlation is low or negative, a better measure may be found, however. Measurement error was a problem. Some districts or locks may not record all the tonnage for the year (*11*). The processing of the data may be incomplete. Some data may be double counted. A change might develop in accuracy (increasing accuracy or enforcement of reporting).

Several districts did not report for several years (1983, 1986). Lock data are incomplete for some years or months. Other observers may classify commodities differently than the operators reporting to WCSC. Some record more nonmetals than does WCSC but considerably less miscellaneous tonnage, for example. Not all operators report their cargoes to WCSC in some years.

WCSC is familiar with the problems of incomplete reporting and poor accuracy, since many operators must be painstakingly coaxed to send accurate and prompt reports of their cargo movements. Experience with LPMS data revealed the pitfalls of high-tech analysis of poor data, which may result in faulty and inaccurate estimates.

Bad data probably accounted for the less accurate estimates. Scatter diagrams and line graphs show the correlation between a likely annual lock total and the WCSC figure. They might indicate that a value is out of line (an outlier). We may then proceed on the expectation that such data points are unreliable. The LPMS staff can double-check the data, or we may omit such points from the analysis.

BEST FIT REGRESSION

How can we be sure that the right variables and the right number of variables in a multiple regression equation are used to maximize the estimation accuracy?

The addition of any variable (even an unrelated one) will decrease the unexplained variation and increase the multiple correlation (*4*,pp.435–436). A dozen unjustified variables can be used in an equation, which would give a perfect correlation but a perfectly awful estimate.

Initially, I relied too much on computer or formula-derived regression equations. Much information was ignored. Regression equation formulas for 1989 were often automatically based on the highest correlation among lock variables and the highest multiple correlation.

Bowerman and O'Connell (*4*) give some better measures for the best fit of an equation: a corrected *R* square, a mean square error, and a *C*-statistic. The "best" equations have the largest corrected *R* square (multiple correlation squared), the smallest mean square error, and the smallest *C*-statistic (*4*,pp.436–441). The corrected *R* square was adopted (also called corrected multiple coefficient of determination):

Adjusted *R* square

$$= \left[R \text{ square} - \frac{(np - 1)}{(n - 1)}\right] * \frac{(n - 1)}{(n - np)} \qquad (2)$$

where n is the sample number and np is the number of variables used in the regression equation, including the constant.

$$C\text{-statistic} = \frac{\text{SSE}}{sp(\text{squared})} - (n - 2k) \qquad (3)$$

where SSE is the unexplained variation (sum of the squares of the error), k is the number of variables in the equation (not including the constant), and sp(squared) is the mean square error calculated from the model with k variables and a constant.

The solution is to select the most logical variables that maximize the adjusted R. Of course each variable in the equation should also have a significant t-score when its coefficient is divided by its error factor, at a .10 probability level.

TABLE 1 Comparison of 1988 and 1989 Measures

	1988	1989
Mean Correlation	.89	.86
Median Absolute Percent Error	16.10	15.37
Average Error 1982-87	13.97	16.83
Average Tons Error	952,819	651,333
WCSC Tons	11,097,162	9,596,500
Number of Estimates	160	278
Correlation of Estimate with Actual tons	.9976	.9982

For the naive model for 1989, Median Absolute % Error = 15.75
Tons Error = 759,102

TABLE 2 Percentage Error Levels for Waterways, 1988 to 1990

	Total Tons By Direction Mean Percent Error			Change
River	1988	1989	1990	
Ohio	1.4	1.4	2.4	Worse in '90
Mississippi	6.8	7.3[a]	6.3	Improvement
Tennessee	7.4	8.1	2.5	Improvement '90
Monongahela	9.1	8.3	2.6	Improvement
Arkansas	9.2	9.3[a]	14.3[a]	Improvement
Black Warrior	12.9	15.8	5.6	Improvement '90
Kanawha	9.0	8.3	3.4	Improvement
Cumberland	10.4	11.6[a]	2.9	Improvement '90
Illinois	8.9	6.6	7.6	Improvement '89
Allegheny	22.6	31.7[a]	15.0	Improvement '90
Columbia	16.3	13.4	11.4	Improvement
Tennessee-Tombigbee	24.5	34.8	11.9	Improvement '90
Apalachicola	37.4	60.0	5.6	Improvement '90
Snake	34.7	24.0	25.0[a]	Improvement '89
Alabama-Coosa	54.5	41.3	5.2	Improvement

[a]On the average of all commodity groups and directions, there was substantial improvement from the previous year.

EVALUATING FORECASTS

When the estimated year's actual WCSC data are available, a check of accuracy is done. Improvement over the previous year's predictions is assessed.

The errors of our estimate can be compared with those of a "naive model" (*1*,pp.84–85; *12*,p.572). The estimate can be compared with a no-change model. In this naive model, next year's value is set to this year's value. If the regression equation "does no better than this naive model, the implication is that it does not abstract any of the essential forces making for change, that it is of zero value as a theory explaining year to year change" (*13*,p.109).

The formula ratio for determining the efficiency of the model is

$$\frac{\text{RMSE (model)}}{\text{RMSE (naive)}} \qquad (4)$$

RMSE is the root mean square error of the forecast (deviation from perfection). For only one estimation, it would be

$$\frac{\text{Absolute (estimate} - \text{actual)}}{\text{Absolute (last year} - \text{actual)}} \qquad (5)$$

A similar method would be to determine whether the direction of change is the same as predicted.

The estimating process is assessed annually. The least accurate estimates and least accurate waterways are screened for the causes of error. Two measures of error were percentage of error and error-tons. Measures of the different variables (correlation, average error, tonnage of commodity in lock) that might affect error are correlated with the measures of error (see Table 1). Estimates are ordered by groups and the average error of each group calculated by waterway (Table 2), commodity group, and number of variables. I went back to the equations to see what pattern could be found. A good assessment question is, Was our estimate better than a random guess? Usually it was. When it was not, why not?

ESTIMATING PROCESS, 1989 VERSUS 1988

An assessment of the 1989 waterway estimates was done to improve the process, assess its value, and avoid pitfalls for the 1990 process.

Validity of Model

Estimates correlated with WCSC data at a slightly improved 0.99816 for 1989 compared with 0.99758 for 1988. Figure 3 shows this high precision for our estimates compared with the actual WCSC tonnage. Of the 278 estimates, the larger tonnage points are close to the ideal of accurate estimates (equality for the two axes). Only the smaller tonnage points (on the left) show some random scatter and outliers. Smaller tonnage sizes account for this, but accuracy on the smaller waterways and commodities is less important.

Average ton error per estimate was 651,333 for 1989 (15 percent) compared with 952,819 for 1988. The 1988 error was reduced a third for 1989 (see Table 1).

The formula for the efficiency of the model is mean error for the model divided by mean error for a "naive" model that compares the previous year (1988) with the year estimated (*1,13*). When using average absolute tonnage in error (WCSC minus estimated), an efficiency of 0.864 was calculated (the smaller the better). By using average percentage error, the figure is 0.959. A figure above 1.0 would give evidence of an invalid model. Our evidence shows that our model does work better than chance. The 1989 process was better than that of 1988 on the basis of these measures.

Our conclusion is that if we estimated 1989 figures by using the 1988 figures (assuming no changes), we would be less accurate than by using our model. Thus, the formula above might have but does not prove that our model is invalid. (By inference, it is valid.) Another method developed was to determine whether our model predicts the right direction of change between 1988 and 1989. For 62 percent of the time the correct direction of change was predicted: when a commodity of a river was predicted to increase, it did. Predictions for the Apalachicola, Columbia, and Kanawha were very poor: the correct direction of change was predicted only 40 percent of the time (chance alone should give us 50 percent). When these were omitted, the rivers were predicted correctly 68 percent of the time.

Lock data for the Apalachicola, Alabama-Coosa, and Columbia were poor and erratic. Much of the commerce does not go through the only reported lock, and tonnages are small for the former two. Using our validity checks, estimates for these waterways were not valid in 1989.

Comparisons with the 1988 Process

These correlations show that for both years, "average error" correlates highly with absolute percentage error for the year studied. The regression formula is absolute percentage error = 1.7 * average error. We can expect the confidence level for our prediction to be within plus or minus 1.7 times the average error. The regression equation for error-tons is 0.0444 * tons estimated. Thus we can expect an average error of 4.4 percent of the tons for that estimate for 1989.

"Year" as a variable increased accuracy somewhat, especially in reducing error-tons. It was used sparingly. Use of more variables in the equation helps lower the percentage of error, especially when two variables are used (a constant was always used for 1989), but one variable was usually better than two. The adjusted R square was not used for 1989, but its use for 1990 indicated when several variables were justified and when they were not, making multivariable equations more efficacious.

The comparison of estimates of totals for waterways is given in Table 2. Estimates with more tonnage have a smaller percentage of error: above 1 million, percentage error is 10 percent; below, it is 44 percent. Higher correlations between variables strongly reduce error, and a lower "average error" for an equation shows the strongest effect on reducing percentage error (with a 0.55 correlation). For all waterways except the Apalachicola and the Tennessee to Black Warrior

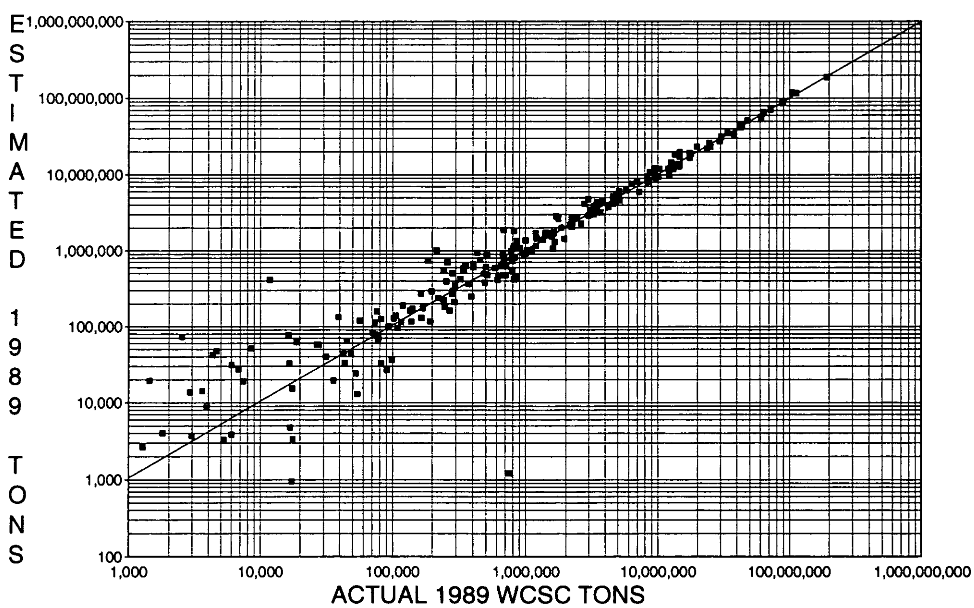

FIGURE 3 Analysis of 1989 estimation process (logarithmic scale).

system, 1989 was an improvement over 1988. Improvement in all waterways in 1990 is noted except for the Ohio and Illinois.

Large-tonnage commodities are more accurate than smaller ones. Fewer locks result in less accurate estimations: the Mississippi is less reliable than the Ohio. For 1990 the one-lock waterways were less reliable: Alabama (mean error of 98 percent), Apalachicola (69 percent), Black Warrior (27 percent). Two- and three- (reporting) lock waterways were somewhat better: Tennessee-Tombigbee (44 percent), Kanawha (30 percent), and Cumberland (30 percent). Past faulty collection of LPMS data also seems a factor in lowering reliability: Alabama (98 percent), Columbia (41 percent), Apalachicola (69 percent). Rivers without these problems were better: Ohio (7 percent), Mississippi (11 percent), Gulf Intracoastal (13 percent), Tennessee (15 percent), Arkansas (21 percent), Monongahela (16 percent), Allegheny (36 percent), and Illinois (35 percent for 1988).

The model for 1989 shows improvement, and data indicate that it is a valid model. Reliability can now be predicted, and several factors increasing reliability are known.

REITERATIVE PROCESS: LEARNING FROM EXPERIENCE

Available recent statistical sources were consulted. Government library facilities were not adequate (except for the loan system), but university libraries were helpful. Opportunities to consult with experienced statisticians working on similar problems might help this process, as might a sense of fallibility and a willingness to drop less successful methods.

Our past regression equations were consulted, but each equation was updated with the newly available WCSC figures every year.

Better methods include using regression equations, larger-tonnage locks, "logical measures" of waterway tonnage even if correlations are lower, and fewer variables except on the larger tonnages.

Graphical analysis was used: scattergrams may pinpoint a year in which the results are out of line. Line graphs of tonnages by commodity between all the locks of a river [e.g., Ohio (Figure 2)] show which lock or sum of locks gives the maximum tonnage for the waterway. Graphs by year of various measures, including actual WCSC data and the more promising regression estimates, may show which is the best estimator, or when the lock or WCSC has not collected all the tonnage data, and perhaps which years might be omitted from the equation (Figure 1).

The adjusted R square, along with common sense, can help select variables. Graphs can show whether there is any pattern to past tonnage relationships to tell whether estimation is justified and, if so, what years to use.

These methods (graphical analysis, adjusted regression equations, common sense, and corrected R square) seem sounder than previous ones. If not, other ways will be sought to perfect the methodology. Advance 1990 WCSC data showed improvement for all waterways except the Ohio and the Illinois. The latter may contain problems, which will be studied. Otherwise the improvement would have been more dramatic. The Mississippi improved slightly in spite of the absence of lock data for the lower Mississippi. Total tonnage error for all estimates decreased by 11 million tons or 7 percent for 1990 over 1989.

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Methodology for Planning Efficient Investments on Inland Waterways

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A methodology that addresses the analytic complications associated with making investment planning decisions for inland waterway improvements is presented. The complications include interdependencies between locks, bidirectional traffic, stalls, dual chamber facilities, and budget limitations. The methodology addresses most steps of the investment planning process for locks, namely project evaluation, sequencing, and scheduling.

The national waterway study and other navigation studies identified a need for substantial investment in the waterway infrastructure on the basis of several trends and observations. The first trend is that lock conditions are deteriorating, giving rise to an increase in tow delays. Currently, there are about 100 locks that have exceeded their design life. The second is that traffic levels are consistently increasing for many locks in the system. Also, prospects for increased grain exports are improving. Currency reform, the grain export enhancement program, reduction in worldwide carryover stocks of grain, and other factors have contributed to increases in exports. A third trend is an increase in tow sizes. Whereas this tends to increase overall transport efficiency, large tows must be disassembled into several pieces to move through the chamber and must later be reassembled. The fourth observation is that additional funding sources for major lock rehabilitation projects is not likely. The major sources of funding for such projects are the federal matching share and fuel tax receipts. The federal share of 50 percent and the fuel tax rate of 20 cents beyond 1995 are not likely to increase in the near future.

The trends identified by these studies present interesting but challenging opportunities for developing a more comprehensive methodology for inland waterway planning and operations analysis. The following are the primary analytical needs in developing such a methodology:

1. More reliable forecasting methods,
2. More reliable techniques for predicting delays at locks,
3. Identification and assessment of the benefits of lock rehabilitation, and
4. More efficient techniques for sequencing and scheduling lock improvement projects.

This paper presents an overview of a methodology designed to address many of the analytical needs resulting from trends in conditions, traffic levels, and funding sources for waterway locks. Particular emphasis is placed on satisfying Items 2 and 4 above. The methodology is the product of several research projects conducted over the last 4 years through the Institute for Water Resources and consists of the following components:

1. Exploratory data analysis and characterization of problems,
2. A microsimulation model of waterway traffic and lock operations,
3. Statistically estimated functions ("metamodels") to approximate the results of the simulation model,
4. An algorithm for prioritizing and scheduling proposed lock improvement projects, and
5. A computer program for cash flow analysis for the Inland Waterway Trust Fund.

BACKGROUND

There are numerous analysis tools available to assist in modeling lock operations and investment parameters. These include benefit-cost analysis, mathematical programming, queuing theory, and simulation. There exist some significant works on the application of these tools to waterway problems. However, extensions of the previously available methods were necessary to meet the analytical demands of current U.S. waterway transportation problems.

Determination of Delays at Locks (Analytic Models)

Two single-lock models based on the application of queuing theory have been found for estimating lock delays. DeSalvo and Lave (*1*) represent the lock operation as a simple server queuing process with Poisson distributed arrivals and exponentially distributed service times. However, these assumed distributions do not adequately fit the physical system of locks on waterways (*2*). Wilson (*3*) improved on this model by treating the service processes as general distributions rather than as exponentially distributed, which is far more realistic (*2*). However, this was for single-chamber locks only, and the Poisson arrivals assumption is not realistic for all locks.

Two other deficiencies exist in both of the above models. First, neither accounts for stalls. Stalls cause service interruptions at locks, thus reducing lock capacities or increasing delays. Their occurrence is very difficult to predict. Second,

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both models were developed to analyze delays at a single isolated lock. Since the delays at adjacent locks may be highly interdependent, it is desirable to analyze lock delays for entire systems.

Queuing theory offers some solutions for more general queuing systems [i.e., those beyond Poisson arrivals and exponential service times (M/M/1)]. In special cases combining Poisson arrivals with general service times (M/G/1) and general arrivals with exponential service times (G/M/1), closed-form solutions for the mean waiting time have been obtained (*3*). G/G/1 queues are difficult cases in queuing theory, and the available techniques for handling them are incomplete. Solving G/G/M queues is even more difficult than solving G/G/1 queues. The methods of approximations and bounds have been proposed to solve G/G/M queues (*4*). These can be accurate and efficient under heavy traffic conditions. However, the methods are difficult to extend to the series and networks of queues found in waterways.

Determination of Delays at Locks (Simulation Models)

An early microscopic simulation model to analyze lock delays and tow travel times was developed by Howe et al. (*5*). In that model, service times were based on empirically determined frequency distributions. To avoid some troublesome problems and errors associated with the requirement to balance long-run flows in that model, Carroll and Bronzini (*6*) developed another simulation model. It provided detailed outputs on such variables as tow traffic volumes, delays, processing times, transit times, average and standard deviations of delay and transit times, queue lengths, and lock utilization ratios.

Each of these models simulates waterway operations in detail but requires considerable amounts of data and computer time, which limits their applicability for problems with large networks and numerous combinations of improvement alternatives. They both assume Poisson distributions for tow-trip generation, which is not always realistic. Moreover, service failures ("stalls"), which are very different in frequency and duration from other events and have significant effects on overall transit-time reliability, are not accounted for. Hence a waterway simulation model that explicitly accounts for stalls is desirable for evaluating and scheduling lock improvement projects.

Benefit-Cost Analysis for Interdependent Improvement Projects

The delays at locks have been shown to be interdependent, that is, delays at one lock are related to delays at one or more other locks (*7*). That is because the departure process from one queuing station (e.g., a lock) in a network affects the arrival process at the next queues in that network. Interdependence not only yields difficulties in predicting lock delays but also in conducting benefit-cost analysis. Current methods of benefit-cost analysis are quite satisfactory for analyzing mutually exclusive projects and reasonably satisfactory for independent projects. However, there is a void in analyzing projects that are interdependent.

In evaluating and sequencing mutually exclusive projects, the net present value and benefit-cost ratio methods (*8*) can be used if the benefits and costs are quantifiable and can be accurately assessed over the planning horizon. This is because, in such cases, the benefits and costs of projects are not dependent on the project set selected. When working with independent projects, we can use an integer programming approach, where the objective is to maximize the sum of net present values subject to a set of budget constraints. (*9*).

However, for interdependent projects, the estimates of benefits and costs must be performed simultaneously with project selection. Therefore, it may be necessary to enumerate all possible project combinations when selecting a set of projects and all possible permutations when sequencing a set of projects. However, as a practical matter, complete enumeration becomes infeasible as a method of finding optimal combinations and permutations of projects as the number of projects becomes even modestly large. An alternative to complete enumeration is an augmented integer programming formulation. Such methods are discussed elsewhere (*9*). To capture some of the interdependence, the objective function includes interaction terms for pairs of projects. These terms represent the deviation from linear addition when summing the net present values for two interdependent projects. For example, if Projects A and B are independent, the net present values may be summed linearly:

$$NPV_{AB} = NPV_A + NPV_B \tag{1}$$

Alternatively, for interdependent projects an interaction term is added:

$$NPV_{AB} = NPV_A + NPV_B + d_{AB} \tag{2}$$

There are significant shortcomings with such an approach. First, only paired interactions are represented; depending on the application, three, four, or more projects may be simultaneously dependent. Second, the number of integer variables and interaction terms is excessive. The estimation of interaction terms is quite complex for most applications. Whereas many problems may be smaller than this example, most integer programming algorithms have serious difficulties with problems of this size.

There is a need to formulate the selection and sequencing of interdependent projects in a manner that is not computationally intractable and that does not require excessive estimation of interaction terms. It seems that overcoming these voids requires the development of a method whereby the numerous permutations of possible programs may be efficiently represented and searched (without complete enumeration) and the determination of efficient project implementation schedules.

COMPONENTS OF THE METHODOLOGY

Simulation Model

In light of the many shortcomings and difficulties associated with analytic methods of estimating delays at locks, a simulation model has been developed to analyze tow operations along waterways. The model may be used to determine the relations among delays, tow trips, distributions of generated travel times, and coal consumption and inventories. The model can account for the stochastic effects and seasonal variations and can estimate the following: tow delays at each lock, interarrival and interdeparture time distributions for each lock and for each direction, tow travel times along the waterway, inventory levels and expected stock-out amounts for commodities delivered by waterway, and many other variables of interest to waterway users and operators.

Development of the model was based on the Lock Performance Monitoring System (LPMS) data. The model is event scanning, with four types of events initiating a status update: (*a*) stochastic generation of tow trips; (*b*) tow entrances at locks as determined by arrival times, chamber availability, and chamber assignment discipline; (*c*) the arrival of a tow at its destination; and (*d*) the occurrence of stalls at a chamber.

Several features of this model lend themselves well to waterway operations. The simulation model is microscopic (i.e., it traces the movement of each individual and records its characteristics, including the number of barges, commodity types, speed, origin and destination, travel direction, and arrival time at various points). Any distributions for trip generation, travel speeds, lock service times, and tow size may be handled by the model. These distributions can be specified for each interval in tables or by standard statistical distributions. Tows are allowed to overtake other tows, and the model simulates two-way traffic through common servers and accounts for stalls. The size of waterway systems that the model can handle is limited only by computer and computer capacity. Further, the model has been developed with "dynamic dimensioning" for additional increases in flexibility in modeling various waterway systems.

The main simplifying assumptions in the current version of the simulation model are as follows:

1. The tows maintain a constant size through the entire trip.
2. The service discipline is first-in-first-out, as are operations on the Mississippi and Ohio rivers.
3. The queue storage area is unlimited.
4. The tow speeds are normally distributed and constant for each round-trip.
5. The time intervals between two successive stalls and the stall durations are exponentially distributed.

These assumptions are not seriously restrictive, but they can still be easily modified.

The simulation model consists of five operation routines and one scheduler routine. The operation routines are associated with the five types of events and are invoked by the scheduler. Figure 1 is a chart of the flow of data as dictated by the model.

To check the logic of this simulation model, its results were first compared with theoretical (but well-established) results from queuing theory. The results of the model were then compared with observed data to demonstrate how closely the model represents real systems and verify its ability to simulate the special features of waterways.

A partial validation of the model is possible by comparing the model to theoretical results for the special case of Poisson arrivals and generally distributed service times. The waiting times predicted by the simulation model at a single lock were compared with those obtained from queuing theory for this special case. A validation has been conducted for a variety of volume/capacity (V/C) ratios ranging from 0.0471 to 0.8934. To reduce the variance of the output, each result was obtained by averaging the output from 30 independent simulation runs. To ensure that results were compared for a steady state, each simulation run discarded the first 10,000 tow waiting times and collected the next 12,000 values for computing the average waiting time.

The results, given in Table 1, confirm that the simulated and theoretical average waiting times are extremely close. Such results verify that the overall mechanism of the simulation model is correct. They also show that generally distributed service times are generated satisfactorily in the simulation model. That is reassuring, since the same logic is used to generate generally distributed interarrival times for G/G/1 queues and, ultimately, to develop metamodels for series of G/G/1 queues.

The simulation results were then compared with the observed data at Locks 22, 24, 25, 26, and 27 on the Mississippi River. These locks were selected on the basis of their criticality and available data. The five locks were simulated as an interacting series. Some of the validation results are summarized in Table 2. Each result is averaged from 80 independent simulation runs. Table 2 indicates that the difference between the simulated and observed average waiting times for each lock is within the 95 percent confidence interval based on the *t* test, except at Lock 25. The observed data also show that tows sometimes were kept waiting at Lock 25 even when the chamber was idle. Therefore, no direct comparison of average waiting times at Lock 25 is appropriate.

Metamodel Approximations to Simulation

Each simulation run takes from a few seconds to a few minutes on a personal computer, depending on the values of various parameters. Despite this high level of efficiency, simulation time becomes expensive for evaluating large combinatorial problems such as investment planning. Furthermore, the project combinations may have to be evaluated over several time periods. A metamodeling approach that statistically estimates unknown parameters of equations from simulation results and then uses these equations as substitutes has been developed to overcome the computational requirements of simulation. The main difficulty with this approach is in finding structural forms for the approximating functions that fit the simulation results as well as possible. This was accomplished by queuing theory insofar as possible for these functions.

In this study, a numerical method has been developed for estimating delays through a series of queues. The method decomposes systems of queues into individual queuing stations. The analysis of each queuing station is further decomposed into three modules: arrival processes, departure processes, and delay functions. Arrival processes at a particular lock depend on the departure distributions from the upstream and downstream locks and the intervening speed distributions. Departure processes depend on the interaction among the arrival distributions and service time distributions at one lock. Delay functions relate the waiting times to the arrival

```
INPUT:

Link & Lock Characteristics
Traffic Demand
Probability Distributions
Inventories & Consumption
```

```
PROCESS:

Origin Nodes: generating tow trips
Destination Nodes: updating: cumulative deliveries
                             cumulative consumption
                             inventory levels
Locks: assigning chamber
       determining number of cuts
       determining lock service times
       calculating queuing times
Links: determining traveling times
       determining arrival times to next locks or
       destinations
```

```
OUTPUT:

Average waiting time per tow at each lock
Average waiting time per tow at each lock for each O-D pair
Means and variances of interarrival and interdeparture times at
 each lock
Cumulative deliveries, cumulative consumption, inventory levels
Average speed
Total number of tow trips for different O-D pairs
Total queuing times for different locks
Total lock service times for different locks and chambers
Total tow travel times & distances
```

FIGURE 1 Structure and elements of the simulation model.

TABLE 1 Comparison of Theoretical and Simulated Results for a Single Lock Queue (M/G/1)

V/C	T_A *1		T_S *2		W_{sim} *3	W_t *4	Devia. *5
	Avg (hr)	Var (hr^2)	Avg (hr)	Var (hr^2)	(hr)	(hr)	(%)
0.893	0.888	0.789	0.793	0.319	4.9516	5.0059	-1.09
0.755	0.888	0.789	0.670	0.227	1.5575	1.5522	0.34
0.566	0.888	0.789	0.503	0.128	0.4926	0.4935	-0.19
0.330	0.888	0.789	0.293	0.044	0.1082	0.1087	-0.46
0.047	0.888	0.789	0.042	0.001	0.00155	0.00156	-0.64

*1 T_A: interarrival times
*2 T_S: service times
*3 W_{sim}: average waiting times from simulation
*4 W_t: average waiting times from queuing theory
*5 Devia.: deviation which is defined as $(W_{sim}-W_t)/W_t*100\%$

and service time distributions. The basic concept of this method is to identify the parameters of the interarrival and interdeparture time distributions for each lock and then estimate the implied waiting times.

To estimate delays in a queuing system, we need to know the means and variances of the interarrival, interdeparture, and service time distributions. For series of G/G/1 queues and bidirectional servers, a difficulty arises in identifying the variances of interarrival and interdeparture times because the interarrival times at each lock depend on departures from both upstream and downstream locks, and the variances of interarrival times cannot be determined from one-directional

TABLE 2 Comparison of Simulated and Observed Waiting Times

Lock	W_{sim} *1 (min)	W_{obs} *2 (min)	Difference (min)	95% Confidence Interval
22	4.09	3.73	0.36	3.49
24	6.12	6.36	0.24	6.72
25	4.49	10.94	6.45	-*3
26	119.40	130.99	11.59	60.73
27	36.49	34.43	2.06	23.92

*1 W_{sim}: simulated average waiting times
*2 W_{obs}: observed average waiting times
*3 The comparison is not appropriate.

scans along a series of queues. To overcome such complex interdependence, an iterative scanning procedure is proposed. The core concept is to decompose the system into individual locks and then sequentially analyze each of those locks. At each lock, the two arrivals from both directions are first combined into an overall arrival distribution and then split into two-directional departure distributions.

The algorithm is initiated by scanning along waterways from either direction, sequentially estimating the interarrival and interdeparture time distributions for each lock. Initially assumed values for the variances of interdeparture times from the opposite direction must be provided for the first scan. Then the scanning direction is reversed and the process is repeated, using the interdeparture time distributions for the opposite direction estimated in the previous scan. Alternating directions, the scanning process continues until the relative difference in the preselected convergence criteria stays within preset thresholds through successive iterations. Waiting times at locks can be computed in every iteration (and then used as convergence criteria) or just once after all iterations are completed.

Arrival Processes

The mean and standard deviation of interarrival times are estimated in two steps. First, the means and standard deviations of directional interarrival times at a particular lock are estimated from the interdeparture time distributions of the adjacent locks. If flows are conserved between locks and the V/C ratio is less than 1.0, such relations are represented in Equation 3:

$$\bar{t}_{aji} = \bar{t}_{djk} \qquad \begin{cases} k = i - 1 \text{ if } j = 1 \\ k = i + 1 \text{ if } j = 2 \end{cases} \tag{3}$$

where

$\bar{t}_{aji}$ = the average interarrival time for Direction j and Lock i,
$\bar{t}_{djk}$ = the average interdeparture time for Direction j and Lock k, and
j = direction index (1 = downstream, 2 = upstream).

Because speed variations change headway distributions between locks, Equation 4 was developed to estimate the standard deviation of directional interarrival times at one lock.

$$\sigma_{aji} = \sigma_{djk} + \underset{(0.002)}{0.0251}\ln\left(1 + \frac{D_{ik}\sigma_{vik}}{\mu_{vik}}\right) \qquad \begin{cases} k = i - 1 \text{ if } j = 1 \\ k = i + 1 \text{ if } j = 2 \end{cases} \tag{4}$$

$R^2 = 0.999954 \qquad n = 107 \qquad s_e = 0.0586 \qquad \mu_y = 5.1685$

where

σ_{aji} = standard deviation of interarrival times for Direction j and Lock i,
σ_{djk} = standard deviation of interdeparture times for Direction j and Lock k,
D_{ik} = distance between Locks i and k,
μ_{vik} = average tow speed between Locks i and k,
σ_{vik} = standard deviation of tow speeds between Locks i and k,
j = direction index (1 = downstream, 2 = upstream),
s_e = standard error of dependent variable, and
μ_y = mean of dependent variable.

This suggests that, theoretically, the standard deviation of directional interarrival times should be equal to the standard deviation of directional interdeparture times plus an adjustment factor depending on the speed distribution and distance.

Second, the overall mean and coefficient of variation of interarrival times for this lock are estimated on the basis of coefficient of variation of directional interarrival times.

$$\bar{t}_{Ai} = \frac{\bar{t}_{a1i} * \bar{t}_{a2i}}{\bar{t}_{a1i} + \bar{t}_{a2i}} \tag{5}$$

$$C_{Ai}^2 = \underset{(0.027)}{0.179} + \underset{(0.014)}{0.41}\,(C_{a1i}^2 + C_{a2i}^2) \tag{6}$$

$R^2 = 0.9188 \qquad n = 79 \qquad s_e = 0.0059 \qquad \mu_y = 0.988$

where

$\bar{t}_{Ai}$ = the average interarrival time at Lock i,
C_{Ai}^2 = squared coefficient of variation of interarrival times at Lock i, and
C_{aji}^2 = squared coefficient of variation of directional interarrival times for Direction j and Lock i.

In Equation 6 the coefficients of variation of upstream and downstream interarrival times carry the same weight in estimating the overall variance of interarrival times, since the mean directional trip rates are equal.

Departure Process

The departure module estimates the mean and coefficient of variation of interdeparture times. On the basis of the flow conservation law, if capacity is not exceeded, the average directional interdeparture equals the corresponding interarrival time:

$$\bar{t}_{dji} = \bar{t}_{aji} \tag{7}$$

The coefficient of variation of interdeparture time is estimated in two steps. First, the coefficient is estimated for combined two-directional departures. Departure processes with generally distributed arrival and service times are analyzed using Laplace transforms. The following metamodel was eventually developed to bypass the difficulties of determining the variances of the lock idle times:

$$C_D^2 = 0.207 + 0.795\,(1 - \rho + \rho) + (\rho^2 - \rho^2)$$
$$= 0.207 + 0.795 = 1.002 \cong 1.0 \tag{8}$$

Next, the coefficient of variation of directional interdeparture times is estimated. The following metamodel was developed for this purpose:

$$\underset{(0.0056)}{C_{dji}^2 = 0.518} + \underset{(0.0068)}{0.491 C_{aji}^2\, C_{Di}^2} \tag{9}$$

$R^2 = 0.9710$ $n = 158$ $s_e = 0.013$ $\mu_y = 0.9164$

where

C_{dji}^2 = squared coefficient of variation of directional interdeparture times for Direction j and Lock i,
C_{aji}^2 = squared coefficient of variation of directional interarrival times for Direction j and Lock i, and
C_{Di}^2 = squared coefficient of variation of interdeparture times for Direction j and Lock i.

Delay Function

The delay function is intended to estimate the average waiting time at a lock. By applying Marshall's formula for the variance of interdeparture times, an exact solution for the average waiting time, W, was obtained as follows:

$$W = \frac{\sigma_A^2 + 2\sigma_S^2 - \sigma_D^2}{2\bar{t}_A\,(1 - \rho)} \tag{10}$$

where

W = average waiting time,
σ_A^2 = variance of interarrival times,
σ_s^2 = variance of service times,
σ_D^2 = variance of interdeparture times,
$\bar{t}_A$ = average interarrival time, and
ρ = volume to capacity ratio.

In this delay function, the average waiting time increases as the variance of interarrival and service times increases and decreases as the variance of interdeparture times increases. The average waiting time approaches infinity as the V/C ratio approaches 1.0.

Comparison of Simulated and Numerical Results

To validate the numerical method, its results were compared with the results of the previously validated simulation model. Various system configurations were compared, including a relatively large 20-lock system.

The parameter values for this test system (e.g., means and standard deviations of input distributions and distances between locks) were obtained from random number generators, except for traffic volumes, which were assumed to be 10 tows per day in each direction throughout the system. The numerical model estimates aggregate waiting times within 8 percent of those simulated. At individual locks, the percent errors are slightly greater but within 10 percent. In its current form, the modeling approach does not consider possible diversion to other modes on the basis of excessive delay. However, the model might be applied iteratively with a demand reestimation model.

Project Sequencing and Scheduling

Sequencing

Either the simulation model or the metamodels may serve as a project evaluation tool. That is, both are able to provide delay estimates for a system of locks for different combinations of proposed lock improvements (i.e., any measure that physically or effectively increases the capacity of a lock). This is the basis for estimating the benefits associated with such improvements. The choice should be based on a trade-off between precision for complete lock operations (favoring simulation) and computational efficiency (favoring the metamodels). Thus, the metamodels may be used for preliminary screening and the simulation for the final detailed evaluation.

The next step in the investment planning methodology is a technique whereby the permutations of investment sequences may be efficiently searched and a corresponding optimal schedule found. The proposed approach for searching the solution space of possible project permutations represents the solution space in two dimensions and applies a heuristic search algorithm in selecting the preferred sequence. Given a system cost evaluation function for interdependent projects $g(\mathbf{X},\mathbf{Y})$, the selection and sequencing problem may be represented in two-dimensional space. The function $g(\mathbf{X},\mathbf{Y})$ incorporates both benefit and cost factors into a generalized cost while accounting for project interdependencies, where $\mathbf{X}$ is a vector of delay variables and $\mathbf{Y}$ represents a particular combination of projects.

Assuming that each set of projects may be viewed as a system generating a common time-dependent output, a two-dimensional representation is feasible. For the lock rehabilitation problem, the costs associated with a given combination of projects in a given time period t may be written as

$$(SC)_{iY} = C_Y + g\{X[\lambda(t)],Y\}(OC) \quad (11)$$

where C_Y is the total capital cost of construction for the set of projects Y. The term $g\{X[\lambda(t)],Y\}$ represents the delay and corresponds to the functions obtained from some interdependent evaluation (e.g., from a simulation model). OC is the opportunity cost of delay (which may be either a constant or a function of time). Evaluating SC at different levels of output for a combination of projects Y defines a curve with annual system costs SC_Y on the vertical axis and output level λ on the horizontal axis. Repeating for different values of **Y** (i.e., different project combinations) produces a family of curves. By always choosing the lowest-cost curve for any given output level λ (i.e., by choosing the "lowest envelope" of the curves in Figure 2), a sequencing and scheduling decision path is defined. Because the output is assumed to be time dependent, the horizontal axis may also represent time periods (e.g., years). Output and time may be linked through a demand function, $\lambda(t)$.

Consider an example with interdependent projects A, B, and C. Figure 2 shows a family of system cost (SC) curves corresponding to the possible combinations of these three projects. Note that in general, combinations involving only one project are preferable (lower SC) for low levels of volume (thus earlier in the horizon stage) and become less preferable as volume increases. Under this representation, one combination is preferred to another at a given output level (or time period) if its corresponding curve lies above the other. (Although the convex and monotonically increasing properties of the curves in Figure 2 are likely to occur for costs with a delay component, they are not a prerequisite for the methodology.)

In the example shown in Figure 2, the selection and sequence of projects is dictated by the lowest "envelope" defined by the curves. This lowest envelope corresponds to the minimization of the time integral of the system cost for feasible expansion paths. Here, all three projects would be accepted if the volume level is expected to eventually exceed Q_2. We see also that the sequence of projects should be A, B, C; this is because Curve A lies below B and C, and AB lies below AC in the relevant regions. Project A is preferred up to volume level Q_1 at the same time Project B should be implemented since Curve AB falls below Curve A. At volume level Q_2, Project C should be added to A and B, thus implementing Combination ABC.

Unfortunately, not all such families of curves can be interpreted as easily as Cases 1 and 2. Consider a second case shown in Figure 3, where Curves A and AB are unchanged but the others are different. Here, Curves AB and AC intersect each other before intersecting Curve ABC. It cannot be stated a priori whether Combination AB or AC should be selected on the expansion path between A and ABC. It is expected that if Area 1 is greater than Area 2, Combination AB is preferred to AC and Project B should precede Project C on the expansion path. Areas 1 and 2 correspond to the difference savings when integrating over Paths A-AB-ABC and A-AC-ABC, respectively.

Scheduling

Under the assumption that the benefits associated with a given combination of projects in some period vary only with the output of the system in that period, the start dates of the projects do not affect the system costs. Thus the SC curves for a project combination depend only on the presence, rather than start times, of particular projects in that combination. The implications in the context of waterways are that the capital cost of construction, operating and maintenance costs, and benefits from reduced delays are not affected by the age of the locks at any given time (i.e., by project start dates) but only by the volume of traffic using the locks. This assumption

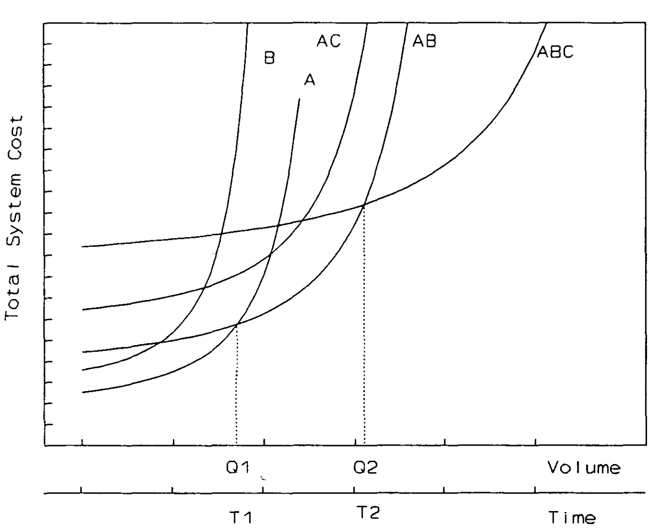

FIGURE 2 System cost for three interdependent projects (Case 1) incorporating a budget constraint.

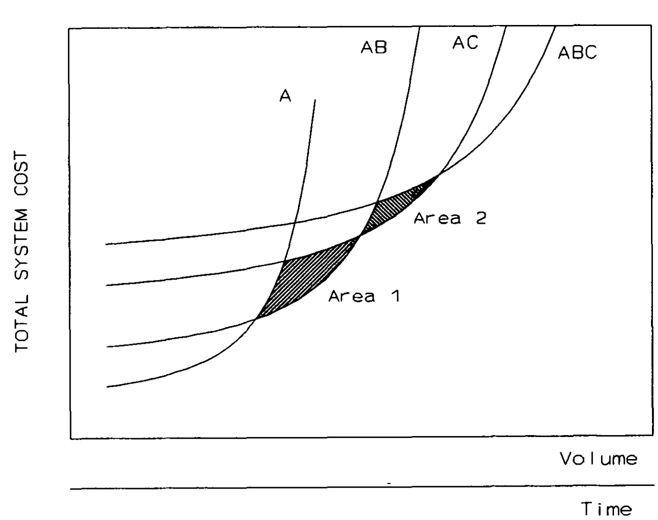

FIGURE 3 System cost for three interdependent projects (Case 2).

is very reasonable for the capital costs but somewhat simplifies the operating and maintenance costs. The assumption is also reasonable for delay benefits, although it neglects the effect of long-term economic changes induced by the presence and performance of waterway investments.

In structuring the budget constraint, it will be assumed that funds not spent in a given period will be available in subsequent periods. Under this assumption, budget limitations have the effect of delaying the earliest feasible start date of a given project combination, just as they limit the earliest start of an individual project. Consider the small example of two projects A and B. In constructing the Curves A, B, and AB, the infeasible portion must not be included. Figure 4 shows that Combination A is not financially feasible until time T_1 corresponding to output Q_1. Combination AB is not feasible until time T_2. The possible expansion paths are then as follows: (*a*) start A at time T_1 and B when Curves A and AB intersect, and (*b*) start B immediately and A when Curves B and AB intersect.

In the validation, systems of four and six locks were used to compare the solution from the algorithm with that obtained through exhaustive enumeration. (Conducting such tests on larger systems is not possible because the optimal solution cannot be determined for comparison with the solution obtained from the sequencing methodology.) In these four- and six-lock experiments the optimal answer was found by the algorithm in 93.3 and 95 percent of the cases. In the suboptimal cases, the cumulative costs were within 1 percent of those of the optimal sequences.

Cash Flow Analysis

The output of sequencing and scheduling algorithm is the order in which the projects are to be implemented and the project start times (i.e., the time when construction is complete and the facility is returned to full operation). Unfortunately, the implementation of construction schedules are not without uncertainties. Often, projects may be delayed

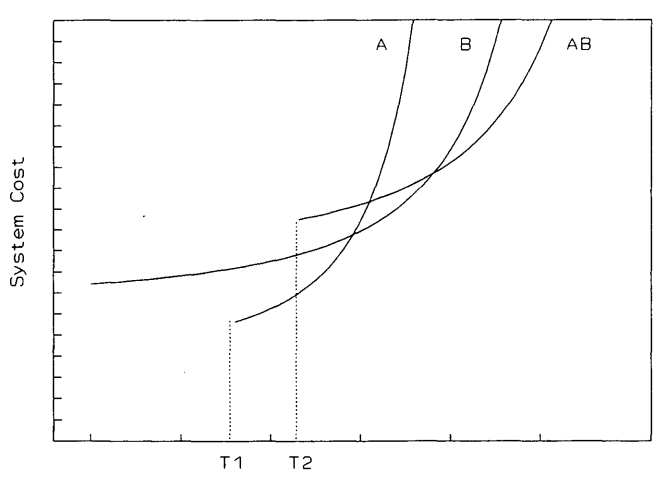

FIGURE 4 Incorporating a budget constraint.

because of funding interruptions, technical complications, cost overruns, or other unforeseen conditions. Such delays and overruns can be binding on the Inland Waterway Trust Fund (IWTF). For example, if soil and geological surveys incorrectly assess the type of foundational rock, a project might be interrupted to permit further engineering and design. For this reason, it is helpful to have a methodology for evaluating financial sensitivities to changes in project costs and schedules.

Such a methodology was developed and programmed for the Corps of Engineers to conduct sensitivity analysis of the IWTF with respect to numerous scheduling and budgeting parameters. The primary computational objective behind the methodology is to reveal the resulting trust fund balance profile over a specified planning horizon. The methodology allows for the inclusion of the numerous factors in obtaining the cash flow profile of the IWTF, for example,

1. Project sequence and start dates,
2. Distribution of project costs over the construction period,
3. Duration of the construction period,
4. Length of any project interruptions,
5. Interest rate accrued on unspent sums over the planning horizon,
6. Fuel consumption rates over the planning horizon, and
7. Fuel tax rates over the planning horizon.

The computer program that implements the cash flow analysis consists of four modules and a comprehensive user interface. The scheduling module provides utilities for controlling project-specific parameters such as project start time, construction duration, and interruptions. The expenditure module considers four basic trust fund parameters: distribution, federal matching share, inflation, and base year for discounting. This module provides for three types of expenditure distributions (normal, uniform, and user defined). The revenue module incorporates the fuel tax, fuel consumption, and account interest rates to determine the total revenues available in each time period. The output module provides a summary table of the trust fund balances and a host of graphic utilities and summary statistics. The computer program has been successfully applied to analyze the sensitivity of the trust fund balance to many of the possible uncertainties.

ADDITIONAL APPLICATIONS OF THE METHODOLOGY

Applications that can be envisioned for this entire methodology or for some of its components include the following:

1. Estimation of lock delays under various conditions such as congestion levels, stall patterns, traffic mix, operational improvements, major capacity improvements, and closures for maintenance;

2. Computer evaluation of various lock operating options such as chamber assignment selection for tows, grouping of vessels in chambers, use of helper boats, priorities among vessels, and platooning (m-up-n-down);

3. Investment planning and programming, including selection and timing of new projects and smaller-scale improvements under financial constraints;
4. Improved management decisions for tow operators (e.g., optimizing fleet schedules and operating speeds under various levels of lock congestion and unreliability);
5. Improved management decisions for shippers (e.g., inventory policies, mode choice, and facility location decisions); and
6. Improved demand forecasting based on an improved estimate of future service levels.

Beyond such waterway applications, it appears that the approximation methods for queuing networks may be applied in other types of systems such as road networks, communication networks, manufacturing plants, and parallel computer processors. The algorithm for scheduling interdependent projects should have even wider applicability.

CONCLUSIONS AND EXTENSIONS

A fairly comprehensive methodology has been developed for evaluating and scheduling waterway system improvements. Some of the elements may be separately used in several other important applications. Some relatively complex aspects of the waterway system, such as the interactions among delays at adjacent locks, the effects of relatively rare lock failures on delays, and the effects of reliability and congestion on tow operating decisions and shipper inventory policies can be analyzed with this methodology.

Further research would be desirable in several areas, including the following:

1. Improved microsimulation components to analyze, in greater detail, various lock operating options;
2. Improved metamodels for the approximation of operating characteristics at multiple chamber locks;
3. Hybrid model switching automatically between simulation and metamodels depending on required model sensitivity;
4. New variants of the scheduling algorithm that trade computation time for improved solutions; and
5. Connections to a model that predicts equilibrium demand over time in a multimodal network.

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Risk Uncertainty in the Transport of Hazardous Materials

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During the last several years, a number of risk estimation models have been developed in North America and Europe for the transport of dangerous goods. Despite similarities in the nature of the transport problems, these models have failed to produce agreement on the nature and validity of the reported risk estimates. Notwithstanding major advances in this field of research, inconsistency continues to plague the estimation process. The nature of the inconsistency in risk estimation is not well understood and has not been adequately addressed in the current research effort. Several risk analysis models have been applied to a common transport problem. By applying these models to a common transport problem, much of the variability in risk caused by assumptions and differences in data has been taken into account. The results of a statistical analysis of risk uncertainty among different models is presented. Significant variations are reported for different risk components by model source. Much of the uncertainty in the risk component estimates was found to cancel out for this transport problem, resulting in good agreement among the model sources in the final societal risk estimate, despite lack of agreement on the value of the various constituents of societal risk.

A number of significant advances have taken place in recent years in the estimation of risks for the transport of hazardous materials. These advances have been made possible by a better understanding of the process and access to improved data bases.

With a better understanding of the process, a corresponding increase in the consistency of estimates as provided by different risk analysts would be expected. However, recent research has only underscored a general lack of agreement among the research community on the nature and validity of the reported estimates. Depending on the source, risk estimates continue to reflect significant variability for similar transport situations and contradictory conclusions regarding the most appropriate actions to take. Much of this variability remains unexplained.

The treatment of risk uncertainty requires a thorough understanding of the nature of the risk analysis process as it applies to the transport of hazardous materials. This process consists of five components: (*a*) accident likelihood, (*b*) containment system failure given an accident or fault, (*c*) volume and rate of material released, (*d*) hazard area associated with each potential threat for different releases and materials, and (*e*) population affected for different levels of damage.

Each of the five components of risk requires specification of separate submodels with a unique set of inputs and outputs.

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Variability in these estimates results from three basic sources (*1*):

1. Underlying assumptions governing the estimates,
2. Jurisdictional differences concerning the validation and application of the models, and
3. Structural differences in the models themselves.

Since many models were developed for specific transportation corridors and shipment conditions, the nature of the adjustments required to yield consistent results is not always evident from the background material provided on each estimate. To understand the nature of risk uncertainty, it is important to account for assumptions and jurisdictional factors that are unique to each model. Any variability in the estimates that cannot be accounted for in this manner is considered "uncertainty" and must be treated statistically.

The purpose of this paper is to present some of the major results and conclusions of a hypothetical corridor exercise on risk uncertainty carried out as part of the International Consensus Conference on the Risks of Transporting Dangerous Goods held in Toronto, April 6–9, 1992. In this exercise, various quantitative risk analysis models were applied to a common transport problem involving the bulk shipment of chlorine, LPG, and gasoline by road and rail along predefined routes.

CORRIDOR APPLICATION

The corridor analysis for the risks of transporting hazardous materials is based on a set of specifications for different modes, weather conditions, and material properties. This problem is designed to limit the extent of variability in the estimates that could be caused by differences in underlying assumptions and jurisdictional data.

Basic Corridor Features

As shown in Figure 1, the test corridor is served by two modes: road and rail. Each route is 100 km in length and is divided into three separate development sections: rural (70 km), suburban (20 km), and urban (10 km). Development densities for population and employment along each of these sections are consistent with densities experienced along typical North American regional transport corridors.

The focus of the corridor risk analysis is on immediate health risks. These risks include fatalities and personal injuries

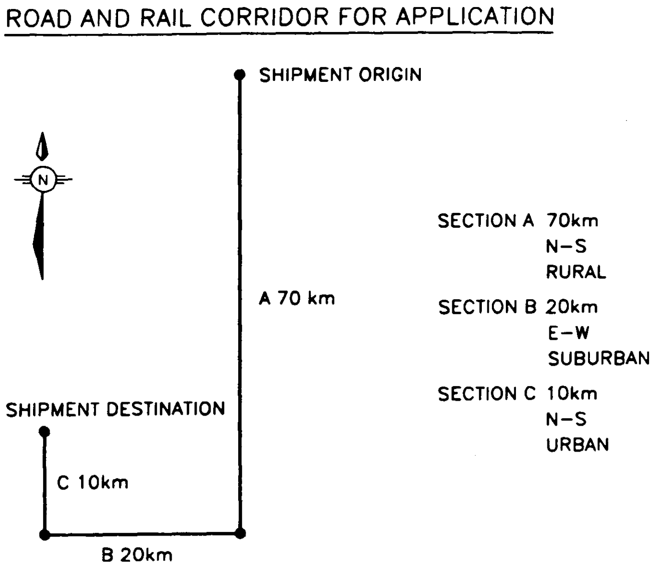

FIGURE 1 Hypothetical corridor features.

experienced near the time of each incident. Long-term health risks and environmental impacts are not considered. For comparison, it is assumed that immediate emergency response capabilities are not available. A number of population and employment distributions and sheltering/evacuation ratios have been assumed for different weather conditions and traffic compositions.

A total of 100,000 tonnes of hazardous materials is shipped annually by each mode along the full length of the corridor from the rural source to the urban destination. Three representative classes of hazardous materials are considered: chlorine (high toxicity, heavy gas), LPG (high flammability and explosiveness), and gasoline (flammable liquid, predominant share of hazardous material road traffic). Representative volumes of materials are shipped in bulk by typical road and rail tankers. The specifications of these tankers are reflective of design standards in use in North America. The use of North American standards of tanker design and corridor development densities should not prejudice the reliability of those models developed for different conditions, since presumably these models are transferable across national boundaries given appropriate specification of the problem and the corresponding model parameters.

The corridor data used in this exercise are "hypothetical," which should not be interpreted to mean unrealistic or impractical. Hypothetical data were used for three major reasons:

1. The estimation process would not be subject to limitations in the data required by more complex risk formulations. Where possible, inputs were provided to reflect the requirements of the most complex models. Simple formulations could choose to ignore these inputs at their discretion.
2. Extreme sensitivities in the results could be assessed while controlling for any combination of factor inputs. The relative consistencies and inconsistencies in the various models could be identified directly in terms of specific corridor features.
3. From a practical perspective, the application would be free from any political controversy generated by a "real" corridor risk assessment. The focus could be better directed at the estimates themselves and not on the political ramifications of the results.

Risk Estimation Sources

Seven risk estimation groups have contributed to the corridor results: Concord Environmental, Health and Safety Executive, Institut de Protection et de Surete Nucleare, Institute for Risk Research, Commission of the European Communities, Netherlands Institute of Environmental and Energy Technology, and Vanderbilt Engineering Center. Background information on each of these model sources is provided elsewhere (*2–7*).

Estimates of risk are reported in terms of each component (i.e., accident, fault, release, hazard area, and population impact) and the final individual and societal risk measures. The analytical basis for each estimate varies considerably from model to model. For example, accident rates were obtained in two ways: direct reference to accident data or as a product of statistical models controlling for any mix of mitigating factors. In some cases, accident rates were estimated by distinguishing vehicles carrying hazardous materials from the accident record of general commodity traffic. In most cases, however, accidents rates were uniformly applied to all kinds of commodity traffic for both truck and rail modes. Release probabilities generally require the occurrence of an accident involving hazardous materials. Estimates of accident-induced release probabilities were obtained in two ways: direct reference to the accident spill data or as a product of a fault tree analysis of containment system failure in an accident situation. In estimating these probabilities, several models distinguished between the occurrence of the containment system fault (breach of containment) and the resultant spill profile; other models treated the two events together. The consequence analysis differed significantly among the various models, depending on the nature of the material involved. In the case of heavy gas dispersion, for example, several models used a Gaussian approximation to obtain the resultant hazard areas; other models used a more detailed heavy gas dispersion formulation that accounts for the puff cloud effect immediately after release. The basic assumptions used by the various sources to obtain the corridor estimates have been summarized by Stewart (*8*) in a background report presented to the International Consensus Conference on the Risks of Transporting Dangerous Goods held in Toronto, April 8, 1992. The implication of these assumptions for explaining variations in the risk estimates has been discussed in some detail by Saccomanno et al. (*9*).

ASSESSMENT OF VARIABILITY IN THE RISK ESTIMATES

The results of this comparative analysis will be presented in two stages:

1. The various risk component estimates are presented graphically for each of the available model sources. Selected

corridor features are invoked where these features are expected to modify the estimates.

2. The models are clustered on the basis of similarities in selected risk component estimates (referred to as seed points). These estimates are used as seed points in the cluster analysis. The resultant model groupings reflect a level of "within group" consistency in these. The significance of the difference in risk component estimates is established statistically using a two-way analysis of variance for the two modes and three shipment materials, with replication for different sources of estimates.

The central issue in this comparative analysis is whether, notwithstanding similarities in the underlying assumptions, the various models yield estimates that differ significantly from one another.

Graphical Analysis of Risk Variability

Figure 2 shows the pattern of accident rates for road and rail along the three sections of the hypothetical corridor. These rates apply to all materials for a given mix of physical design features, traffic composition, and environmental conditions. With the exception of Model D values, most rail accident rates were relatively insensitive to section-specific conditions. On the other hand, most models suggested a gradual reduction in road accident rates from the urban to the rural section, possibly in response to lower volumes and reduced traffic conflicts. A significant amount of variability is present in the road and rail accident rate results among the various models. On the average, rail accident rates per tanker-kilometer are lower than road accident rates by a significant factor of 7.6 for all three development sections. Depending on the source of the estimates, differences in accident rates between the two modes vary significantly. For example, the rail accident rate from Model A on the suburban section is 13.3 times lower than for road per tanker-kilometer traveled. Models B and C consistently yield rates that are lower than the average regardless of mode, whereas Model D yields rail accident rates that are higher than the average and road accident rates that are lower than the average. Despite the use of similar data for the estimates, Model G yields a different result (i.e., lower rail accident rates and higher road accident rates relative to the average). For a given set of corridor conditions, rail accident rates vary by a factor of 10 between the lowest estimate (Model G) and the highest estimate (Model D). For road, the factor of difference is approximately 9 between the lowest estimate (Model B) and the highest estimate (Model A). Notwithstanding these differences, all the models were consistent in predicting lower accident rates for rail relative to road for the same tanker-kilometers traveled.

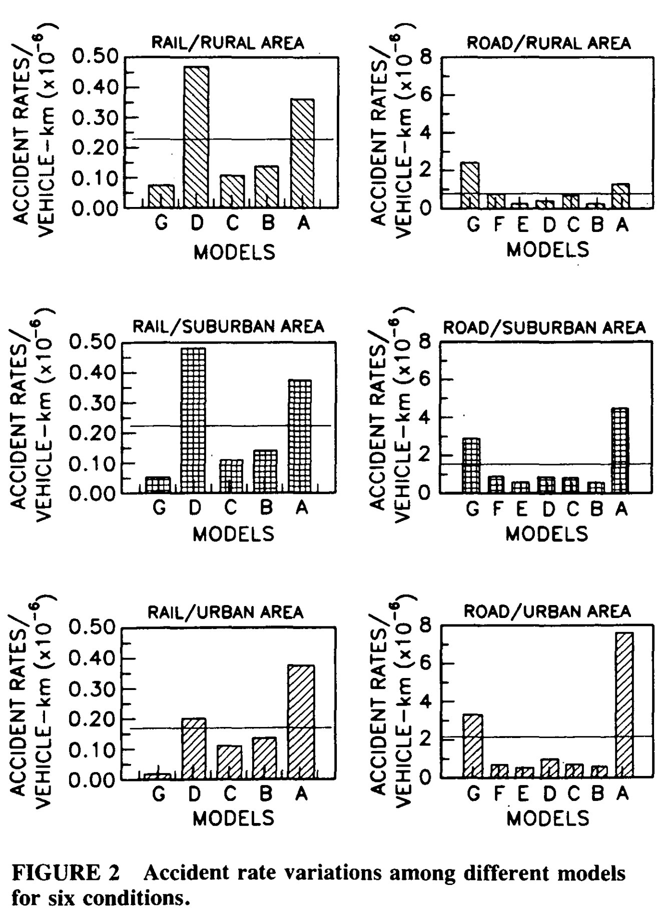

FIGURE 2 Accident rate variations among different models for six conditions.

Are variations in accident rates statistically significant? The answer to this question will be given statistically later in this paper. However, given the fact that all models have been applied to a common set of assumed conditions, the variations cast doubts on the reliability of the final risk estimates. Even if it can be shown that risk values are reasonably close among the various models (i.e., that errors of estimation in the components somehow compensate one another), the case for consistency remains weak, and the resultant risk estimates must be viewed critically. This aspect is important in view of the analysis of variance results that will be discussed later in this paper.

Figure 3 shows the release probabilities for rail and road as estimated by the various sources for each of the three materials being transported (chlorine, LPG, and gasoline). The probabilities assume a prior occurrence of an accident involving a road or rail tanker carrying the designated hazardous material. All models yield release probabilities that are insensitive to section-specific conditions. The models do not appear to yield consistent results as to which mode is more likely to produce a release in an accident situation. Model A suggests significantly higher release probabilities for rail, by a factor of 2.1 for LPG and 4.8 for chlorine. For gasoline, Model A suggests lower release probabilities for road by a factor of 0.8. Whereas most models suggest slightly higher release probabilities for rail than for road, even these results are not consistent for all sources and materials.

Uncertainty in the estimates of release probability renders difficult any conclusions on the relative likelihood of accident-induced releases between the two modes. For chlorine, LPG, and gasoline, an average of 6.5, 8.0, and 18 percent of rail tanker accidents, respectively, result in some type of release. This can be compared with release percentages on road of 2.5, 5, and 18 percent, respectively, for chlorine, LPG, and gasoline. It would appear from these results that material-specific tanker design features are instrumental in explaining variation in accident-induced release probabilities for both road and rail. These results also suggest that the approach

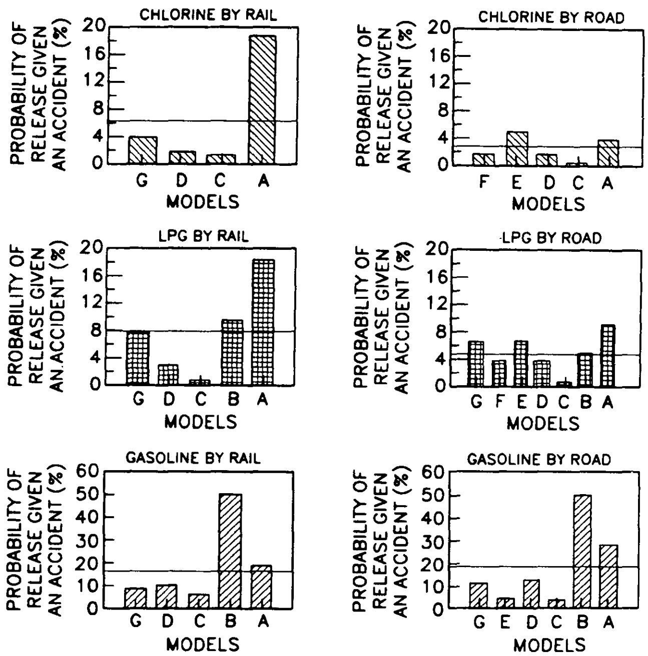

FIGURE 3 Probabilities of hazardous material release per rail and road accident.

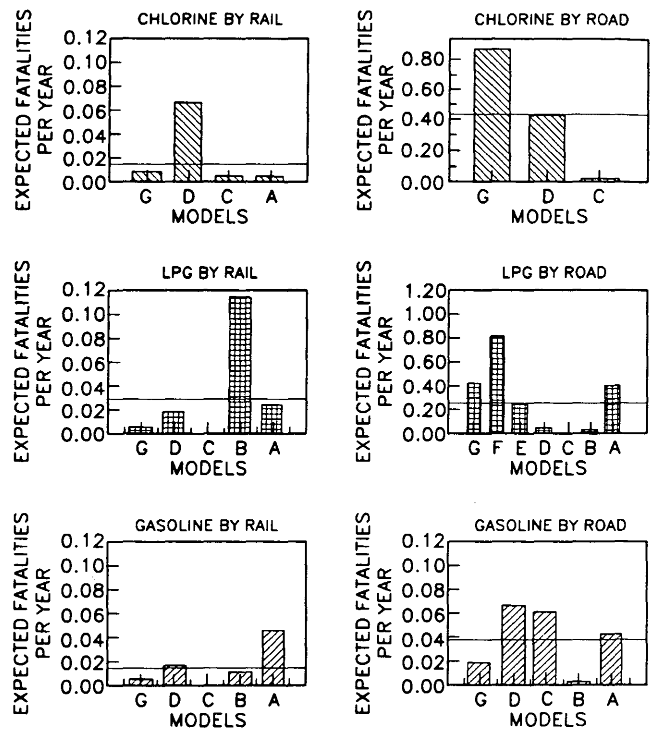

FIGURE 4 Societal risk by mode for chlorine, LPG, and gasoline.

adopted in many studies to lump information on release probabilities for all material types could contribute to significant variability in the estimates depending on the nature of the release data.

Variability in hazard areas was significant among the various sources. Given the complexity of the dispersal relationships and the as yet unaccounted for assumptions, this result was not entirely unexpected. A wide range of hazard area profiles was reported for different materials and shipment conditions. Many applicants based their estimates on assumptions that did not lend themselves to a common basis of comparison. As a result, these estimates have not been presented in this paper.

Societal risk in this analysis is defined in terms of the expectation of fatalities on each mode over the entire length of the corridor for 1 year of shipment activity for each of the three materials. As shown in Figure 4, some variability is present in these values. Much of this variability, however, may be accounted for by differences in one or two model results. For the rail shipment of chlorine, LPG, and gasoline, Models A, B, and D yield values significantly higher than the average. Models C and G were consistently lower than the average for all materials. The ratio of variability between the lowest and highest reported values for chlorine, LPG, and gasoline are 8.5, 14.8, and 5.0, respectively. These values exclude the negligible values reported by Model C for this exercise. Similar results were obtained for societal risks by road. The ratio of variability between the lowest and highest estimate is 2.0 for chlorine, 21.8 for LPG, and 3.8 for gasoline.

All models are consistent in estimating lower material-dependent risks for rail than road. On the average, the annual expected fatality risk for chlorine shipment by rail is 0.02, compared with 0.6 for road. For LPG, the average risk by rail is 0.04 compared with 0.30 by road. For gasoline, the average rail risk is 0.02 compared with 0.04 by road. These risks account for lower per tanker payloads and a higher number of shipments on road relative to rail. This analysis was carried out for comparable population/employment distributions and a mix of environmental conditions along each route.

Despite consistency in predicting lower societal risks by rail, significant variability among the models raises some concerns regarding the true nature of the threat posed and how it can best be reduced. It is questionable whether cost-effective safety policies can be established and justified without first accounting for this uncertainty.

Individual risk is defined in terms of the distance from an incident required to sustain a certain chance of death for 1 year of shipment activity. These results are shown in Figure 5 for those models that were able to provide the information. Most models yield reasonably close results, which is surprising given the variability present in the elements of the individual risk estimate. In general, the rail mode reflects more extensive individual risk isolines than road. This is expected given the larger volume of material being transported by each rail tanker. The important point to observe is that all individual risk estimates are essentially de minimus given a standard level of acceptability of one chance per million per year (the chance of being struck by lightning).

The 95 percent confidence intervals were established on each risk component estimate for each mode. The results are summarized in Table 1 for the transport of LPG by rail and road.

The results in Table 1 suggest that for both rail and road many of the source estimates are outside the 95 percent confidence intervals for each of the selected risk components, including societal risk. The source models, themselves, exhibit

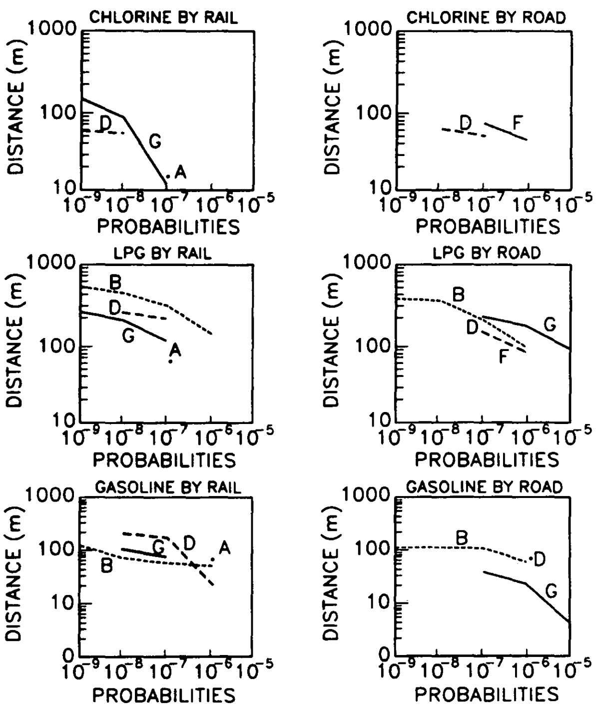

FIGURE 5 Individual risks for rail and road for chlorine, LPG, and gasoline.

some inconsistency as to whether specific risk estimates are within or outside the 95 percent limits. Variability in societal risks is particularly problematic for road transport, where four of the reported five values are outside the confidence limits. For rail transport only one reported societal risk value is outside the established upper limit.

These results suggest a canceling out of errors in estimating societal risks for the various participating groups. Whereas several estimates of societal risks were found to lie within the 95 percent confidence interval, the same groups may have obtained values of accident rates and release probabilities (constituents of societal risk) that were outside the 95 percent intervals. Conversely, several groups failed to satisfy the 95 percent criterion for societal risk despite obtaining acceptable values for the risk constituents, accident rate and release probability.

Analysis of the Significance of Model Variability

A number of risk component estimates were obtained by applying various models to the transport of LPG by road and rail along the sample corridor. The results of these calculations are used as seed points in a hierarchical cluster analysis of the models into groupings of consistent estimates. The distance metric for this clustering exercise is euclidean and makes use of Ward's minimum variance method.

TABLE 1 Confidence Intervals on Selected Risk Estimates for the Transport of LPG by Rail and Road

Rail Transport

Accident Rate	Release Probability	Large Release Probability	Societal Risk
0.37	0.19 *	0.30	2.50
0.14	0.10	0.03 *	11.70 *
0.11	0.01 *	0.50	0.07
0.46 *	0.03	0.86*	1.90
0.06 *	0.08	0.10	0.56
Mean 0.23	0.08	0.36	3:35
SD 0.17	0.06	0.30	4.27
95% Confidence Intervals			
0.09 - 0.37	0.03 - 0.14	0.10 - 0.62	- 0.40 - 7.09

Road Transport

Accident Rate	Release Probability	Societal Risk
2.60 *	0.09 *	0.41
0.31	0.05	0.04 *
0.70	0.01 *	0.002 *
0.58	0.04	0.04 *
0.35 *	0.07	0.26
0.84	0.04	0.82 *
2.60 *	0.07	0.43
Mean 1.14	0.05	0.29
SD 0.94	0.03	0.27
95% Confidence Intervals		
0.44 - 1.84	0.03 - 0.07	0.08 - 0.49

* Estimates outside the 95% limits.

The primary purpose of the cluster analysis is to assign individual models to larger groups on the basis of consistency of results for an array of risk component estimates. The previous graphical analysis was able to assess consistency visually for individual estimates taken one at a time. The cluster analysis is able to account for variations in a more extensive set of risk estimates. Models that failed to provide complete estimates for at least one seed point were not considered in this exercise. For road transport, seven models provided comparable estimates for all the risk components used in this cluster analysis. For rail transport, five models were used. Input values for this exercise are summarized in Table 2 for both the rail and the road modes.

Figure 6 shows the dendrograms for rail and road LPG transport. The dendrograms represent the sequence of linkages between the various models, based on their risk component estimates. A certain degree of intuitive judgment is applied in setting the most appropriate cutoff for distinct groupings. For road transport, the models that reflect the closest initial linkage are Models F and D, Models B and E, Models A and G, and Model C in its own group. At the next higher level, Models B, D, and E can be assigned to a single group. Models A and G continue to be linked together, and Model C continues to comprise its own cluster. Model C joins Models B, D, and E at the two-cluster cutoff. For the road transport of LPG, it appears that, with the exception of Model D, the seven models reporting results can be clustered into a decided North American–European pattern.

For rail transport only five models were grouped. Again the cutoff value is intuitive rather than statistical and is subject to some divergence of interpretation. Nevertheless, the results appear to differ significantly from the pattern associated with road. Models B and G link first, followed by Models A and C, and finally Model D standing alone. Model D continues to occupy its own cluster, well after all the other models have been clustered together.

From this analysis, it remains unclear whether more complex models yield results that differ significantly from simpler formulations. All clusters appear to include models of both

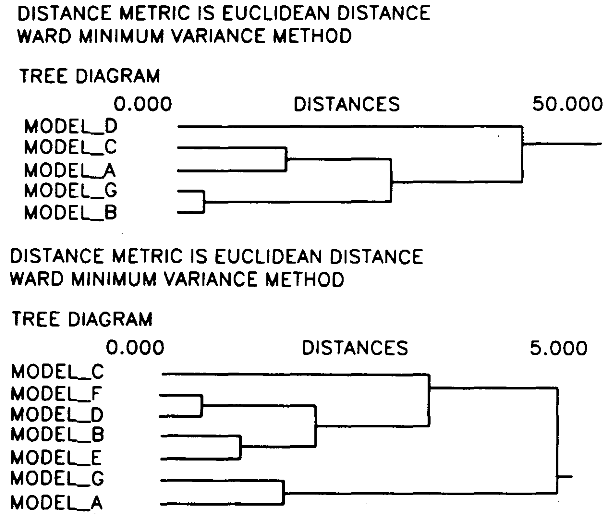

FIGURE 6 Dendrograms for LPG transport: *top*, rail; *bottom*, road.

types. Models that used fault trees to analyze release probabilities do not yield results that differ from models that obtain their estimates directly from data. Finally, the use of data from similar jurisdictions (as is the case for Models D and G) gives no assurance that the results will also be similar. In general, the patterns suggested by this exercise are difficult to explain in terms of what is known a priori about these models.

The results of a three-way analysis of variance of the model estimates are summarized in Tables 3, 4, and 5 for accident rates, release probabilities, and societal risks for road and rail, respectively. At the 5 percent level of significance, the results in Table 3 indicate that accident rates vary by mode and model source. Rail accident rates are significantly lower than road accident rates for all route sections. Individual route sections did not yield statistically different rates for each of the two modes. These results suggest statistically significant

TABLE 2 Risk Input Values to the Cluster Analysis for Road and Rail LPG Transport

Rail Transport

Risk Model	Accident Rate (X 10^{-6})	Release Probability (% of Accident)	Large Release Probability (% of Releases)	Societal Risk E (F/Yr)
MODEL A	0.37	19.0	30.0	0.025
MODEL B	0.14	10.0	3.0	0.117
MODEL C	0.11	1.0	50.0	0.001
MODEL D	0.46	3.2	86.0	0.019
MODEL G	0.06	8.1	10.0	0.006

Road Transport

Risk Model	Accident Rate (X 10^{-6})	Release Probability (% of Accident)	Societal Risk E (F/Yr)
MODEL A	2.60	9.2	0.410
MODEL B	0.31	5.0	0.039
MODEL C	0.70	0.6	0.002
MODEL D	0.58	3.7	0.038
MODEL E	0.35	6.6	0.261
MODEL F	0.84	3.7	0.820
MODEL G	2.60	6.6	0.429

TABLE 3 Results of Three-Way Analysis of Variance for Accident Rates for Rail and Road

Rail Transport

Model Source	Route Section Rural	Suburban	Urban
MODEL A	0.37	0.37	0.37
MODEL B	0.14	0.14	0.14
MODEL C	0.11	0.11	0.11
MODEL D	0.48	0.48	0.20
MODEL G	0.07	0.05	0.02

Road Transport

Model Source	Route Section Rural	Suburban	Urban
MODEL A	1.30	4.50	7.70
MODEL B	0.20	0.50	0.70
MODEL C	0.67	0.70	0.83
MODEL D	0.47	0.76	1.00
MODEL G	2.50	2.90	3.20

ANOVA Summary Statistics

	F - Ratio	Tail Probability
Route Section	0.970	0.395
Model Source	3.006	0.040
Mode of Transport	12.537	0.002

Accident Rates (x 1.0 E -06) per Vehicle Kilometer for LPG Transport

TABLE 4 Results of Three-Way Analysis of Variance for Release Probabilities for Rail and Road

Rail Transport (Units % of Accidents)

Model Source	Material in Transit Chlorine	LPG	Gasoline
MODEL A	19.0	19.0	17.6
MODEL B	1.0	1.0	5.1
MODEL C	1.6	3.2	9.5

Road Transport (Units % of Accidents)

Model Source	Material in Transit Chlorine	LPG	Gasoline
MODEL A	4.0	9.2	27.7
MODEL B	0.4	0.6	3.2
MODEL C	1.6	3.7	12.0

ANOVA Summary Statistics

	F - Ratio	Tail Probability
Material	5.334	0.022
Model Source	16.622	0.000
Transport Mode	0.596	0.455

Probability of Release Given an Accident

TABLE 5 Results of Three-Way Analysis of Variance for Societal Risks for Rail and Road

Rail Transport (Units: Expected Fatalities per Year).

	Material in Transit		
Model Source	Chlorine	LPG	Gasoline
MODEL D	67.00	19.00	15.80
MODEL C	4.20	0.68	0.17

Road Transport (Units: Expected Fatalities per Year).

	Material in Transit		
Model Source	Chlorine	LPG	Gasoline
MODEL D	431.00	37.70	61.00
MODEL C	9.70	2.30	2.90

ANOVA Summary Statistics

	F - Ratio	Tail Probability
Material	1.410	0.306
Model Source	2.693	0.145
Transport Mode	1.380	0.279

Expected Fatalities (x 1.0 E -3) per Year

differences in accident rates, depending on model source for rail and road transport.

The results in Table 4 suggest that at the 5 percent level of significance, variations in accident-induced release probabilities depend on the material transported and on model source. These probabilities do not appear to be affected by the mode. Differences in release probabilities by mode of transport from the previous graphical analysis appear to be random, after the material type and model source have been taken into account.

The analysis of variance results for societal risks in Table 5 are most interesting. At the 5 percent level, variations in societal risks are not dependent on material type, mode of transport, or model source. When all model estimates and materials are taken into account, the lower societal risks for rail suggested by the previous graphical analysis do not appear to be significant. Given the significant variations in accident rates and release probabilities as explained by material type, mode, and model source, it is interesting that societal risk estimates are unaffected by these same factors. Both accident rates and release probabilities are inputs into societal risk.

Is uncertainty a problem for risk estimation? Are the various model sources consistent in the estimation of societal risk, as suggested by the above ANOVA? The results of the ANOVA must be viewed simply as a case of compensation in random errors for a unique transportation corridor exercise. Despite these results, inconsistencies in model sources remain a problem in risk estimation. The whole must be viewed as the sum of its parts. A statistically significant variation in any one of the risk input factors must be viewed as a significant variation in the final risk product.

CONCLUSIONS

The analysis of risk estimation variability among different models suggests the following conclusions:

1. Much of the variability in risk estimation can be accounted for by differences in underlying assumptions, data, and model structure. However, even when many of these factors are taken into account in a common transport problem, significant variability in the estimates was found to be present.
2. Grouping the models into similarities in risk component estimates failed to reveal any pattern among the models themselves. It cannot be concluded that more complex models yield results that differ significantly from simpler formulations or that consistency is more readily obtained when models are calibrated for similar data bases and jurisdictions.
3. Whereas differences in risk component estimates were significant, the various estimates of societal risk for the chosen transport problem were similar. Much of the unexplained variability in risk component estimates appears to have canceled itself out in the final risk estimate (i.e., societal risk). This finding may be unique to the chosen transport problem. Furthermore, it underscores the fact that a simple sensitivity analysis on the final risk estimate, as is often done in this type of study, would show consistency in the estimates by model source where no such consistency is present.

Risk estimation is plagued by problems of inconsistency in the various model sources. Many of the inconsistencies cannot be fully accounted for by controls on assumptions and input data. In the interest of more informed decision making and public credibility, uncertainty in risk estimation must form an integral part of the overall risk analysis process.

The results of this corridor analysis should be viewed as a useful first step in understanding the extent of variability in the risk estimates from different model sources. In this way, effective action can be taken to account for this variability in the reporting of risk analysis results.

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The purpose of this paper is not to comment on the validity of one set of estimates over another, but only to point out the pattern of differences where they occur. The reasons for these differences are best provided by those who carried out the analysis.

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Assessing Hazardous Materials Emergency Response Capability: Methodological Development and Application

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The emergency response community is facing important challenges in the current economic, political, and technical environment. Mandated requirements combined with tight budgets are necessitating the use of innovative techniques to meet the needs of emergency response planning and management, particularly for hazardous materials incidents. As public awareness of the manufacture and transport of hazardous materials increases, the demand for adequate emergency response related to these activities has become more focused. The complexity of possible consequences due to hazardous materials incidents and the need for responder awareness of these consequences have led to a need for a systematic approach in evaluating the capabilities of responders. The development and implementation of such an approach are described. A matrix of different response capability levels for varying types of hazardous materials incidents is presented along with the corresponding methodology to evaluate emergency responders. This provides responders, elected officials, shippers, and carriers with the ability to assess the current level of preparedness, evaluate the level of preparedness desired, and develop a cost-effective means for attaining that level. The resulting methodology provides a uniform procedure for evaluating hazardous materials emergency response capabilities at the local, regional, and national levels. The basis for this work has the potential to be expanded to any emergency response evaluation (e.g., flood or hurricane) and to real-time management of emergencies.

Increased concern for public safety and environmental awareness have brought about a need for improved practices to adequately plan for and manage emergencies. An emergency, as defined in this context, is an unexpected event of limited duration that can adversely affect the surrounding area and population. Whether natural or induced by society, these events typically involve several factors, from identification to cleanup, and normally require interaction and cooperation among numerous public and private entities.

The management of an emergency has four major components: (*a*) identification of the nature of the emergency, (*b*) evacuation and rerouting of the population at risk from the affected area, (*c*) containment or isolation of the incident, and (*d*) cleanup and mitigation of the effects of the emergency. Emergency response relates to all of these components either directly or indirectly.

Among the types of emergency events, hazardous materials incidents have taken a prominent position. The manufacture and transport of hazardous materials have been subjected to increased public scrutiny because of the threat to health and safety that a major incident could create. If emergency response is timely and qualified, the incident may be controlled before any serious consequences occur. However, as additional time elapses, the likelihood of more serious consequences increases, potentially leading to injury, death, and loss of productivity. Thus, the essence of effective emergency response is to minimize the consequences of an incident when one occurs.

EMERGENCY RESPONSE PLANNING

Effective emergency response requires planning and is mandated by existing legislation. The Superfund Amendments and Reauthorization Act of 1986 (SARA) requires each local emergency planning committee to prepare comprehensive hazardous substances emergency response plans, primarily for facilities. Likewise, the Hazardous Materials Transportation Uniform Safety Act of 1990 was enacted to provide guidance to enhance state and local hazardous materials emergency planning and training for transportation. Similar legislation addresses specific responses for incidents such as oil spills. The two laws and their supporting documentation have provided guidelines for establishing emergency response plans. However, a systematic approach is still required to effectively implement these plans.

To have an effective plan, several information elements are needed, including types of possible emergencies, capabilities and locations of emergency responders, and time required for responders to reach the incident location. Complete emergency management planning includes several additional factors, which are beyond the scope of this paper.

To address the preceding considerations, a matrix of responder capabilities to address different types of emergencies is proposed. Having every responder with the maximum capabilities for any possible incident is impractical both technically and economically. Conversely, not having a responder available that can adequately handle an incident can be costly

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in terms of lives and dollars. By establishing different capability levels for responders, any jurisdiction can effectively allocate its resources to meet the needs of its community. The same reasoning applies in assessing regional and national response coverage and needs.

The majority of emergency responders do not currently have advanced capabilities to handle hazardous materials incidents. However, these responders are often the first authority on the scene. It is important to distinguish, therefore, the different aspects of *first responder* versus *qualified responder* in the planning process. The first responder may not be prepared to enter the site of an incident but still must protect the surrounding population and area until a qualified responder can arrive to begin containment.

Although every incident has its own unique characteristics and special considerations, hazardous materials incidents can be grouped according to the type of response that would prove effective. This grouping allows the planner to establish the levels of response that must be available within an area and to identify the location of qualified responders.

Once the responders have been identified and their capabilities established, this information can be used to determine response coverage to potential incident sites. For a large area with multiple responders, performing this task manually would be extremely cumbersome, if not impossible. The distance from every responder to every accessible point in the area would have to be measured or calculated and the minimum response times determined. The use of a geographic information system to determine the precise locations of response units and transport facilities and the application of network routing algorithms make this a much more manageable task. The travel time to each point along the road network is then easily measured from the closest first and qualified responders to any location.

Using this approach in the planning process can help reduce the likelihood and severity of consequences. In the discussion to follow, a methodology for assessing emergency response capability according to this logic is presented.

EMERGENCY RESPONSE EVALUATION

Currently, most emergency responders in the public sector are fire departments. This is particularly true for first responders. These range from small, rural volunteer units to paid urban, multistation professional units. Similarly, a variety of hazardous commodities are stored or travel through the areas served by these departments.

To develop an understanding of the significance of this relationship, five response capability levels were defined, corresponding to the material involved and level of expertise required to constitute a qualified response. This multitiered approach provides several advantages. Local responders and elected officials can determine the level of preparedness they choose to have on the basis of local characteristics. This approach also allows jurisdictions to develop a cost-effective means for reaching funding and training goals. At the same time, this system provides a measurement for defining the specific types of materials and incidents to which a team is qualified to respond. Within this framework, it becomes apparent when a potential incident would be beyond a team's capability, resulting in the need to request or locate a more advanced team.

Team Levels

Whereas no national standards for response teams currently exist, the five capability levels were developed on the basis of existing training and equipment standards for entry levels as defined by the National Fire Protection Association (NFPA) (*1*).

As requirements for each level were established, they were reviewed with the Tennessee Emergency Management Agency (TEMA) to ensure validity. The requirements, as they currently exist, are being used by TEMA to evaluate Tennessee's emergency response capabilities (*2*).

Level 5 is the lowest capability rating. Fire departments with this level have the ability to do only minimal assessment, work in nonhazardous areas, and Level D entry as defined by the NFPA. Although this level does not require the formation of a hazardous materials team, members of the department must have basic training in hazardous materials awareness. By current legislation, every fire department in the country should be at this level.

Level 4 teams are able to handle explosives and flammables and could perform related assessment and containment. This level does not include any chemical protection. Approximately 50 percent of all hazardous materials incidents require this response capability.

The capability to respond to chemical incidents begins with Level 3. Primarily corrosives and peroxides are handled by this level, which corresponds to the NFPA Level C entry classification and is appropriate for an estimated 75 percent of hazardous materials responses.

Level 2 teams can respond to poisonous and etiologic materials and have capabilities that correspond to the NFPA Level B entry classification. This level includes specialized training and more extensive air supplies than Level 3. Approximately 85 percent of incidents can be handled by teams at this level.

A unit with a Level 1 rating (the most qualified response team) has the greatest chemical protection, Level A by NFPA definition, and can respond to incidents involving poison gases.

These classifications are progressive, meaning that a Level 2 team can respond to Level 3, 4, and 5 incidents, and so forth.

Team Capability Evaluation

To evaluate a hazardous materials response team, four important components of overall response capability were identified: adequate numbers of trained personnel, proper equipment, medical surveillance, and proper site planning and documentation. The specific requirements for each team level based on these four areas are given in Table 1. From these requirements, a detailed survey shown in Figure 1 was developed to serve as a basis for rating fire departments and other agencies that are primary responders to an incident.

Information from this survey is linked directly to the qualifications given in Table 1. For example, the personnel and

TABLE 1 Hazardous Materials Response Team Capability Criteria

Level 5 Capability - (Minimum for all fire departments)

Personnel:	Senior Officer -	First Responder Operations Level Incident Command Training
	HM Team Leader -	Not applicable
	Team Members -	Not applicable
	Support -	First Responder Awareness Level Thoroughly familiar with assigned PPE
Equipment:	Binoculars DOT HM Response Guidebook Radio Communications	
PPE:	SCBA SFPC	
Planning:	Approved & Exercised Title III Plan	
Medical:	Not applicable	

Level 4 Team

Personnel:	Senior Officer -	First Responder Operations Level Incident Command Training
	HM Team Leader -	Technician Level Incident Command Training
	Team Members -	4 Members First Responder Operations Level
	Support -	First Responder Awareness Thoroughly familiar with assigned PPE and procedures
Equipment:	Binoculars DOT HM Response Guidebook Radio Communications Two flammable gas detectors Fire fighting foam Equipment to extinguish spill, fires and suppress flammable vapors At least 4 reference books in portable library Dyking materials CDV-777-1 Radiological Monitoring Kit	
PPE:	SCBA SFPC	
Planning:	Approved & Exercised Title III Plan	
Medical:	Team Members meet OSHA physical requirements	

Level 3 Team

Personnel:	Senior Officer -	Technician Level Incident Command Training
	Team Leader -	Specialist Level Incident Command Training
	Team Members-	4 Members Technician Level
	Support -	First Responder Operations Thoroughly familiar with assigned PPE and procedures
Equipment:	Binoculars DOT HM Response Guidebook Radio Communications Two flammable gas detectors Fire fighting foam Equipment to extinguish spill, fires and suppress flammable vapors At least 6 reference books in portable library Dyking materials Decontamination equipment pH paper Simple plugging supplies Highway hazard Radiological Kit	
PPE:	Level C	
Planning:	Approved & Exercised Title III Plan	
Medical:	Team Members	

(*continued on next page*)

TABLE 1 *(continued)*

Level 2 Team		
Personnel:	Senior Officer -	Technician Incident Command Training
	Team Leader -	Specialist Level Incident Command Training Additional specialized training
	Team Members-	4 members Technician Level At least 2 with Specialist Level
	Support -	Technician Level
	Dept. Adm Officer	Technician Level
Equipment:	Binoculars DOT HM Response Guidebook Radio Communications Two flammable gas detectors Fire fighting foam Equipment to extinguish spill, fires and suppress flammable vapors At least 6 reference books in portable library Dyking materials Decontamination equipment pH paper Simple plugging supplies Highway hazard Radiological Kit	
PPE:	Level B 1 hour rated SCBA On or near-sight SCBA refill capability	
Planning:	Approved & Exercised Title III Plan	
Medical:	Team Members meet OSHA physical requirements	
Level 1 Team		
Personnel:	Senior Officer -	Technician Level Incident Command Training
	Team Leader - At least 2 leaders	Specialist Level Incident Command Training Rad Inst III Additional specialized training
	Team Members-	4 members Technician Level At least 3 with Specialist Level
	Support -	Technician Level
Equipment:	Binoculars DOT HM Response Guidebook Radio Communications Two flammable gas detectors Fire fighting foam Equipment to extinguish spill, fires and suppress flammable vapors At least 6 reference books in portable library Dyking materials Decontamination equipment pH paper Simple plugging supplies Highway hazard Radiological Kit	
PPE:	Level A 1 hour rated SCBA On or near-sight SCBA refill capability Flame resistant coveralls	
Planning:	Approved & Exercised Title III Plan	
Medical:	Team Members meet OSHA physical requirements	

County:	**HAZARDOUS MATERIALS**	EM USE ONLY
City:	**EMERGENCY RESPONSE**	Team Level:
Region:	**SURVEY**	Date:
Date:		Rated By:

Instructions: (1) Please type or print clearly. (2) Complete a separate form for each station/substation with HazMat response capability. (Make additional copies as needed.) (3) Return completed surveys to:

1. General Information

Department/Agency: 1__________ Team Leader: 2__________

Mailing Address: 3__________ Business Phone: 4(___)__________

City: 5__________ State: 6_____ Zip: 7_____ Emergency Phone: 8(___)__________ (Other than 911)

FAX Number: 9(___)__________

Station Location (Street Address): 10__________

Location (if known) Latitude: 11__________ Longitude: 12__________

No. Paid: 13_____ No. Volunteer: 14_____ No. Assigned to Team: 15_____ Avg. Response Time: 16_____

2. Jurisdictional Profile *(please include a map indicating boundaries and response stations)*

Total Population Served: 17__________ Area (square miles): 18__________

Major Highways: 19__________ Major Railroads: 20__________

Navigable Rivers: 21__________ Airports: 22__________

Multi-jurisdictional Response? 23___Yes___No Industrial Mutual Aid Agreement? 24___Yes___No

List Jurisdictional(s) served by written mutual aid agreements:

25__________

Comments:

26__________

3. Capabilities Assessment

Planning: Has the jurisdiction completed SARA Title III Emergency Management Plan? 27___Yes___No

Has the plan been successfully exercised and evaluated? 28___Yes___No

Date of last exercise: 29__________

Medical Surveillance: Are team members participating in a medical surveillance program in accordance with OSHA 1910.120? 30___Yes___No

FIGURE 1 Hazardous materials emergency response survey. ***(continued on next page)***

training for a Level 3 team would require the following entries in the survey:

- Boxes 33 and 34 would each require at least 1 for the senior officer,
- Boxes 39 and 41 would each require at least 1 for the team leader,
- Box 46 would require at least 4 for the team members, and
- Box 50 would require at least 1 for the support staff.

Additional requirements follow similar logic to define the capability of a team from the results of the survey.

The guidelines for site planning and documentation required for hazardous materials teams are specified in SARA Title III legislation. Similarly, the medical surveillance program is defined by Occupational Safety and Health Administration regulations in 29 CFR 1910.120. The training specifications follow the requirements defined by NFPA (*3*). The required number of personnel and level of training for each team level were established on the basis of experience and guidance provided by several government and state agencies. Necessary equipment, which includes personal protection equipment (PPE in Table 1), was also established from experience and guidance from NFPA (*4*) and the Environmental Protection Agency (EPA) (*5*).

4. Training: *(List the total number of personnel currently trained to the levels listed below. Do not include anyone who has not received initial and/or refresher training in the past two years)*

	Awareness	Operations	ICS	Technician	Specialist	Advanced
Senior Officer: Check if Team Leader ___	31	32	33	34	35	36
Team Leader(s)	37	38	39	40	41	42
Team Members	43	44	45	46	47	48
Support Personnel	49	50	51	52	53	54
Totals	55	56	57	58	59	60

5. Equipment: *(List number of pieces in the appropriate blanks)*

PPE	Detectors	Respirators	Containment
Turnouts (SFPC) 61___	Combustible Gas 71___	30 min SCBA 81___	Booms/Pads 91___
Level C 62___	Oxygen Level 72___	60 min SCBA 82___	Plugs/Patches 92___
Level B 63___	Detector Tubes 73___	Air Line 83___	Plastic 93___
Level A 64___	Photoionization 74___	1/2 Mask Cartridge 84___	Shovels 94___
Fire Res Coveralls 65___	Flame Ionization 75___	Full Mask Cartridge 85___	Absorbants 95___
Proximity Suit 66___	Organic Vapor 76___	86___	Recovery Drums 96___
Disposable Suits 67___	CDV-777-1 Kit 77___	87___	Solidifiers 97___
Cooling Vests 68___	Rad Hwy Haz Kit 78___	88___	Neutralizers 98___
69___	Strips 79___	89___	99___
70___	pH Paper 80___	90___	100___

Non-Sparking Tools? 101___Yes___No SCBA Refill: Cascade: 111_____Fixed 112_____Portable

Decontamination? 102___Yes___No Compressor: 113_____Fixed 114_____Portable

No. Reference Books? 103______ Foam (enter no. of gal): Alcohol: 115_____Protein: 116_____

DOT P 5800.5 1990 ERG 104___Yes___No Light water: 117_____ Other: 118_____

List Additional 105________________ 108________________

106________________ 109________________

107________________ 110________________

6. Communications/Information Management

Cellular Phone 119___Phone Number(s) 120________________

Radio: 121___Bands(s)/Frequency(s) 122________________

FAX: 123___Fixed: Phone Number 124____________ 125___Portable: Phone Number 126____________

Computer: 127___Fixed 128_____IBM compatible 129_____Apple/Mac

130___Portable 131_____IBM compatible 132_____Apple/Mac

Programs: 133___Cameo 134___Archie 135___Plume Modeling 136___EIS 137________________Others

7. Survey Completed by:

Print Name ________ Title/Rank ________ Signature ________

Date:________________ Phone Number:(____)________________

FIGURE 1 *(continued)*

In addition to the information required to evaluate a response team, the survey includes three other sections where relevant information is gathered: team identification and location, jurisdictional profile, and communications and information management capabilities.

By using this approach to evaluate response capability, two purposes are realized. First, the current capability level of the response unit is identified. Second, and just as important, the necessary improvements for a team to move from one level to the next higher level can be determined.

HAZARDOUS MATERIALS RANKING

Because of the diversity of hazardous materials that are manufactured or transported, the qualifications necessary to respond to incidents involving each type of material must be understood. For the most part, materials that have similar characteristics behave comparably. Therefore, at the screening level it is appropriate to consider general classes of materials for emergency response rather than each of the thousands of chemicals and chemical compounds independently.

Various organizations have established or defined classes or lists of hazardous materials for regulatory or rapid identification purposes. These include the U.S. Department of Transportation (DOT), the International Maritime Organization (IMO), EPA, and NFPA. Recently, DOT redefined its classifications to closely match the IMO system, which is used by other countries. The DOT *Emergency Response Guidebook* uses this classification system (*6*).

Because emergency response teams must handle incidents for transported material as well as for fixed facilities, the DOT hazard classification scheme was adopted to provide the initial link between response capabilities and hazardous material type. As more detailed planning is performed, additional criteria may be incorporated, such as container type and size.

Most materials within the same hazard class require the same level of response, and once that level has been identified, the appropriate responder can be determined. Table 2 gives these classes with the corresponding minimum team level as defined previously.

RESPONSE TIMES

To complete the evaluation of emergency response coverage, the location of response units and their qualifications are interfaced with the transportation network. Information technologies such as geographic information systems combined with network algorithms can facilitate determination of the time required for any responder to reach any point in the network.

This analytical environment provides the ability to perform several planning tasks. The first is to determine the expected response time to an incident location. Another application is the identification of geographic areas of inadequate response

TABLE 2 Emergency Response Requirements by Hazardous Materials Class

CLASS		TEAM LEVEL
Class 1	Explosives	
1.1	Explosives with a mass explosion hazard	4
1.2	Explosives with a projection hazard	4
1.3	Explosives with predominantly fire hazard	4
1.4	Explosives with no significant blast hazard	4
1.5	Very insensitive explosives	4
1.6	Extremely insensitive explosive articles	4
Class 2	Gases	
2.1	Flammable gases	4
2.2	Nonflammable gases	4
2.3	Poison gases (Class A Poisons)	1
2.4	Corrosive gases (Canadian)	4
	Chlorine (old designation)	2
Class 3	Flammable liquids	
3.1	Flashpoint below -18C	4
3.2	Flashpoint between -18C and 23C	4
3.3	Flashpoint between 23C and 61C	4
	Fuel Oil (old designation)	4
Class 4	Flammable solids; Spontaneously combustible materials; and materials that are dangerous when wet	
4.1	Flammable solids	4
4.2	Spontaneously combustible material	4
4.3	Materials that are dangerous when wet	2
Class 5	Oxidizers and Organic peroxides	
5.1	Oxidizers	4
5.2	Organic peroxides	3
	Oxygen	4
Class 6	Poisonous and Etiologic (infectious) materials	
6.1	Poisonous materials (Class B Poisons)	2
6.2	Etiologic (infectious) materials	2
Class 7	Radioactive materials	4
Class 8	Corrosives	3
Class 9	Miscellaneous hazardous materials	4 until identified
	ORM D	4 until identified

coverage for a specific hazardous materials shipment or fixed facility. Finally, this information can be used to allow individual emergency response units and the organizations that manage them to examine their current capability and identify the additional personnel, training, and equipment necessary to advance to a higher level of response capability, if deemed appropriate. This analysis environment can be easily extended to assess the value of establishing regional response teams that might have greater capabilities than local teams. The regional team would cover a larger area, and the necessary resources required to operate the team would be distributed over several jurisdictions.

CASE STUDY

To illustrate the use of this methodology in practice, these techniques were applied in performing an emergency response capability assessment for a selected county in southern Texas.

County Response Capabilities

The county currently has three fire departments that could respond to a potential hazardous materials incident. Each department was contacted and requested to fill out a capabilities survey. On the basis of the completed response, each department was assigned a capability rating as summarized in Table 3. The necessary requirements for each department to improve to the next capability rating are also included in Table 3.

Fire Department 1 is currently the most qualified response team in the county and has a Level 3 rating. This team requires only additional training to move from Level 3 to Level 2. Improving to Level 1 would require adding a second team leader and obtaining fire resistant coveralls for the team.

Fire Department 2 currently does not qualify for a Level 5 rating. By developing an emergency response plan and providing department members with minimal hazardous materials training, the department would be able to achieve a Level 5 capability.

Although Fire Department 3 was also assigned a Level 3 capability rating, the department would require additional training and upgrading of the self-contained breathing apparatus from 30- to 60-min capacities to reach Level 2. An increase to Level 1 capability would require adding equipment, upgrading personal protection equipment, and adding training.

Establishing Required Response Capability

A commodity flow study carried out at the proposed site enumerated the types of hazardous materials that pass through the county. From Table 2, materials within Classes 1.4, 1.5, 3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 5.1, and 5.2 were identified as the materials involved. On the basis of the corresponding minimum response team capability needed among these groups, Class 4.3, materials that are dangerous when wet, requires the highest level of response capability at Level 2. Consequently, qualified response can only be met by units with capabilities of Level 2 or Level 1. At a minimum, therefore, having at least one Level 2 team within the county is necessary.

Measuring Response Coverage

Using network optimization algorithms designed to determine minimum travel times from any point in the county to all other points, minimum response times to various highway locations in the county were computed. Figure 2a shows a map of the major highways in the county. Figure 2b shows the same map with highway names removed and the addition of a unique number assigned to each major junction. In Figure

TABLE 3 Summary of Case Study Responder Capabilities

Fire Dept	Capability Rating	Required Improvements to Reach Next Level	
1	Level 3	To acquire Level 2:	2 Team Members with Specialist Training
			Support Personnel with Technician Training
2	Not rated	To acquire Level 5:	Jurisdiction acquire HM Response Plan
			Senior Officer with First Responder Operations Training and Incident Command Training
			Support Personnel with First Responder Awareness Training
3	Level 3	To acquire Level 2:	Senior Officer with advanced training
			2 team members with Specialist Training
			Support Personnel with Technician Training
			PPE must upgrade to 60-min SCBA's

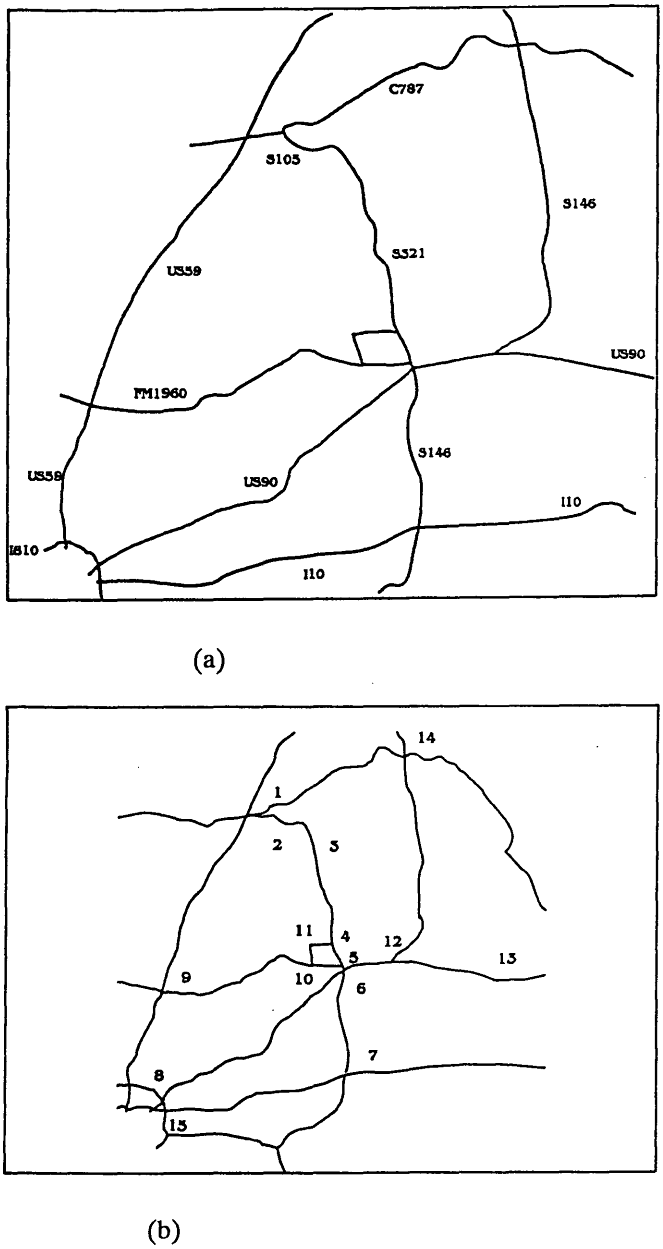

FIGURE 2 County road network: (*a*) major highways, (*b*) numbered junctions.

2b, the locations of Fire Departments 1, 2, and 3 correspond to Intersection Points 1, 6, and 12, respectively.

The map in Figure 2b was used as the basis for determining the most rapid response time from each responder to each point in the county. Table 4 gives a summary of calculated response times, presented as a matrix by response team and highway location.

The results of this analysis can be used to illustrate the array of options available to the county. Initially, if the hazardous material ranked under Class 4.3 from Table 2 did not pass through the county, emergency response coverage would be adequate and no improvements would be required. Because of the existence of this material, at least one of the fire departments should be upgraded to Level 2 capabilities. From

TABLE 4 Response Times Within the Texas County

Junction Number (Figure 2)	Response Times (min)		
	Fire Dept 1	Fire Dept 2	Fire Dept 3
1	0	39.74	46.61
2	1.39	38.35	45.22
3	7.94	31.80	38.67
4	31.50	8.24	15.11
5	38.49	1.25	8.12
6	39.74	0	6.87
7	62.06	22.32	29.19
8	54.62	36.25	43.12
9	31.87	48.08	54.95
10	48.92	12.86	19.73
11	40.21	16.95	23.82
12	46.61	6.87	0
13	81.61	41.87	35.00
14	44.93	47.47	40.60

Table 3, Fire Department 1 be the least expensive to upgrade. However, if a response time of more than 60 min is considered unacceptable, this department has two areas with excessive response times (from Table 4). This might indicate that the extra expense to upgrade Fire Station 3 should be incurred. If the acceptable response time were established as 45 min, Fire Departments 1 and 3 would both require upgrading to Level 2 capability. Collectively they could then respond within this window to any potential hazardous materials incident that might occur in the study region.

EXTENDED APPLICATIONS

Although the discussion presented centers on emergency response planning for hazardous materials, this approach can be extended to regional- and national-level planning, real-time incident management, and applications involving earthquakes, floods, fires, and other emergencies.

Regional and National Planning

The process discussed in this paper is directly applicable to broader planning processes. Extending this to regional and national plans is straightforward. The approach to evaluating responder qualifications and material classifications remains unchanged. Response times would be adjusted to reflect the level under consideration.

By establishing a uniform procedure for hazardous materials incident planning, such as the one presented, the planning process becomes consistent and easily adaptable to any planning level.

Incident Management

With the appropriate communications links, this emergency response planning methodology can be extended to encompass incident management. When an incident is reported, the location and material involved would be used to identify and contact the nearest qualified responder. The time for that responder to arrive at the scene could be reported to the acting incident commander, giving that person critical information on which to base decisions concerning immediate actions that should be taken.

This information could also provide input into an overall emergency management package that included evacuation and rerouting capabilities. The location of sensitive areas could be provided to the incident commander to allow that person to make informed decisions about personnel and equipment deployment, cordoning, containment, and evacuation, if required.

Other Emergencies

Although response to hazardous materials emergencies has received much attention in the form of legislation and public concern, other emergencies that often affect significantly larger populations and geographic areas occur frequently, albeit randomly. Forest fires, floods, earthquakes, and other natural disasters require varying levels of emergency response that could be evaluated by extending this methodology. In a similar manner, this methodology could be applied to police work. Special teams, such as SWAT teams, have different levels of qualifications for different situations.

In these instances, the definition of capability ratings and location of qualified teams will vary, but the approach is identical to the one used for hazardous materials emergency response. Overlaying this information on a spatial platform adds a new dimension to incident management and planning that has previously been unavailable.

CONCLUSIONS

Effective emergency response in the event of a hazardous materials incident can be literally a matter of life or death. The best way to ensure an effective response is through adequate planning and preparation. Planning requires information about the responders, the possible incidents, and the time involved. Preparation requires having qualified responders available.

The approach presented herein provides a systematic procedure for achieving this goal. The response capabilities within a planning area can be uniformly evaluated. As finances become available, response teams can be upgraded using a logical and consistent rationale.

This methodology is extremely flexible and can be used in a variety of applications. It can be applied at the local, regional, or national level for single jurisdictions or multiple-planning areas. Whether a potential incident occurs at a fixed facility or while in transport, the methodology is equally valid.

Effective emergency response coverage for natural and man-made disasters is essential to the well-being of our population and the environment. A consistent, flexible approach, such as the one presented here, can facilitate this goal.

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Canada's National Capital Region Goods Movement Study

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The economic viability of an urban area is closely related to the availability of an adequate transportation system. The ability to transport goods efficiently to, from, and within the urban area is a critical element in the promotion of continued economic development. Therefore, the planning of transportation facilities must be cognizant of the needs and requirements of all users, including those of the goods movement industry. This requires a clear understanding of goods movement operations and characteristics. A high priority had been placed by the various levels of government on the development of a goods movement data base and a review of a number of issues and policy considerations facing the local trucking industry in Canada's National Capital Region (NCR). Consequently, in 1989, a study of the characteristics of and issues surrounding goods movement in the NCR was undertaken. The study provides a sound data base for urban goods movement planning in the NCR. It also provides insight into data collection and policy issues of interest to planners in other cities. The findings of that study are reported.

Historically, issues related to urban freight transportation have received less attention than issues related to urban passenger transportation. In recent years there has been renewed interest in undertaking goods movement studies to better define its economic importance, outline its nature and role, ascertain its traffic impact and the impact of traffic on its operations, develop policies and regulations, and implement strategies.

In 1987 a study of urban goods movement operations was completed for metropolitan Toronto, Canada's largest municipality. Its findings created considerable interest in the subject area. The need to undertake studies for other communities to evaluate whether conditions, problems, solutions, and policies were similar to those found in that analysis was soon made apparent.

A study was initiated in 1989 by the member agencies of TRANS, a joint technical committee on transportation systems planning to investigate the nature of goods movement operations in Canada's National Capital Region (NCR). The NCR encompasses Canada's capital: Ottawa, the neighboring city of Hull, and the surrounding suburban and rural communities. Its boundaries closely approximate the Regional Municipality of Ottawa-Carleton (RMOC) in Ontario and the former Communauté régionale de l'Outaouis (CRO) in Québec (Figure 1). The urban area is bisected by the Ottawa River, which also defines the provincial boundary between Ontario and Québec.

A steering committee composed of representatives of municipal, regional, provincial, and federal governments guided the project, which was undertaken by a consultant. Throughout the duration of the study, trucking industry associations and trucking operators, law enforcement and emergency response agencies, and other government offices were consulted.

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CONTEXT

The NCR had a 1990 population of 922,000, making it the fourth largest urban area in Canada. The region's economy, however, is principally based on government functions—about 60 percent of all employment is in services and public administration. Consequently, it does not have the firms that traditionally generate or attract much truck traffic, such as intermodal transfer, manufacturing, and wholesaling. One indication of this is that Ottawa-Hull ranks only 11th among major Canadian urban areas in terms of for-hire trucking revenues by origin, and 7th by destination (*1*).

The NCR has several other unique attributes that figure prominently in goods movement:

- Because the urban area is spread over two provinces, truckers operating in both parts must conform to several sets of regulations. These are directed primarily at serving intercity goods movement. Multiple urban jurisdictions are common in the United States but rare in Canada.
- Most roads and highways in the NCR are under municipal, regional, or provincial jurisdiction. The federal government operates scenic parkways in the NCR from which commercial vehicles are prohibited.
- The federal government is responsible for the five interprovincial bridges across the Ottawa River. Only three are open to commercial vehicles. The proximity of these bridges to the central areas (central business districts) of Ottawa and Hull necessitates the routing of truck traffic through or near the core, regardless of origin and destination.
- Problems of access to the central areas and the interprovincial bridges are further complicated by the lack of a direct, high-capacity link between the bridges and the freeway network on the Ontario side. The significance is that both sides of the Ottawa River tend to be served by depots located on the Ontario side; this is evidenced by the proportion of development in Ontario (i.e., in the RMOC): 83 percent of employment and 77 percent of population.

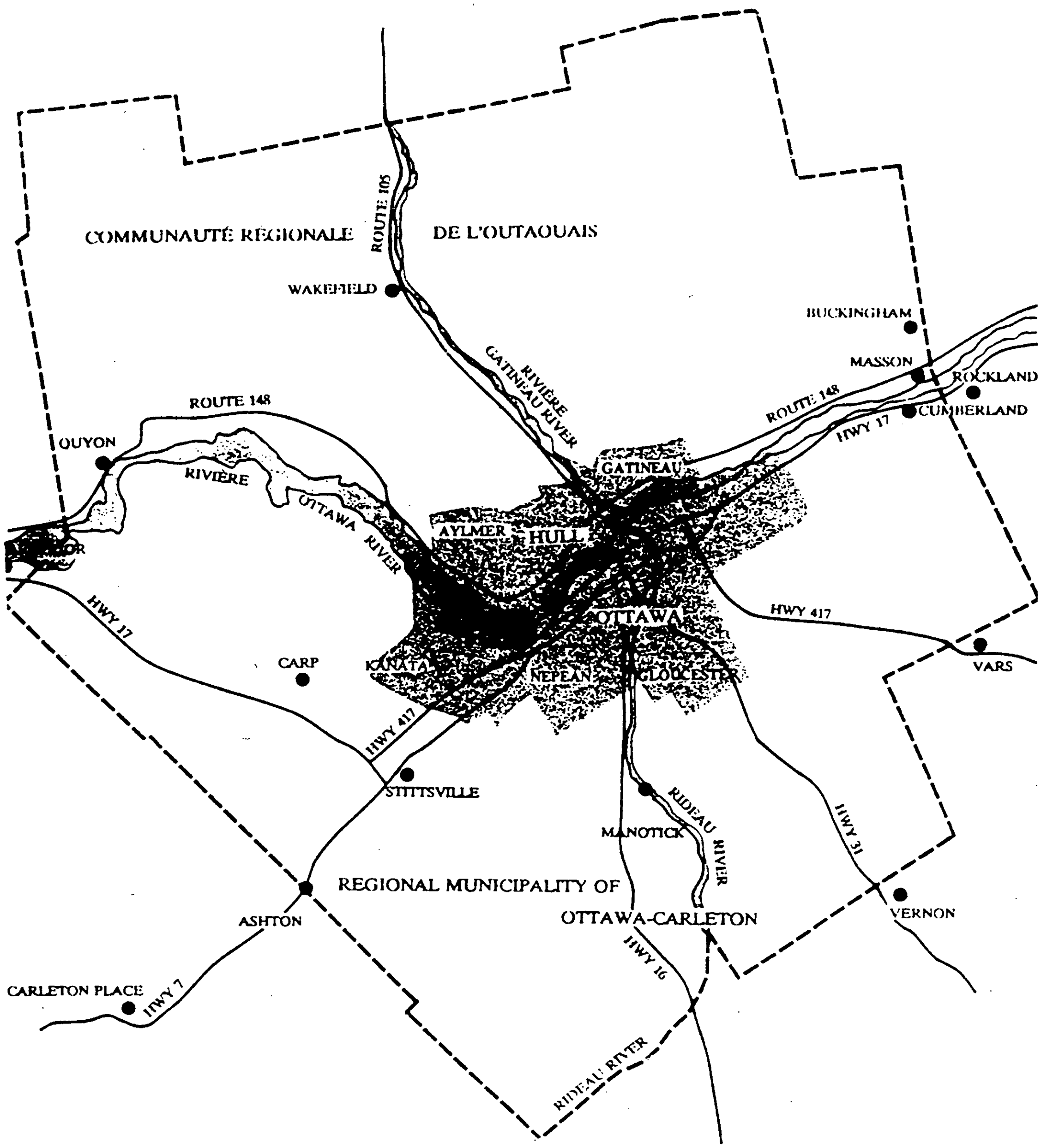

FIGURE 1 NCR study area.

STUDY OBJECTIVES

The four principal objectives of the study were to

- Collect information on the travel patterns and costs of goods movement operations in the NCR,
- Evaluate the effectiveness and effects of goods movement on the existing transportation network,
- Evaluate the implications of possible changes to the existing transportation network with regard to current and future goods movement operations, and
- Review the policies and restrictions governing the movement of goods in the NCR.

Urban goods movement issues can be generally grouped into four broad categories: transportation planning, traffic engineering and design, safety, and its economic relationship. The objectives of the study were somewhat shaped by the issues at hand. Specific to the NCR was the need to address the following:

- The adequacy of current building bylaws and, in particular, on-street parking and loading regulations in the two central areas;
- The characteristics of interprovincial goods traffic as they pertained to the bridges and to through movements in the central areas;
- The adequacy of the NCR truck route networks and the need to institute a dangerous goods truck route system as well;
- The costs of goods movement operations in the NCR and the effects of congestion on these costs; and

• The means of incorporating urban goods movement considerations into the urban transportation planning process, particularly in light of the influence of land use plans and policies.

METHODOLOGY

Three data collection methods were used to collect quantitative and qualitative information on goods movement activities. Survey 1 consisted of three truck origin-destination surveys. Survey 2 represented three follow-up telephone surveys. Survey 3 consisted of several "focus group" sessions (Figure 2).

A major component of the data collection program was the bilingual origin-destination mail-back surveys (Survey 1). This survey had three components: A, the principal sampling of overall goods movement activities, and two special-purpose surveys—B, which constituted a survey of "external" vehicles, and C, a documentation of vehicles that crossed the interprovincial bridges.

The sampling frame established for the survey was the provincial (state) commercial vehicle registrations in the subject area, consistent with previous studies in Toronto, Vancouver, and Chicago. However, unlike those studies, multiple registries were used (i.e., those of both Ontario and Québec). Since major differences existed in the two provincial classification systems, a common means of classifying vehicles was developed on the basis of vehicle weight. Vehicles were categorized by weight class and body type into three groups, labeled light, medium, and heavy for convenience.

There were approximately 59,600 trucks registered locally in the NCR on the basis of provincial records, although the actual truck population in the NCR was estimated to be about 24,000. The difference is explained partly by seasonal variations (the surveys were conducted in late autumn), a variation in vehicle registrations between the provinces, and an activity rate affected by the beginning of the economic downturn.

For Survey 1A, 3,650 trucks were sampled (6.2 percent), but only 2,520 were active in goods movement. (The sample was weighted to get greater representation of heavier vehicles.) Completed responses were obtained from 710, whereas 250 trucks, or approximately 1 percent of the actual NCR truck population, recorded trips on the day of the survey in the NCR.

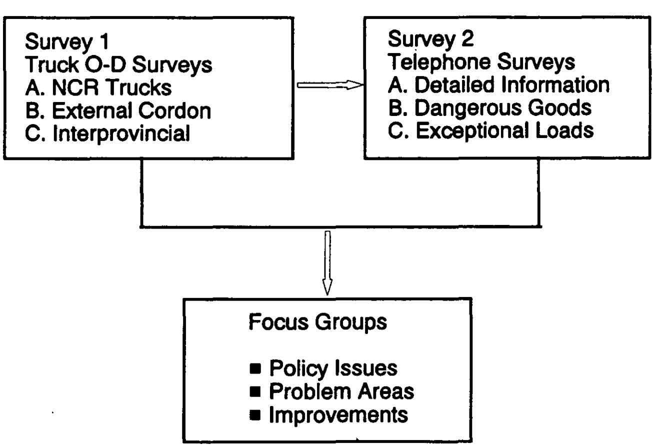

FIGURE 2 Data collection.

It was recognized that externally based vehicles were also active in the study area, making pickups and deliveries, and subject to the same conditions as locally based vehicles. Accordingly, a sample of externally based vehicles (i.e., vehicles registered outside the NCR) was selected from data collected at a cordon drawn across highways near the NCR boundaries. A sample of 700 trucks was drawn from the observed population of 2,870 trucks from which registry data were available; completed responses were obtained from 130 trucks for Survey 1B.

One of the principal issues in the NCR was the need for additional interprovincial bridge capacity. A separate survey, 1C, focused on all commercial vehicles crossing the existing bridges linking the provinces of Ontario with Québec. A similar sample of 700 trucks was drawn from an observed population of 2,866 trucks; 96 completed responses were obtained.

Each survey targeted vehicle trips made over a 24-hr period—Tuesday, December 12, 1989, for Survey 1A, and Tuesday, October 24, 1989, for Surveys 1B and 1C. The first part of the survey requested information on the respondent's firm, fleet size, and type of business.

The second part requested information on the vehicle's characteristics, load/commodity, trip origin, destination, timing, and routing information over that 24-hr period. The results from these surveys were edited, validated, weighed, and expanded. A combined origin-destination trip matrix was then calibrated according to observed values collected along major regional screenlines.

Telephone surveys were undertaken to collect detailed information from trucking managers and dispatchers on their organizations, general characteristics, perceptions and problems, and operating costs. The sample was stratified according to factors such as economic sector, fleet size, and composition. The first survey sampled 100 firms, from which 71 valid interviews were collected. The other surveys focused on dangerous goods carriers (22 interviews of 30 sampled firms) and exceptional load carriers (28 interviews of 30 sampled firms).

Four focus group discussion sessions were held in English and French with representatives of interested parties to further explore the traits and conditions identified in the previous surveys. The sessions included trucking operators, police forces, and industry associations.

PRINCIPAL FINDINGS

It was estimated that there were approximately 153,100 goods movement trips made daily in the NCR in 1989. Goods movement trips accounted for about 11 percent of all vehicular trips. Eighty-five percent of all trips involved an RMOC origin or destination, compared with 9 percent for CRO points and 6 percent for external locations. Areas with high concentrations of industrial activity and transportation and communications industries generated the largest numbers of goods movement trips.

Only 8 percent of all trips had an origin or destination in the central area of Ottawa-Hull. About 96 percent of goods movement trips from the RMOC were contained within the RMOC, whereas 74 percent of goods movement trips from the CRO were contained within the CRO. Only 2 percent of the trips involved crossing the provincial border between the RMOC and the CRO.

Goods movement activities were found to be greater on the Ontario side of the NCR (Table 1). However, the combined NCR trip generation rate of 0.16 trips per person was comparable with that observed in the 1987 metropolitan Toronto study.

Interprovincial trips (Survey 1C sample) constituted about 5 percent of all NCR goods movement trips, with slightly greater involvement of Ontario-based vehicles. In addition, some 53 percent of external trips were identified as being through trips and did not involve either an NCR origin or destination. Close to one-half of trips in the central areas were through trips as well.

Goods movement trips originating in and destined to the same zone accounted for over half (57 percent) the unlinked trips. It is recognized that this rate is somewhat dependent on zone boundaries, but a significant proportion (37 percent) of linked trips were also intrazonal. Unlinked trips represented the true origin/destination sequence of movements, whereas linked trips were desire line patterns of stops served from the vehicle's base of operations.

The overall average daily trip rate was 8.7 trips per vehicle, comparable with the rates observed in Toronto (9.7) and Vancouver (7.7) (*2*; summary of 1988 Vancouver truck survey). Medium-sized trucks tended to have the most stops per vehicle, whereas the heaviest group of trucks had, predictably, the highest trip times and trip lengths (Table 2). They also tended to have a greater proportion of external versus local trip origins/destinations than did the smaller trucks.

Because all interprovincial trips pass through or near the urban core, it was found that compared with all other internal trips, these were longer, on the average, and had lower average speeds (Figure 3).

An indication of the differences between intraurban and interurban travel was found by examining the trips per vehicle in Surveys 1a and 1b. The average of 12.0 trips per vehicle

TABLE 1 Population, Employment, and Trip Generation

Area	RMOC (Ontario)	CRO (Québec)	NCR (Combined)
Population	706,400 (77%)	215,800 (23%)	922,200
Employment	381,100 (83%)	77,000 (17%)	458,100
Per capita employment	0.54	0.36	0.50
Trips generated:			
- per capita	0.18	0.07	0.16
- per job	0.34	0.20	0.32

TABLE 2 Overall Average Trip Characteristics

Province Of Registration	Class Of Truck	Trips Per Vehicle	Trip Length (km)	Trip Time (min)	Stop Time (min)
Ontario	Light	9.7	12	17	31
	Medium	10.3	14	21	29
	Heavy	5.4	75	72	54
	All	9.1	19	23	33
Québec	Light	4.2	21	**	**
	Medium	7.4	22	32	44
	Heavy	6.0	41	43	27
	All	5.9	34	40	32
Ontario & Québec	All	8.7	20	25	32

** insufficient data

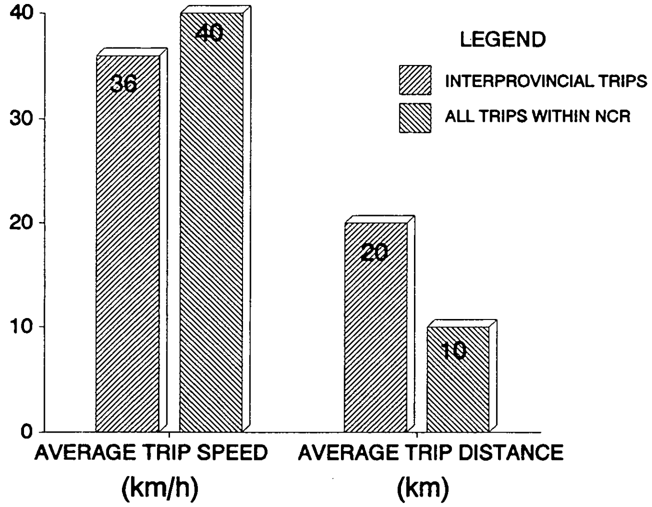

FIGURE 3 Interprovincial goods movement characteristics.

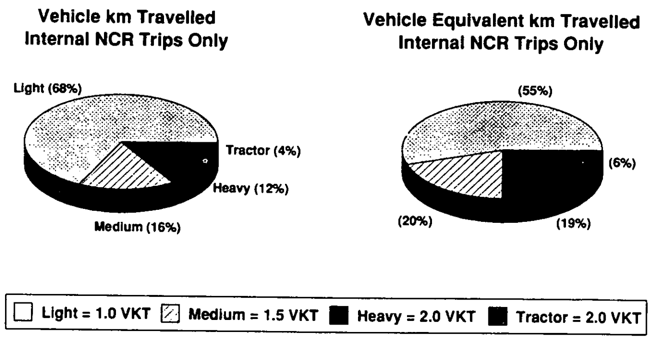

FIGURE 4 Trip characteristics.

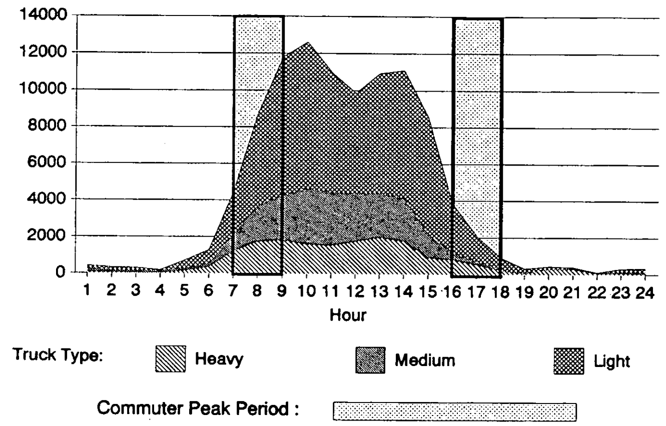

FIGURE 5 Hourly trip distribution.

for trips completely internal to the NCR and 3.5 trips per vehicle at the external screenlines is consistent with the differing forms of operation (Table 3).

The external trip data also showed that vehicles engaged in intercity travel were making multiple stops in the urban area (although information on the ultimate origin or destination of transshipped goods was not collected).

Whereas the heavy truck population is small compared with that of lighter trucks, the impact on the transportation network was disproportionately higher, based on heavy trucks' passenger car equivalents. In terms of actual distance traveled, light trucks dominate, but heavy vehicles (including tractors) have a much greater effect on capacity—60 percent greater than actual distance traveled (Figure 4).

Goods movement trip generation largely coincided with the normal business day. Ninety-five percent of firms surveyed indicated that they were in operation between 8:00 a.m. and 4:00 p.m., in part governed by customer demand. Peak-period congestion tended not to be a factor in determining the hours of operation. Only 18 percent of truck trips were generated during the two commuter peak periods (Figure 5).

In examining the destination, size, and composition of loads, it was found that

- Deliveries were more than twice as frequent as pickups;
- Fewer pickups and deliveries to the Ottawa and Hull central areas (70 and 40 percent, respectively) used off-street facilities than was the case for the NCR in general (80 percent);
- Aside from "other" goods, finished or processed products represented the largest category of goods carried;
- One-third of all vehicles were empty, 18 percent were full, and the remainder were carrying partial loads;
- Only 2 percent of commodities transported were dangerous goods; 47 percent of the dangerous goods were flammable liquids and compressed gases; and
- Less than 1 percent of goods transported were oversized or overweight loads requiring special transport permits.

Multiple regression analysis was used to develop truck trip generation rates based on the origin-destination data. The analysis derived generation rates as a function of zonal pop-

TABLE 3 Mean Trip Characteristics (Ontario and Québec)

Category	Survey 1a (internal)	Survey 1b (external)
Trips per vehicle	12.0	3.5
Trip Length (km)	10.5	71.2
Average Trip Time (min)	15.8	72.0
Average Stop Time (min)	27.9	54.9

ulation and employment. It was found that

- Population has a minor influence on truck trip generation,
- Government (public administration and related agencies) is not a large generator of truck trips,
- Equations for both light and medium trucks each have high coefficients of correlation (approximately 0.90), and
- Equations for heavy trucks exhibit small coefficients of correlation (0.362).

The equations are useful in providing order-of-magnitude forecasts of truck trip generation. More precise forecasts might be derived from detailed surveys of major generators at the individual site level or at office or industrial parks. In addition, the randomness inherent in truck pickup and delivery itineraries requires a more elaborate tracing of representative individual vehicles, both to corroborate observations and to gain further insight into daily variations. Finally, the trip generation rates were based on the relative aggregate indicators of population and employment; other indicators—notably measuring construction activity as an indicator of heavy truck activity—are required.

VALUE OF GOODS MOVEMENT AND THE IMPACT OF CONGESTION

The cost of transporting a product or its component parts accounts for a small, yet pivotal, portion of the final price of a product, and ultimately it reflects on the relative competitiveness or economic viability of a community. Under extreme, prolonged conditions, congestion also influences the location of industries that are dependent on truck access (*3*). The operating costs of moving goods in the NCR are affected directly by factors such as congestion, whose costs are passed onto consumers in the form of increased prices.

To obtain a measure of the value of goods movement in the NCR and the impact of congestion, hourly operating cost data were obtained from in-depth operator interviews (Survey 2a). These were confirmed by other operators during the focus group discussions. On the average, hourly operating costs ranged from $30.00 to $47.50 (Canadian dollars) for vehicle and driver, depending on the class of vehicle used.

Though not directly comparable because of the size and economic base served, Toronto costs ranged from $28.15 to $36.00 (1986), and Montréal costs were between $35.15 and $43.40 (1988) (*2*; data provided by Association du Cammionnage du Québec from a 1988 study of its members in the metropolitan Montréal region). The NCR averages were not comparable with the provincial averages for Ontario and Québec. This was expected given the dominance of interurban trucking and related economies of scale in the provincial cost data. However, the average operating costs generally were the same across the NCR (whereas the two provincial averages differ). This suggests that the location of a firm and its source of labor are not dependent on the provincial jurisdiction within the NCR.

The NCR costs were applied to average daily vehicle hours of travel based on trip rates, and mean travel and stop times, by vehicle class. Expansion factors were then applied to represent annual levels of travel and cost. The total cost of moving goods in the NCR based on this approach was estimated to be about $500 million annually.

Approximately one-half of the operators interviewed (Survey 2) believed that congestion contributed significantly to their operating costs. However, in examining the most commonly cited areas of congestion, it was found that location influenced the identification of congestion points only to a certain extent (i.e., frequency of use of a facility to the operator's location).

Congestion costs were determined from Survey 1 data by grouping trips by vehicle class by time of day, comparing travel time differentials, and then applying hourly costs. It was found that approximately 15 percent of morning and evening peak-period travel time was directly attributable to congestion, consistent with the experience of operators in Survey 2. The cost of congestion to the goods movement industry during the peak hours was estimated to be between $14 million and $18 million annually.

However, peak truck activity occurs outside the peak periods (i.e., 9:30 a.m. to 3:30 p.m.). Congestion, though reduced significantly in most areas, is also evident and may be attributable to, among other things, less road capacity due to on-street parking. It was determined that 11 percent of travel times for trips beginning between the two peak periods could be attributable to congestion, and the cost was estimated to be between $25 million and $33 million. The overall cost of congestion was between $40 million and $50 million, or approximately 8 to 10 percent of the annual cost of goods movement in the NCR (Figure 6).

ISSUES

A series of issues was identified by the surveys of shippers and operators and by the focus groups:

- The inadequacy of on-street loading facilities,
- Congestion in both central areas,
- Operational and geometric constraints,
- Too many parking/stopping restrictions,
- Inconsistencies in and quantity of regulations among the jurisdictions (municipal as well as provincial),
- The utility of a dangerous goods truck route network,
- The need for more interprovincial bridges,

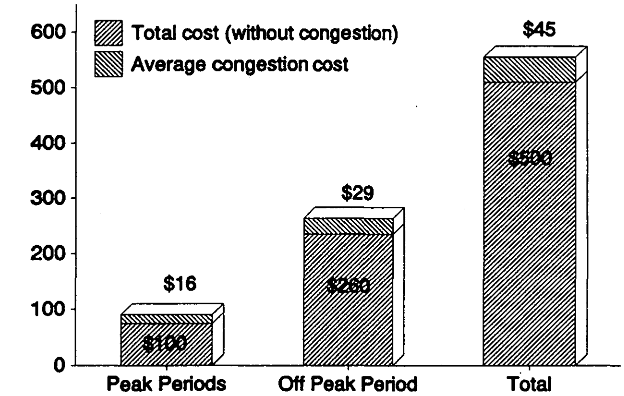

FIGURE 6 Cost of congestion.

- An already inadequate and shrinking truck route network, and
- The need for improved and increased communications among those involved in goods movement in the NCR.

These issues were evaluated in the context of the data collected and the ability to implement a solution. A manifestation of the latter was the opposition by NCR community groups concerning the designation of new truck routes near the Ottawa central area because of concerns about truck noise, vibration, and pollution. The conclusions and recommendations of the study were drafted with a view to responding to the issues at hand.

STUDY RECOMMENDATIONS AND DISCUSSION

There were 14 principal recommendations; they are discussed below. An impact assessment of five possible changes to the road network also was conducted. Two of those changes dealt with the issue of additonal interprovincial bridges. The results will be used in the planning and prioritization of new roads and bridges.

The first recommendation was to provide for new alternate truck routes bypassing the Ottawa central area to reduce through goods movement trips and congestion. The means to do so was left to a further study. The second recommendation was to increase enforcement of the use of on-street loading/unloading facilities to eliminate infringement by unauthorized private vehicles. The largest number of concerns on any issue was recorded with regard to on-street loading/unloading in the central business district.

The third recommendation was to enhance existing curbside management strategies and to introduce new ones through an investigation of new technologies and a better understanding of current policies. RMOC already has a curb space management policy for the Ottawa central area (*4,5*) that gives priority to commercial loading after essential needs (such as clearance for fire hydrants, bus stops, accesses, and intersections) have been addressed.

The principal problem in the NCR is common to the downtowns of most North American cities where several transportation uses are competing for the same limited space (*6*). A common means of increasing street and intersection capacity is to reduce or eliminate on-street parking and loading/unloading areas (*7*).

The intention of the study's recommendation was to seek out a strategy as broad based as possible, taking into account competition among several users for the curbside lane. It was recognized that a more detailed understanding of on-street loading/unloading operations would be required, given, for example, that the space requirements and duration vary according to commodity and land use. One such analysis is now being undertaken in Toronto, as a follow-up report to the 1987 *Metropolitan Toronto Goods Movement Study*.

The fourth recommendation was to review and revise municipal bylaws in the respective central areas to ensure their adequacy and consistency. For example, a review of municipal bylaws indicated that the loading requirements of suburban communities appeared to be stricter than those of the inner cities. It was also recognized that solutions in this area tend to be long term and cannot be retroactively applied unless there are redevelopment opportunities at individual sites. There was also a need to acknowledge, on the basis of the stop time evidence presented in Table 3, the varying parking and loading requirements of goods movement trips based on time and truck size.

Problems concerning interprovincial travel within the NCR related to permits required to operate interprovincially and the use of the three bridges on which trucks are allowed. The fifth and sixth recommendations were drafted with a view to considering the results of this study in the future planning for bridges and ensuring that local operators were aware of, and made available, interprovincial operating requirements. The latter recommendation was directed at the needs of independent operators (which tend not to be part of the interurban carrier industry). Larger operators understood the regulatory requirements for interprovincial operations in the NCR and had few difficulties in meeting them.

The seventh and eighth recommendations dealt with the issue of truck routes, specifically, the "shrinking" truck route system and resultant discontinuities, even in emerging growth areas. A single, coordinated NCR truck route system (or map of one) does not exist. Links have been removed from the system in recent years because of complaints from residents. Nighttime restrictions have been imposed on other residential links. Nighttime deliveries are not prohibited, although the activities tend to be confined to industrial and commercial areas. A night delivery strategy was attempted at a major shopping center but was abandoned as not being cost-effective.

Reinstituting those removed truck route links would be difficult. However, the study recognized and recommended that it is important both to enhance the means used to designate routes in the NCR and to ensure that the entire NCR truck route system is well known to operators.

The 9th and 10th recommendations dealt with the issue of seasonal load restrictions. These were imposed in the spring months to account for structural constraints that occur from spring thaw. The resulting discontinuities in the truck route network were reported to increase travel times and operating costs, especially since some operators had to use a greater number of trucks and movements to transport a given load. However, it was recognized that road reconstruction incurs significant public costs. The conclusion of the report was to attempt to minimize seasonal road discontinuities and to factor roads and bridges that are subject to seasonal load restrictions into the process that determines priorities for facility rehabilitation.

With respect to dangerous goods, it was discovered that there are about 500 dangerous goods incidents each year, most occurring on private property (i.e., at storage terminals or loading/unloading facilities). Municipalities in Ontario and Québec, among them the RMOC, have considered or proposed the limitation of urban dangerous goods movement to specific truck routes. Operators were generally not in favor of the limitations because of perceived cost increases and logistical problems.

The designation of these systems, however, is under provincial jurisdiction. In Ontario, the Ministry of Transportation has not designated dangerous goods truck routes because of concerns about increased accident and spill risks, additional economic burdens on the trucking industry, and further enforcement required by police forces. It was subsequently recommended (the 11th recommendation) that the current practice of not designating them be maintained until justification, through a risk assessment ascertaining need, is demonstrated.

The issue of oversized loads was also of interest because some 1,120 such permits were issued in the NCR in 1989, the movement of some of these loads required police or other escorts, and there were regulatory and operational differences among municipalities and between the municipality and the province governing their movement on facilities under their respective jurisdictions. A twelfth recommendation was made to establish a committee to address those regulatory differences.

Inherent in all the preceding issues was the need for improved and increased communications among those involved in goods movement in the NCR. The thirteenth recommendation was that the dialogue initiated in this study be maintained. In particular, it was also recommended that trucking operators organize to speak with a single voice. Currently, trucking associations exist by province, region, or industry type—no single association represents the entire NCR.

The fourteenth recommendation was to monitor and refine the characteristics and relationships developed in this study and to establish liaison with other technical committees to evaluate and perhaps apply their strategies.

CONCLUSION

The results of the study have focused attention on the needs and concerns of the goods movement industry. A number of agencies were involved in guiding the study and, consequently, have each gained considerable knowledge of the scope and magnitude of goods movement operations within their communities.

A strong data base now exists and contains comprehensive data on goods movement activities across the NCR. Future studies may evaluate the impact specific proposals will have on goods movement within the NCR.

The study represents the largest goods movement survey ever undertaken locally and provides a clear understanding of local goods movement operations. In short, there is a greater appreciation of the travel patterns, costs, and needs of the industry. This is critical for planners and transportation practitioners, considering the impact of the goods movement industry on the urban economy. Increased costs and delay are important factors in the total cost of moving goods and are ultimately reflected in the selling price of a product or commodity.

A committee consisting of most of the study's municipal and provincial participants has since been formed to develop a process by which the findings of the study can be implemented.

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Truck Travel in the San Francisco Bay Area

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In travel demand forecasting, truck travel demand is often combined with automobile demand and converted to automobile equivalencies. This typically increases automobile person-trip forecasts by 5 to 15 percent. This practice does not accurately reflect the actual origins and destinations of trucks or the travel demand on those roadways where trucks are restricted. Since data on truck travel are sparse, a research program was conducted to provide information to develop a travel demand model for trucks. The model was needed to evaluate alternatives in the I-880 Intermodal Corridor in western Alameda County, California, extending from Oakland to San Jose. Although the study area focused on this corridor, the model and data base include the entire nine-county San Francisco Bay Area. The study area includes this region to consider the many trucks that had one trip end in Alameda County or passed through the county. The process by which the truck travel demand model was developed included the definition of trip types and the expansion of survey results as well as the development of four submodels: trip generation, trip distribution, peak-hour factoring, and trip assignment. The model validation showed that the truck model does a reasonable job of reproducing existing truck travel in the Bay Area. Future project scenarios will be tested later.

This paper documents and summarizes the findings and conclusions of a study conducted by Barton-Aschman Associates, Inc., to collect truck travel data and produce a truck travel model for Alameda County and adjacent counties in the San Francisco Bay Area. [Alameda County has an area of 1,906 km^2 (736 mi^2) and a population of approximately 1.3 million.] The report is part of the I-880 Intermodal Corridor Study sponsored by the California Department of Transportation (Caltrans) and the Federal Highway Administration.

The truck travel model was created to improve the ability to estimate future congestion in the study corridor (see Figure 1) and understand how trucks contribute to this congestion, since truck travel is not explicitly modeled in the existing Alameda Countywide Multimodal Transportation Model.

FINDINGS FROM OTHER STUDIES

Two other urban areas have recently conducted surveys on regional truck travel for input into truck travel forecasting models—Chicago and Phoenix (*1–3*). Both of these cities conducted extensive data collection programs and had some common findings:

1. Trip length distribution by size of truck: Generally, the larger the truck, the longer the average trip length.
2. Number of daily trips by size of truck: Generally, the larger the truck, the fewer the number of average daily trips.
3. Daily peak patterns: Truck travel is heaviest in the midday period and declines before the p.m. commute period.
4. Land uses served by trucks: A majority of truck trips are destined for retail establishments (25 percent), manufacturers (20 percent), or terminals/warehouses (20 percent).
5. Sensitivity to local conditions: Truck (or commercial vehicle) travel characteristics may vary in each urban area. For example, Chicago is a central hub for truck and rail, Phoenix is on a through route from the east to Southern California, and Alameda County is a coastal port with very little through travel.

Key factors include, but are not limited to, labor rules (e.g., Port of Oakland), break-of-bulk points (e.g., Chicago), the location of specific industries (e.g., wholesale distribution, trucking companies, and certain manufacturers), and geographic and physical constraints (e.g., tunnels, bridges, low undercrossings, mountains, etc.).

TRUCK TRAVEL SURVEYS

The primary objective of the truck travel research program was to obtain a more accurate and detailed understanding of current truck travel. Existing data are limited. Three gaps in present knowledge of truck travel in the San Francisco Bay Area were identified: time-of-day patterns, origin and destination data, and goods carried.

Four travel surveys were conducted to obtain information regarding travel patterns of trucks operating within the San Francisco Bay Area:

- Truck classification counts at 11 freeway locations (see Figure 2) for a 5- to 7-day period;
- Truck-intercept surveys at five California Highway Patrol (CHP) weigh stations, which resulted in completion of more than 8,000 interviews (see Figure 3), and at four toll bridge crossings, which produced almost 700 completed postcard surveys;
- Employer surveys of truck trips generated; and
- Surveys and interviews with truck drivers, terminal operators, and planning staff at the Port of Oakland, which

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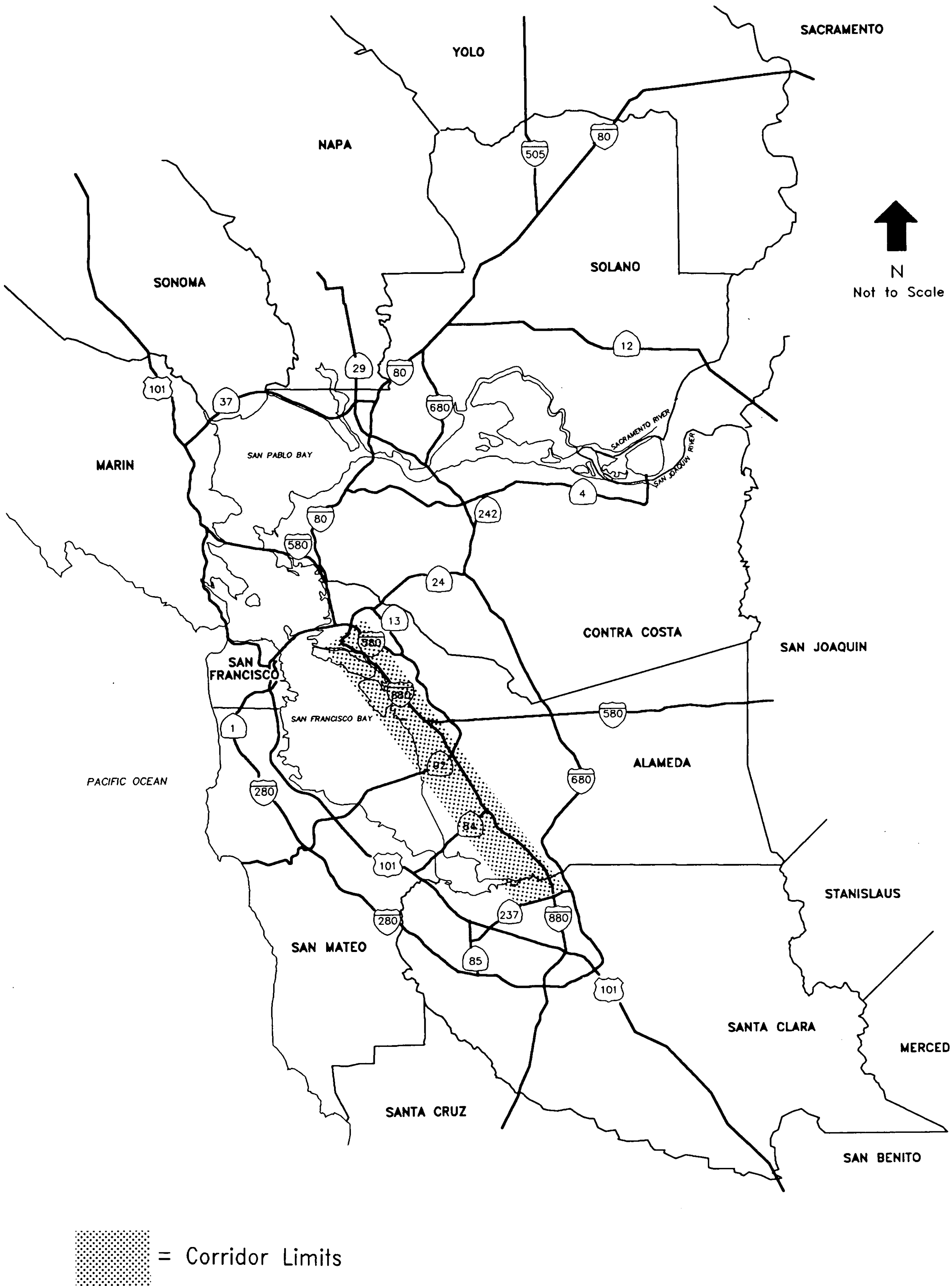

FIGURE 1 Study location.

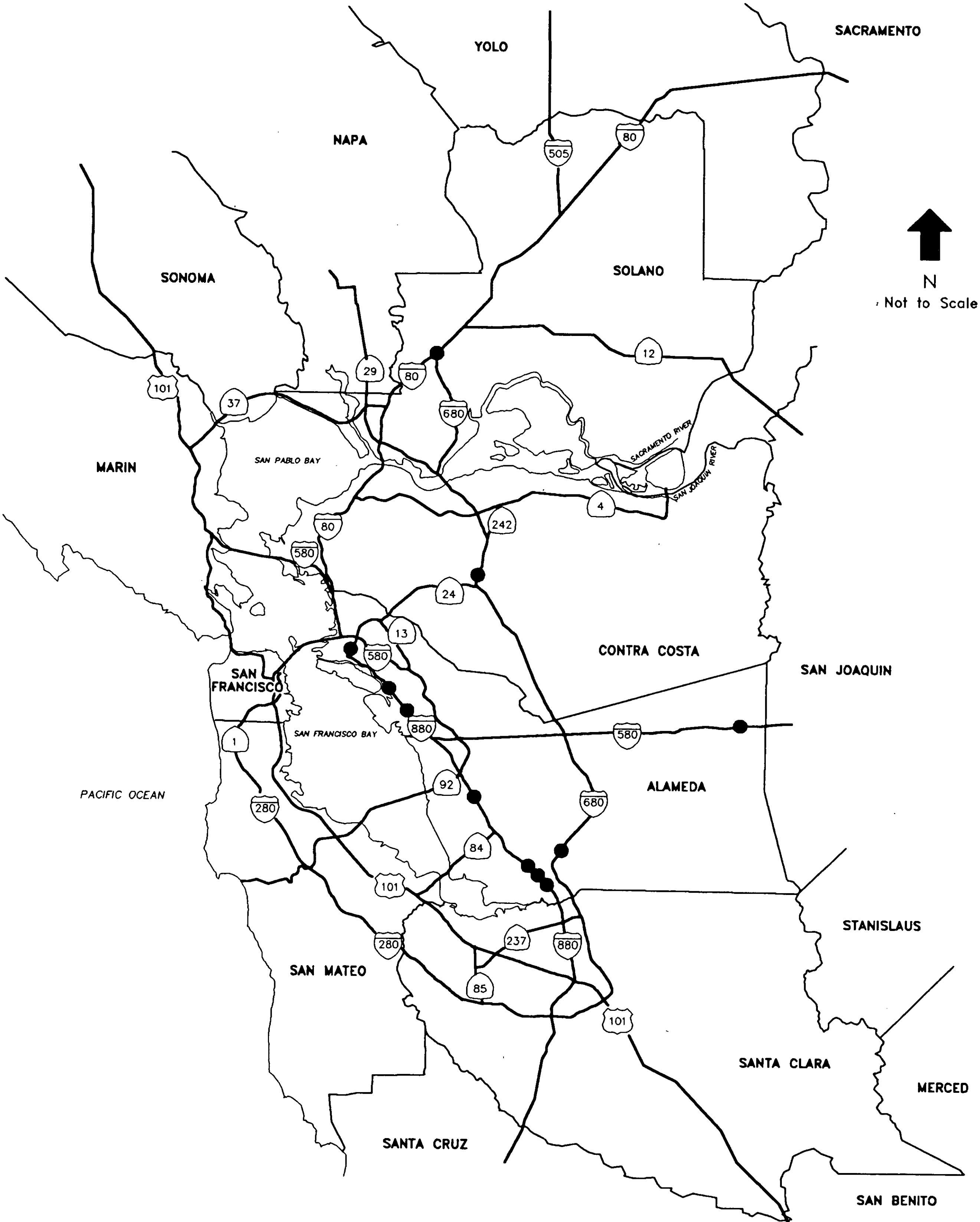

FIGURE 2 Truck classification count locations.

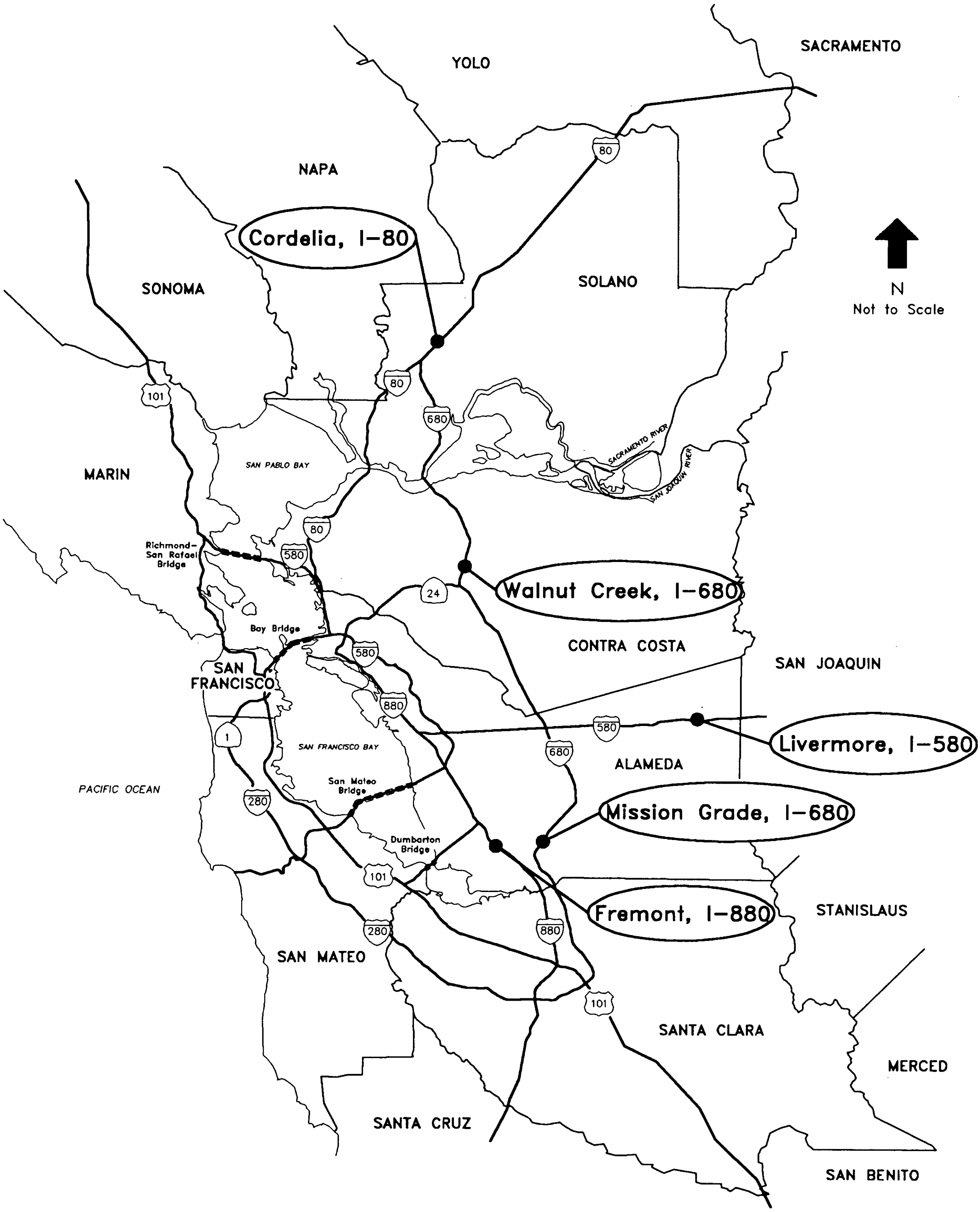

FIGURE 3 Truck intercept interviews station locations, number and direction of travel.

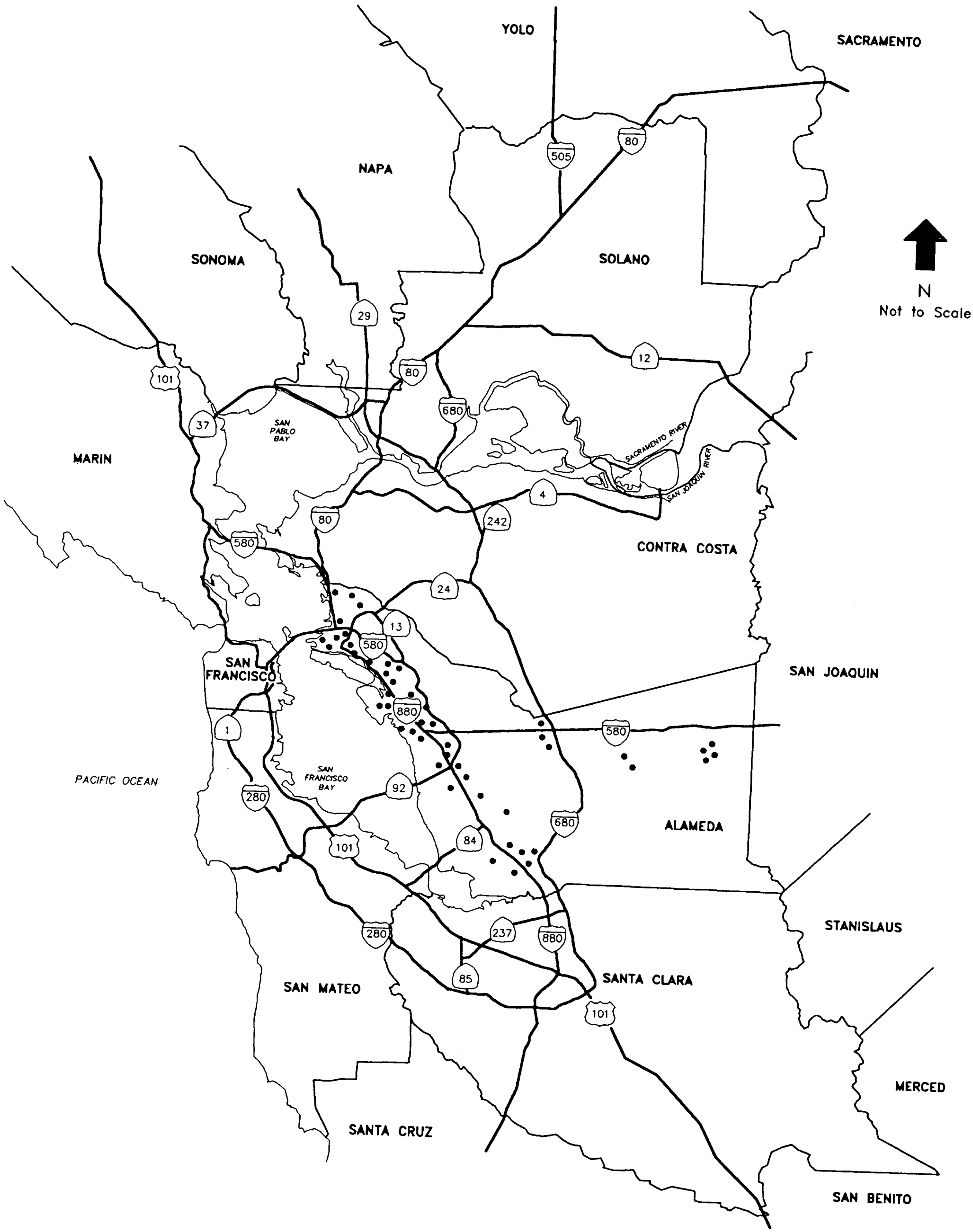

FIGURE 4 **Employer survey, concentration of companies.**

resulted in 1,172 surveys that represented 3,800 daily truck trips generated by the port.

In the employer surveys of truck trips generated, a combined telephone and mail-back survey contacted 698 employers in Alameda County (see Figure 4) representing more than 36,000 employees. The overall response rate exceeded 79 percent. Responses from 87 companies that had trucks provided detailed trip data for 2,700 truck trips.

The results of these data-gathering efforts were used to develop the model.

SURVEY CONCLUSIONS

The most important findings of the truck travel research program are the following:

- The peak period for truck travel is midday, not in either the a.m. or the p.m. peak commute periods. This is consistent with findings from other Bay Area and national studies (*4,5*) (see Figure 5).
- Most truck trips in the San Francisco Bay Area are within the nine-county Bay Area. At five CHP weigh stations and four bridge crossings, 98 percent of the truck trips surveyed had either origin or destination in one of the nine Bay Area counties.
- Many of the approximately 5,000 daily truck trips in the Port of Oakland area are local trips that never access a freeway. Trucking is an important component of the port's complex, intermodal network of transportation facilities and services. Most of the truck trips at the port (59 percent) originate in the nine-county Bay Area. The San Joaquin Valley, east of the Bay Area, accounts for 19 percent of originating truck trips to the port.
- Most employers (68 percent) do not own or lease trucks. Brief telephone interviews established which employers did not own or lease trucks and which might have trucks and should be mailed a truck trip log. For one category of employers (business services), more than 97 percent of those contacted did not own or lease trucks.
- Overall, 35 percent of the employers own or lease trucks. However, this percentage varies by employer type and size (see Table 1). Large employers are more likely to have trucks than small employers. Manufacturing firms are four times as likely to own or lease trucks as business service firms. Only 11 percent of business services firms own or lease trucks, whereas 45 percent of manufacturing firms do. A large proportion (45 percent) of "other employers," a category that includes wholesale companies, own or lease trucks.
- The disproportionate stratified sample of employers used in this study provided a sample of employers that included all sizes and industries while minimizing the number of interviews. The survey obtained information about the number

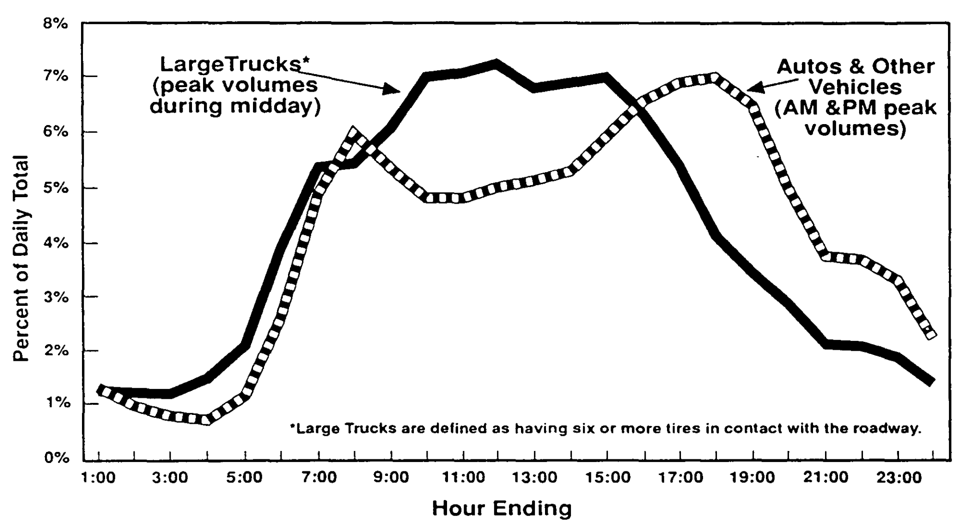

FIGURE 5 Hourly traffic distribution as a percentage of the 24-hr total.

TABLE 1 Percentage of Employers that Have Trucks, by Size and Type of Company

Employer Type	Number of Employees 1-9	10-99	100 +	All Sizes of Employers
Business Services	11	20	28	13
Manufacturing	41	49	54	45
Other (includes wholesale)	39	64	68	45
Retail	NA	35	39	35
All Types of Employers	24	34	48	35

of employees the company had and the type of business, as well as the truck trip information. This type of survey lends itself to creating models of truck travel and goods movements because the truck trips can be directly related to employment through the use of employer data bases that are readily available. In this study, Equifax Marketing Decision Systems and Rich's Everyday Business Directory provided the employer data. Employment data are commonly forecast by regional planning organizations, so future truck travel can be estimated by relating existing truck trip rates to employment forecasts.

- The intercept surveys combined with the classification counts at the weigh stations worked well. They provided reliable data at a reasonable cost with no complaints or accidents.

GOODS MOVEMENT

Although goods movement is the most common reason for urban truck travel, collecting detailed commodity data was beyond the scope of this study. Furthermore, the relationships among industries, modes of transport, and commodities are too complex for the present analysis.

Some commodity data were collected during the truck intercept surveys and employer interviews by asking what types of goods were being hauled, if any. (No details about weight or volume of goods carried were sought.)

For this study, goods were classified into 10 categories. The categories and some examples are given in the following table.

Goods Category	*Examples of Goods*
Agriculture	Tomatoes, meats, plants
Chemicals	Chlorine, liquid nitrogen
Construction	Backhoe, forklift
Construction materials	Bricks, concrete
Empty	Empty
Manufacturing	Packing supplies, bottles
Miscellaneous freight	Plastic parts, Port-a-Pits
Retail	Food, furniture
Service	Tow truck, utility
Waste	Garbage, sewer sludge

Figure 6 summarizes goods distribution by category. Empty trucks represented a large proportion of trips. Retail-related trips were the next highest among the 10 goods categories.

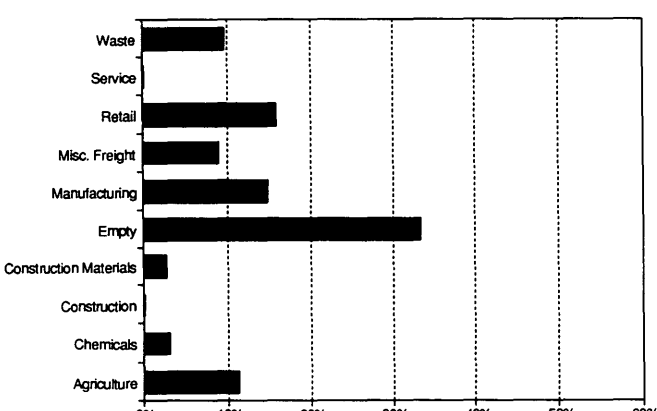

FIGURE 6 Goods distribution, port survey—inbound direction.

PURPOSE OF THE TRUCK TRAVEL MODEL

The truck travel demand model was developed as part of the I-880 Intermodal Corridor Study. The study area is a 48-km (30-mi) corridor in western Alameda County, but the truck travel study area was expanded to include the entire nine-county San Francisco Bay Area. The model was not intended to forecast goods movement but, rather, truck travel. Specifically, it was designed to forecast average weekday and p.m. peak-hour volumes for two-, three-, and four-or-more-axle trucks.

TRUCK TRAVEL MODEL DEVELOPMENT

The truck travel forecasting process consists of four components: trip generation, trip distribution, peak-hour factoring, and trip assignment. The model was developed using existing Bay Area highway networks, 1990 Metropolitan Transportation Commission socioeconomic data, and results of various surveys conducted in 1991 as part of the overall truck study. Truck volume counts from 1991 were used to validate the travel model.

The four surveys described earlier produced three types of data, all of which were used to create the model: (*a*) interview survey data from employers, which provided a representative sample of truck travel that occurred within the Bay Area; (*b*) intercept survey data, which provided an accurate representation of truck travel for vehicles having at least one end of a trip outside of the Bay Area; and (*c*) classification counts at various freeway locations, which provided the information needed to determine the diurnal travel patterns and to calibrate the model.

Since each survey represents only a sample of truck activity, the results were expanded to represent all trucks for each trip type. This study assumed that truck travel and goods movements remain constant from day to day during the weekdays and from week to week during the year.

The model was designed to estimate travel for three general truck trip types and three truck types. The three truck types are two-, three-, and four-or-more-axle. The three general trip types are external-external, internal-external, and internal-internal. "External" refers to an origin or destination outside the nine-county Bay Area region. Internal-external trips have either an external origin or destination and include external-internal trips. Internal-internal trips are further subdivided into garage-based and linked trips. Garage-based trips are trips in which the truck travels from its origin to its destination and returns to its origin. Linked trips involve departure from the origin and travel to several destinations before returning to the point of origin. The internal trips were classified into these two categories since there are many trips of both types (see Table 2), and they are significantly different. Garage-based trips tend to start in industrial areas and travel elsewhere, whereas linked trips occur throughout the region.

External-external trips were modeled by estimating a trip table of these trips from the intercept surveys and then factoring this trip table on the basis of employment growth for future years. Trip generation and distribution models were created for internal-external and internal-internal trips by truck type.

TABLE 2 Employer Survey Trips by Truck Type and Trip Type

Trip Type	Number of Axles	Trips	Percent
Internal Garage-Based			
	2	552	20
	3	240	9
	4+	178	6
Subtotal		970	35
Internal Linked			
	2	826	30
	3	519	19
	4+	290	10
Subtotal		1,635	59
Internal-External			
	2	48	1
	3	15	1
	4+	87	3
Subtotal		150	6
Total		2,755	100

For trip generation, equations were formulated for productions and attractions using methods similar to those used when creating a typical regional model. The garage-based trip productions were estimated as trip rates using the employer survey (see Table 3). The garage-based trip attractions were estimated by testing numerous relationships between survey trip destinations and the socioeconomic data for the cities in Alameda County using multiple linear regression. The socioeconomic data considered included total employment, retail employment, manufacturing employment, service employment, other employment, population, households, and average household income. The analysis showed that the most meaningful correspondence between socioeconomic categories and trip ends was achieved by using either "total employment" or "other employment" categories. This happened because the survey trip end data were collected at the city level, and the cities in Alameda County are large enough that there tended to be a better relationship between the different types of socioeconomic data than between the socioeconomic data and the survey trip end data.

Linked trips were estimated in a way similar to non-home-based trip equations. This is because they are similar in that most of these trips do not have one end at the employer's location. Instead, they are typically delivering goods to a series of stores. Both the trip productions and the trip attractions were estimated in the same way as the garage-based trip attractions. The trip rates are also given in Table 3.

The internal-external trip productions were estimated using the truck volumes at the external stations, and the attractions were estimated by relating the internal ends of the intercept survey trip to the socioeconomic data for each city in the Bay Area (see Table 3).

All of the trip generation equations were refined through an interactive process in which the model-estimated volumes were compared with the observed volumes for each truck type. This method produced the final trip generation rates, as given in Tables 2 and 3.

To better understand the approximate number of trips per employee by truck type and employment type, the trip rate data used to construct this model are summarized in Table 4, which indicates that there are 85 truck trips per thousand employees for the Bay Area.

The survey data provided information adequate to develop trip distribution submodels for each trip and truck type category. The trip distribution submodels consisted of standard gravity models with friction factors but no K factors. Table 5

TABLE 3 Trip Production and Attraction Rates by Trip Type, Employment Type, and Truck Type—per 1,000 Employees

Trip Type/ Employment Type	Truck Type 2-Axle	3-Axle	4+ Axle
Internal Garage-Based Productions			
Manufacturing	11	2	4
Retail	14	–	–
Business Services	1	–	–
Other Employment	5	4	8
Internal Garage-Based Attractions			
Other Employment	–	5	14
Total Employment	23	–	–
Internal Linked Productions & Attractions			
Total Employment	32	4	7
Internal-External Productions			
Manufacturing	–	2	22
Other Employment	–	1	9
Total Employment	4	–	–

TABLE 4 Trip Rates by Trip Type and Truck Type—Trips per 1,000 Employees

Trip Type	Truck Type 2-Axle	3-Axle	4+ Axle	All Trucks
Garage-Based	23	2	4	29
Linked	32	4	7	43
Internal-External	4	1	7	12
All Types	60	6	19	85

TABLE 5 Comparison of Trip Length Distribution—Average Trip Length in Minutes

Trip Type	Survey Data	Model Result
Internal Linked Trips		
2-Axle Trucks	16	16
3-Axle Trucks	20	20
4-or-More-Axle Trucks	29	29
Internal Garage-Based Trips		
2-Axle Trucks	24	25
3-Axle Trucks	25	26
4-or-More-Axle Trucks	40	40
Internal-External Trips		
2-Axle Trucks	54	53
3-Axle Trucks	59	58
4-or-More-Axle Trucks	59	59
Internal-Internal Port Trips		
3-Axle Trucks	16	16
4-or-More-Axle Trucks	23	22

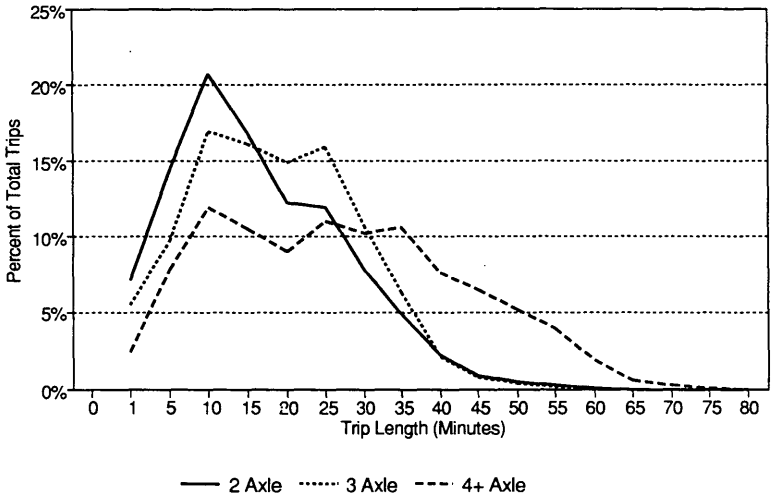

FIGURE 7 **Estimated trip length distribution for internal linked trips.**

summarizes the average trip lengths calculated for the survey data and the model for each trip and truck type. The model results come very close to replicating the survey data, with no more than a 1-min difference for any trip type. In general, the two-axle truck trips are the shortest, and the four-or-more-axle trips are the longest. Linked trips were approximately 30 to 50 percent shorter than garage-based trips. Trip-length distributions by truck type for internal linked trips are shown in Figure 7.

The p.m. peak hour (5:00 to 6:00 p.m.) trip tables were created by factoring the daily trip tables for each truck type and trip type. These factors were first derived from the survey data and the external station classification counts. The factors were then refined using an interactive process in which the factors were adjusted until the estimated volumes matched the classification counts as well as possible. The final peak-hour factors are given in Table 6.

MODEL VALIDATION

Daily and p.m. peak-hour trip tables were created for two-, three-, and four-or-more-axle truck trips. These trip tables were then assigned to the Bay Area highway network. From these assignments, the estimated vehicle-kilometers traveled (VKT) and percent root mean square error (RMSE) were calculated. Percent RMSE is the variation between observed and estimated data that is expected to occur approximately 66 percent of the time. The daily validation statistics are given in Table 7, and the p.m. peak-hour validation statistics are given in Table 8.

TABLE 6 **P.M. Peak-Hour Truck Trip Factors by Truck Type and Trip Type**

Truck Type	Internal-Internal	Internal-External	External-External
2-Axle	0.05	0.04	0.05
3-Axle	0.04	0.05	0.04
4-or-More-Axle	0.04	0.03	0.04

TRUCK TRAVEL SUMMARY

As indicated by the validation statistics, the truck forecast seems reasonable when examined both by county subareas and on a link-by-link basis. However, the model has not been used to test alternative future scenarios yet.

Table 9 summarizes the number of daily trips in the Bay Area generated by the model for each truck type and trip type. Except for the internal-external port trips, external-external trips constituted the lowest percentage of total truck trips. The daily vehicle-hours traveled (VHT) for each trip type and axle type are presented in Table 10.

The following observations can be made from Tables 9 and 10:

- Daily internal-external trips were 14 percent of the total truck trips, yet they constitute 32 percent of the total VHT.

TABLE 7 **Daily Truck Travel Validation Statistics**

Truck Type	Estimated/ Observed VKT	Percent Root Mean Square Error
2-Axle	1.004	30.6
3-Axle	1.003	57.3
4-or-More-Axle	1.026	54.9

TABLE 8 **P.M. Peak-Hour Validation Statistics**

Truck Type	Estimated/ Observed VHT	Percent Root Mean Square Error
2-Axle	0.993	37.8
3-Axle	1.000	68.9
4-or-More-Axle	1.000	70.4

TABLE 9 Daily Truck Trip Summary

Trip Type	2-Axle Trucks	3-Axle Trucks	4-or-More-Axle Trucks	Total	Percent
Internal-Internal					
Linked	99,521	11,972	22,209	133,702	50
Garage-Based	72,086	4,730	14,176	90,992	34
Port	0	1,430	2,779	4,209	2
Subtotal	171,607	18,132	39,164	228,903	86
Internal-External	13,481	1,852	21,593	36,926	14
Internal-External Port	0	167	914	1,081	0 [a]
External-External	233	26	1,251	1,510	1
Total	185,321	20,177	62,922	268,420	101
Percent	69	8	23	100	

[a] Less than 0.5%.

TABLE 10 Daily Truck Vehicles-Hours Traveled

Trip Type	2-Axle Trucks	3-Axle Trucks	4-or-More Axle Trucks	Total	Percent
Internal-Internal					
Linked	32,427	4,306	11,149	47,882	37
Garage-Based	22,971	1,667	9,803	34,441	27
Port	0	395	1,028	1,423	1
Subtotal	55,398	6,368	21,980	83,746	65
Internal-External	14,782	2,291	24,958	41,671	32
Internal-External Port	0	196	1,066	1,261	1
External-External	454	50	2,346	2,849	2
Total	70,634	8,905	49,990	129,529	100
Percent	55	7	39	100	

- Three-axle trips accounted for the smallest percentage of total travel (8 percent of trips) and the smallest portion of VHT (7 percent).
- Whereas large trucks (with four or more axles) accounted for one-third as many trips as two-axle trucks, the corresponding VHT for four-or-more-axle trucks was more than 70 percent of two-axle truck VHT.

RECOMMENDATIONS

The following suggestions are offered on the basis of the experience with this study:

1. The origins and destinations of trips that begin or end within the study area should be geocoded to the transportation analysis zone rather than to zones representing entire cities. This would allow the creation of more accurate trip production and attraction equations.
2. A larger sample of employers (perhaps three times as many, or about 1,800) would be desirable. Since the number of employers with three-or-more-axle trucks was very small, a larger sample size would increase confidence in the trip generation and trip distribution submodels.

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