TRANSPORTATION RESEARCH RECORD

No. 1263

Rail
Freight Transportation

Ports, Waterways, Rail, and International Trade Issues 1990

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1990

Transportation Research Record 1263
Price: $18.00

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Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Ports, waterways, rail, and international trade issues. 1990.
p. cm.—(Transportation research record, ISSN 0361-1981 ; 1263)
ISBN 0-309-05019-7
1. Inland water transportation—Congresses. 2. Ferries—Congresses. 3. Harbors—Congresses. 4. United States—Commerce—Canada—Congresses. 5. Canada—Commerce—United States—Congresses. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 1263
[HE617]
388 s—dc20
[387'.009730] 90-13335
CIP

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Foreword

The papers in this Record deal with topics of international trade, waterborne passenger transportation, inland waterways, ship handling, and modeling techniques for ferry boat and railroad operations.

Discussed in two papers are aspects of trade between the United States and Canada. The paper by O'Callaghan and Hartgen assesses the impacts of the U.S.-Canada free trade agreement. The agreement is expected to increase present border traffic by 6 percent per year, which will create the need for additional road maintenance and border crossings. In the second paper, Gorys identifies changes in the value of trade between the United States and Ontario and the shifts in transportation modal shares. In the third paper, by Olson and Grier, the Panama Canal and the St. Lawrence Seaway are used as a comparison to show the impacts of technological change on foreign trade.

Two papers address ship-handling. The paper by Low and Wilson develops a statistical analysis technique for predicting the probability of a ship-bridge collision. In the second paper, Jakobsen, Miller, and Daggett describe the application of ship maneuvering simulations in the evaluation of restricted channels that are required to accommodate two-way ship traffic.

There are several papers on passenger ferry service. Schoon, Furth, and Lieb suggest in their paper that supplemental freight can be carried on passenger ferries in such a way that passenger service is not disrupted or made less attractive. Such freight would be a means for obtaining additional revenue. Berkowitz presents two papers on ferry service, one on the feasibility of high-speed ferries to replace the existing Staten Island Ferries and the second a logit-based demand model to evaluate the viability of implementing new waterborne passenger transportation systems. Similarly, Harker presents a series of models and algorithms for use with advanced train control systems technology on railroads to improve reliability and costs of operations.

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Contents

Transportation Impacts of the U.S.-Canada Free Trade Agreement

Janet E. O'Callaghan and David T. Hartgen

Trade between the United States and Canada is the largest in the world, totaling $166 billion. The Free Trade Agreement signed between the United States and Canada in January 1989 will have varying impact on the transportation systems in both countries. Discussed and analyzed in this paper are the following five areas indicating the possible effects of the agreement: (a) the specifics of the Free Trade Agreement, (b) the Canadian transportation system, (c) the present and projected import and export volumes between the two countries, (d) present and projected automobile-truck traffic crossing the border and (e) the probable impacts of the Free Trade Agreement on transportation. Present border traffic consists of about 70 million vehicles annually and has been increasing at about 6 percent per year. The agreement is projected to accelerate automobile and truck traffic growth, particularly in the middle states of the United States, creating the need for additional road repairs and border crossings. These repairs may cause a "border tilt," the effects of which will be felt first in Canada and then in the United States. Special problems relating to truck traffic growth in Washington and Maine may politicize the effects of the Free Trade Agreement in those two states. The authors conclude by noting that the Free Trade Agreement will provide many opportunities and advantages for businesses, but it will also pose substantial transportation problems for both the United States and Canada.

The United States and Canada are the world's largest trading partners. The United States is Canada's principal supplier and major customer, providing 70 percent of Canada's imports and purchasing 78 percent of Canada's exports. In 1987 United States exports to Canada reached $60 billion, just slightly less than the United States' exports to the 12 member-countries of the European Community. Also in 1987, the two countries exchanged goods and services totaling $166 billion, and bilateral direct investment totaled $79 billion (*1*). A lifting of trade barriers between the United States and Canada is likely to further increase trade between the two countries.

The Free Trade Agreement (FTA), signed by the United States and Canada in January 1989, covers trade and trade-related issues. It is also expected to cause an increase in trade between the two countries. The lowering of the trade and investment barriers to North American manufacturers, service providers, and investors means that more Americans and Canadians will be crossing the border to conduct business (*2*). This expected increase in trade will undoubtedly affect transportation between the two countries. For example, the transportation infrastructure between the two countries may have to be upgraded or expanded as a result of the trade increase. Additionally the customs service and traffic regulations will require upgrading and review. To better understand these effects, the following five subjects will be reviewed:

1. FTA,
2. Canadian transportation system,
3. Present and projected import and export volumes between the two countries,
4. Present and projected automobile-truck traffic crossing the border, and
5. Probable impacts on transportation.

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FREE TRADE AGREEMENT

On January 1, 1989, the United States and Canada signed an agreement establishing the world's largest free trade area, (stretching across North America from the Arctic Circle to the Rio Grande). The FTA between the United States and Canada removes existing barriers to trade and investment for many industrial, agricultural, and service sectors. The agreement translates the Elements of Agreement reached on October 4, 1987 into binding, legal language. It is divided into eight parts:

Part One	Objectives and Scope: contains the objectives and scope of the agreement and definitions used in the agreement;
Part Two	Trade in Goods: sets the rules for trade in goods, border measures, national treatment, technical barriers, agriculture, wine and distilled spirits, trade in energy, trade in automotive products, emergency action, and exceptions for trade in goods;
Part Three	Government Procurement
Part Four	Services, Investment, and Temporary Entry: contains the three ground-breaking chapters in the agreement: services, business travel, and investments;
Part Five	Financial Services
Part Six	Institutional Provisions: contains the general dispute settlement provisions and the special arrangements for dealing with anti-dumping and countervailing duty procedures;
Part Seven	Other Provisions: collects in one chapter a series of provisions that do not fit readily into any of the other chapters;
Part Eight	Final Provisions: deals with annexes, entry into force, and duration.

Under the agreement, professional persons have the right to cross the border into Canada under streamlined documentation and procedural requirements. The FTA divides business travelers into four categories: (a) business visitors, (b) professionals, (c) traders and investors, and (d) intracompany transferees (*3*). These travelers will no longer have to face labor certification tests or other similar procedures, which often delay or deny entry.

Before the agreement, over 70 percent of American exports to Canada were duty free, but the remaining tariffs, averaging 9.9 percent of dutiable import costs from the United States, were effective barriers to many U.S. exports. Products affected include apparel, alcoholic beverages, furniture, and chemicals (*4, 5*). Individual goods tariffs will be rolled back (eliminated) on one of three schedules (immediate, more than 5 years, and more than 10 years), and all tariffs will be removed by 1988 (Figure 1). Once all Canadian tariffs are eliminated, the costs of U.S. exports to Canadian business and consumers will have been reduced by more than $1.3 billion/year, or about 2 percent in current dollars. Conversely, U.S. business and consumers will save more than $650 million/year, or about 1 percent, on imports from Canada. The U.S.-Canada FTA

October 3, 1987
President Reagan sends notice of intent to sign a trade agreement with Canada to the United States Congress triggering the fast track approval process.

October 4, 1987
Elements of Agreement signed by Canadian and U.S. negotiators.

December 10, 1987
Chief negotiators initial legal text of trade Agreement.

December 11, 1987
Tabling of legal text of trade Agreement in the House of Commons.

January 2, 1988
Signature of the Agreement.

Spring 1988
Drafting of implementing legislation in Canada and the United States and introduction of legislation in House of Commons.

January 1, 1989
The Trade Agreement and its rules covering such issues as procurement, services and investment and border measures come into effect after both countries exchange Instruments of Ratification. The first round of tariff reduction will begin. For the sectors ready to compete, tariffs will be eliminated: other goods will begin phasing out their tariffs over a five-year of 10-year period.

October 1, 1989
Tariffs on exports to the United States of speciality steel products are lifted in stages.

January 1, 1990
Tariffs drop another fifth or tenth depending on the schedule.

January 1, 1991
Foreign investment review for direct takeovers rises to $100 million; for indirect takeovers, $500 million. Tariffs will continue to drop; the 35 percent United States duty on Canadian shakes and shingles is scheduled to come off.

January 1, 1992
The trigger for investment review rises to $150 million; indirect takeovers will no longer be scrutinized. Tariff reductions continue.

January 1, 1993
Tariffs will be lifted on another 35 percent of dutiable goods.

January 1, 1994
United States customs user fees and duty drawbacks will end. United States foreign trade zone provisions will change to Canada's benefit. New rules on countervail and anti-dumping should come into effect.

January 1,1995
Tariff reduction.

January 1, 1996
Another tariff cut. This is the final deadline for Canada and the United States to agree on new trade remedy rules. Production-based duty waivers for production in the auto industry will end.

January 1, 1997
Tariff reduction.

January 1, 1998
Tariffs end on remaining goods.

The snapback provision on vegetables and fresh fruit will remain for another decade.

FIGURE 1 Timetable.

is likely to bring net economic benefits to Canada by promoting stronger economic growth, creating more jobs, and lowering inflation. But the agreement is also expected to increase the Canadian federal government deficit by more than $4.2 billion by 1997.

The FTA was reached after lengthy resistance in Canada. The main focus of the 1988 Canadian election campaign was centered on the FTA. Opponents argued that it favored the United States, relatively and absolutely, and furthered the Americanization of Canadian business and culture. Cries of Canada becoming the "fifty-first state" were widely voiced. Proponents, on the other hand, saw the agreement as a natural continuation of trade with the United States. The majority of Canadians were persuaded that the second view was more accurate and the Conservative Party won a solid victory in the 1988 fall election campaign.

TRANSPORTATION SYSTEM

The Canadian transportation network is not as extensive as it is in the United States, most notably in the northern latitudes. But it is fairly intense near the border with the United States, especially in the northeastern United States. The primary focus of this paper is on the road transportation network between the United States and Canada, thus the Canadian water, air, and rail service will only be briefly reviewed.

Although restricted by seasonal freezing, internal water transport is widely used. Canada has 25 large deep-water ports and about 650 smaller ports and multipurpose government wharfs. These ports are located on the east and west coasts, along the St. Lawrence Seaway, Great Lakes, in the Arctic, and on inland lakes and rivers. With coasts on both the Atlantic and the Pacific oceans, and the St. Lawrence Seaway extending inland for more than 2,000 mi along its southern border, Canada has a considerable number of water transportation routes. U.S. shipping firms handle about 25 percent of all Canadian water-transported exports, and about half of Canada's water-transported imports. The leading Canadian ports, in approximate order of tons of cargo are Vancouver (British Columbia), Sept-les-Pointe-Noire (Quebec), Montreal (Quebec), Port Cartier (Quebec), Thunder Bay (Ontario), Halifax (Nova Scotia), Saint John (New Brunswick), Quebec City (Quebec), Prince Rupert (British Columbia), and Hamilton (Ontario) (*6*).

The United States and Canada have extensive air service connections, with well-developed facilities for freight and passenger traffic, which provide interior access between the two countries. The three largest Canadian carriers are Air Canada, Canadian Airlines International, and Wardair. Other smaller carriers provide regular, charter, contract, and specialty services to many regions not served by the larger carriers. In addition, many American carriers provide regular air service to Canada.

Railways are Canada's most important means of transportation for freight and bulk goods. Two transcontinental railway systems, the Canadian National Railways and the Canadian Pacific Railway Company, provide most of the Canadian railway transportation. Both companies have supplementary facilities for highway and waterway transport, telecommunications, and storage. Railways are a reliable form of transportation over much of Canada, where the remoteness of many areas makes it uneconomical to develop major road networks.

The road networks of Canada are not as extensive as those in the United States, especially in the Northern Provinces, Alberta, Saskatchewan, and Manitoba. Canada is continuing to expand its network of paved highways. At present, however, Canada does not have a multilane highway that runs across the southern portion of the country. U.S. Interstates 90 and 94 provide this service for the United States. The border is punctured by approximately 130 crossing stations, which provide adequate access between the two countries. In the more populous east, additional crossings and the expansion of existing roads may become necessary as travel between the two countries continues to increase.

Recent deregulation of the Canadian trucking industry and road expansions have allowed truck transport to become competitive with rail transport. Deregulation makes it easier for firms to enter the Canadian market. Truckers who wish to cross provincial and international borders no longer have to prove that their service is consistent with public convenience and necessity (*6*). American firms are allowed to ship their manufactured goods to destinations in Canada in their own trucks. However, they may not carry goods back to the United States or act as a common carrier, although some states have made reciprocal arrangements with adjacent Canadian provinces.

TRADE VOLUMES: PRESENT AND FUTURE

Canada is the United States' largest trading partner and its largest customer. The volume of trade between the United States and Canada is the greatest in the world. In 1986 it totaled more than $124.5 billion in goods alone. Canada buys twice as much in goods from the United States as Japan does and more than do Mexico, West Germany, and the United Kingdom combined. Canada is also the United States' fastest-growing export market, buying manufactured goods from all 50 states and the District of Columbia. Between 1982 and 1986, when all U.S. overseas sales grew by less than 2 percent, its Canadian sales grew by 45 percent.

Detroit, Michigan, was the most active customs district in the United States, with $2,461 million of imports (Figure 2), (these figures include imports received by water, rail, and road). Other customs districts showing large amounts of imports were Seattle, Chicago, and Buffalo. The busiest customs districts were located in the Pacific Northwest, the Midwest, and the Northeast; the obvious explanation is that the major population centers for both Canada and the United States are located in these regions.

U.S. exports to Canada reached $59,814 million in 1987, an increase of 7.7 percent from $55,512 million in 1986 (Figure 3). Imports of manufactured items increased 7.3 percent from 1986 to 1987. Office and ADP machines showed the greatest growth from 1986 to 1987, with an increase of 39.6 percent. All sectors of trade between the U.S. and Canada increased, with the exception of coal and automobiles. The automotive sector, which includes vehicle parts, is the largest sector in United States-Canada trade, accounting for approximately 32 percent of total bilateral trade in 1987 (*7*), but according to

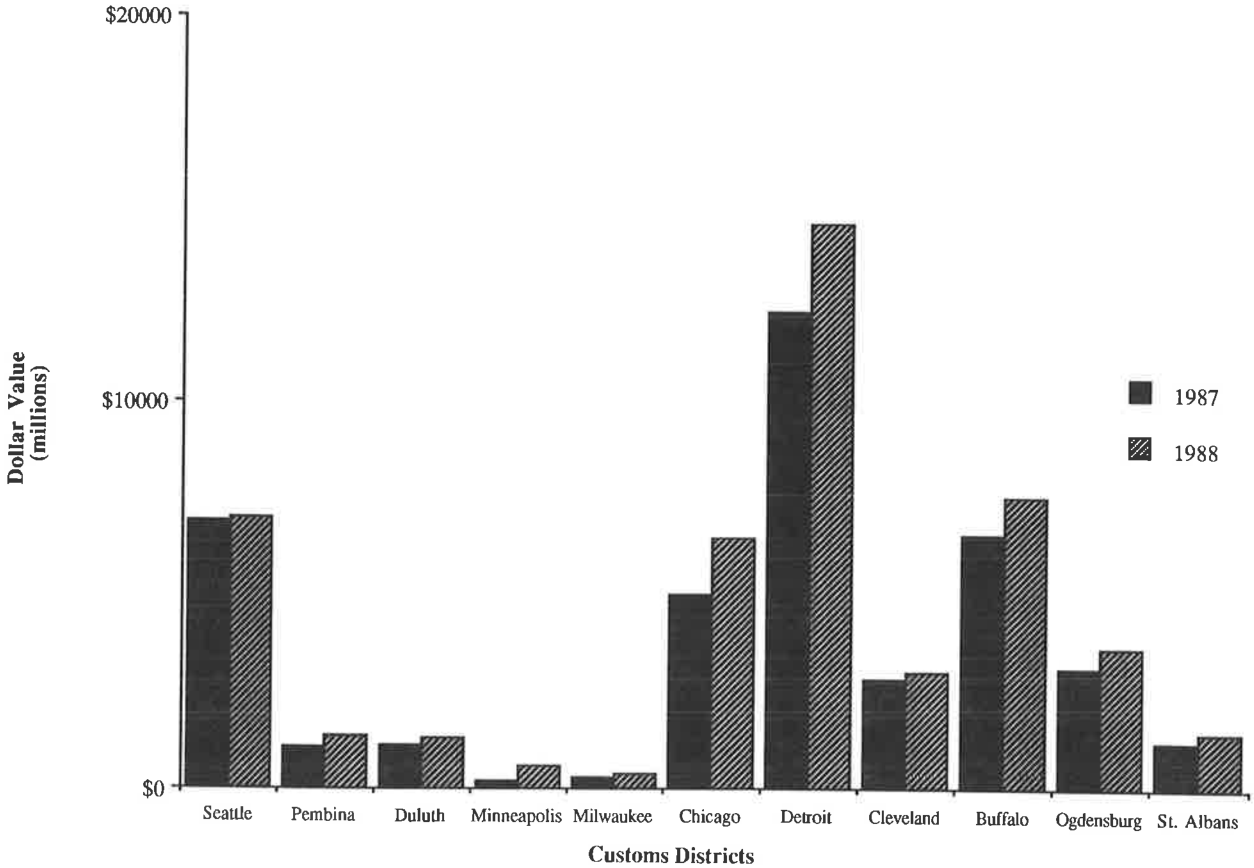

FIGURE 2 **U.S. imports by customs district, 1987–1988.**

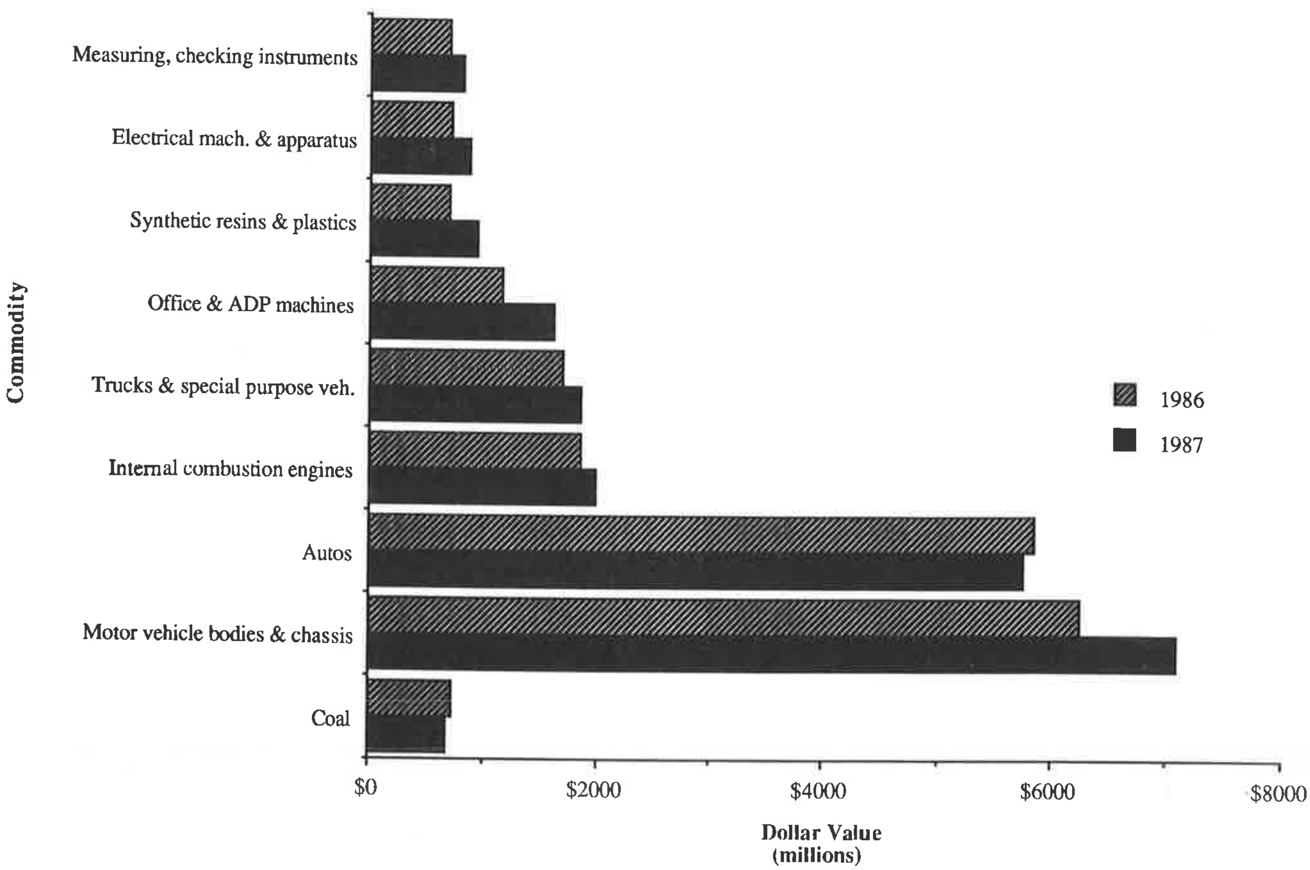

FIGURE 3 **U.S. exports to Canada, 1986–1987.**

Figure 3, automobile imports to Canada actually declined from 1986 to 1987. This may have been caused by the overall drop in U.S. automobile sales worldwide. At present, 95 percent of the automotive trade is duty free under the U.S.-Canada Automotive Products Trade Agreement (APTA). Thus, the FTA should have no effect on automotive trade in the future. Essentially, recent trends suggest that trade in high-tech and machinery products are increasing, whereas trade in automobiles and coal are decreasing.

Canada is a major importer of U.S. services, so trade figures that report only the exchange of goods give a distorted picture. U.S. nonmerchandise exports to Canada reached $8 billion in 1986. The United States has a world surplus in nonmerchandise trade. Last year approximately half that surplus was earned in Canada.

U.S. imports from Canada also showed an increase of 4.1 percent from 1986 ($68,662 million) to 1987 ($71,510 million) (Figure 4). Pulp and waste paper showed the greatest growth in 1987 with a 29.7 percent increase over 1986. Other commodities that showed large increases were special purpose motor vehicles and paper and paper board. The majority of commodities showed an increase from 1986 to 1987, with the exception of natural gas, automobiles, and aircraft-spacecraft parts, all of which showed significant decreases. As Figure 4 shows, the majority of goods imported from Canada are raw materials or direct products of raw materials, so it is unlikely that the FTA will cause a significant change in the types of commodities traded.

The specific effects that the FTA will have on imports and exports between the two countries is uncertain, although trade is expected to increase. Keim (*2*) describes some of the profit sectors that offer the best export opportunities for American companies in 1989 to 1990. Products that offer the best export opportunities are medical equipment, household furniture, textiles and apparel, sporting goods, laboratory instruments, computers, automobile parts, telecommunications equipment, trucks, trailers, buses, aircraft, plastic materials, construction machinery, electronic components, analytical and scientific instruments, industrial organic chemicals, books and periodicals, and metal-working equipment. Trade in many of these items is expected to increase, perhaps dramatically, after all of the tariffs are lifted (Figure 1).

TRAFFIC: PAST, PRESENT, AND FUTURE

Automobile

The 10 highest border crossing stations (1988 to 1989) are shown in Figure 5. The Windsor, Ontario, to Detroit, Michigan, crossing leads the list with 6.5 million annual northbound crossings, or almost 27,500 annual average daily traffic (one way). Fort Erie, Ontario, to Buffalo, New York, is next, then Douglas, British Columbia, to Seattle, Washington, and others. These 10 crossings account for almost 50 percent of the total northbound traffic in 1988 to 1989.

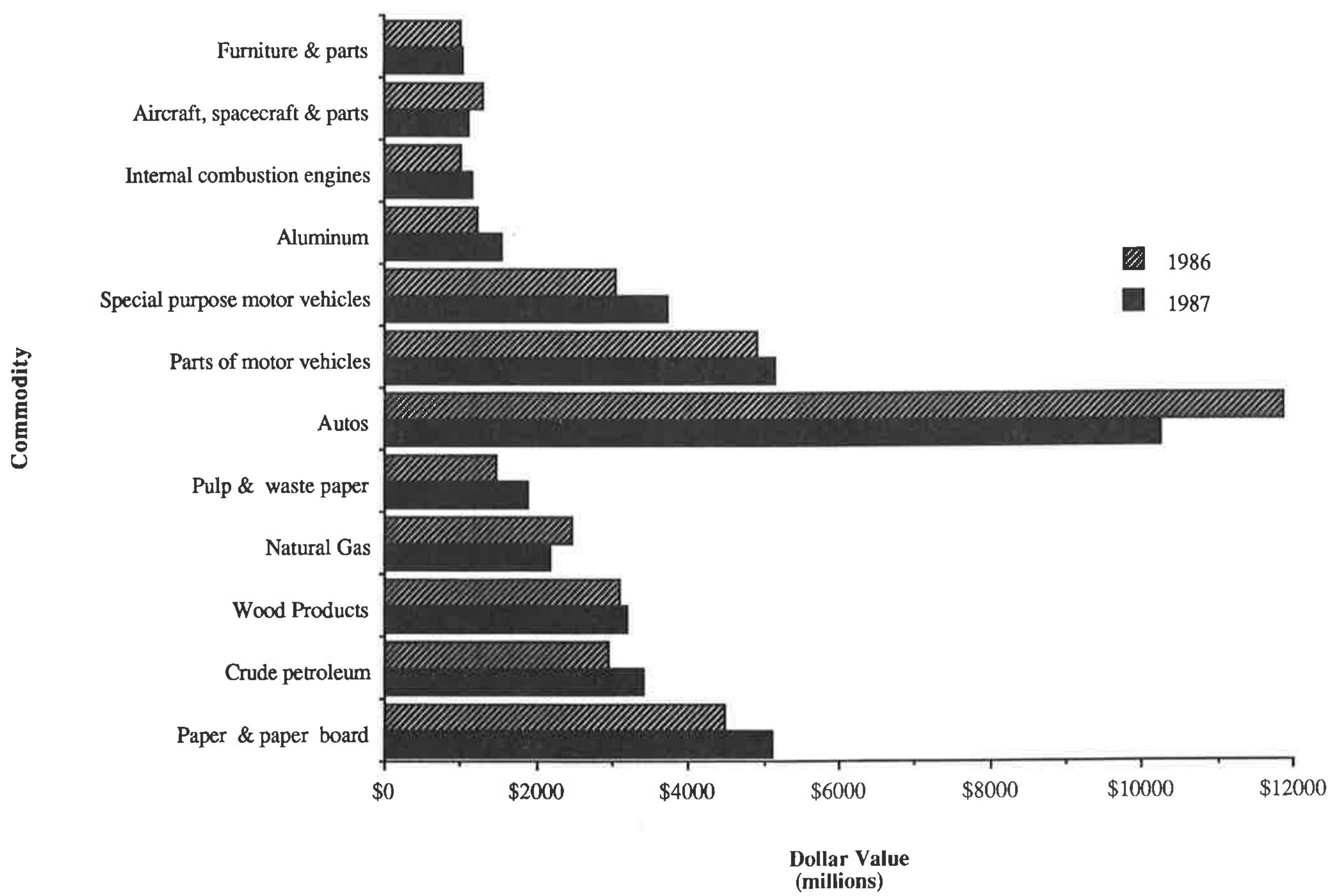

FIGURE 4 U.S. imports from Canada, 1986–1987.

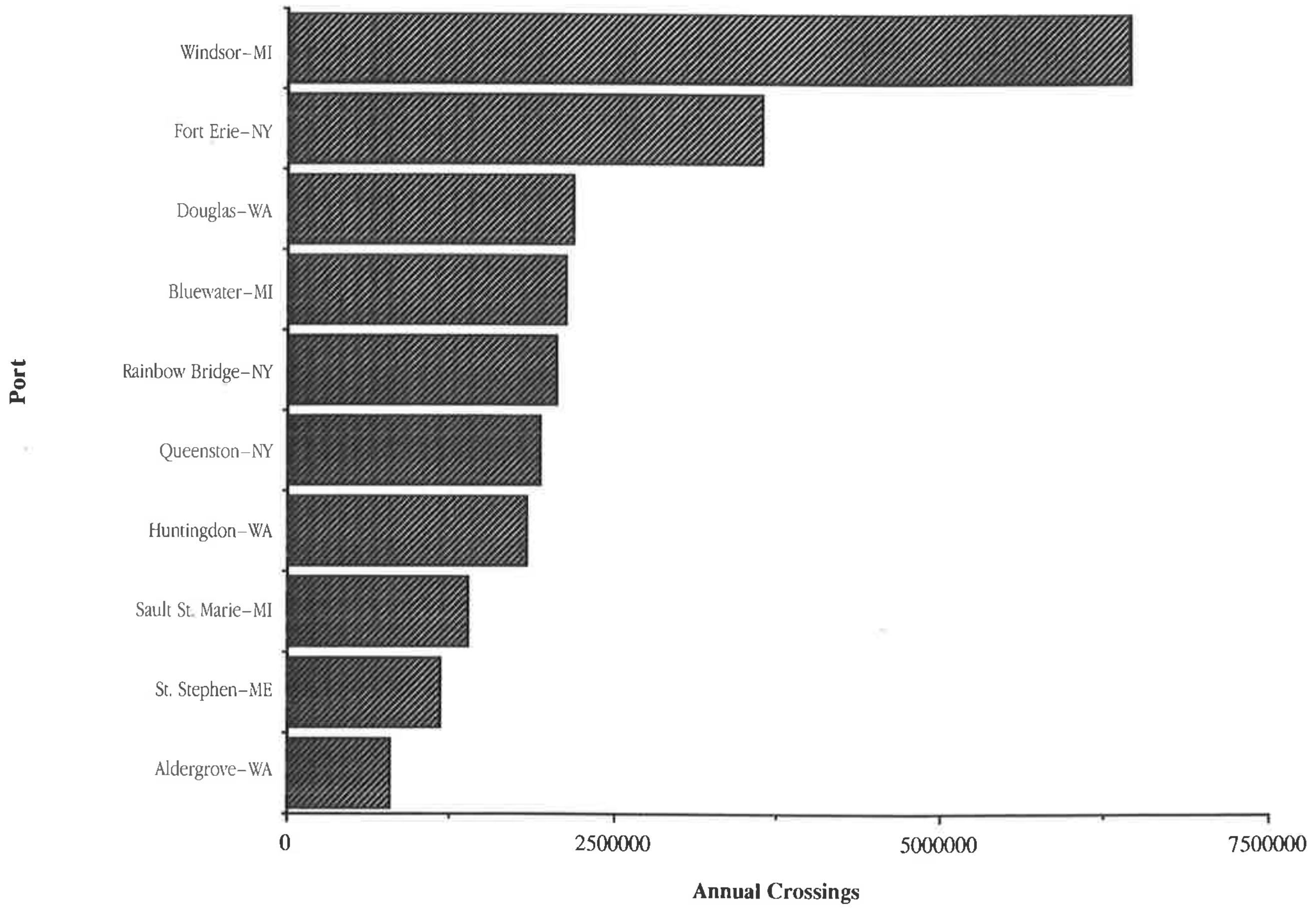

FIGURE 5 Top 10 border crossings, United States to Canada, 1988–1989.

Ninety percent of vehicles crossing the United States-Canadian border are automobiles. About 35 million automobiles crossed the border into Canada in 1988 to 1989, an increase of 25 percent from 1985 to 1989, which translates to about a 6.9 percent increase per year in automobile traffic (Figure 6). Different regions of the United States show markedly different levels of traffic crossing the border (Figure 7). Washington, Michigan, and New York have significantly higher volumes of automobile traffic crossing into Canada than the rest of the border states, although Maine and Vermont show relatively high volumes of traffic, which is probably related to recreational traffic. The high volumes of traffic in Washington, Michigan, and New York can be attributed to their close proximity to major population centers in Canada: Washington is close to Vancouver; Michigan is close to Windsor; and New York is close to Montreal, Ottawa, and Toronto.

Washington, Idaho, and North Dakota have shown the highest growth rates in automobile traffic crossing into Canada (Figure 8), but only Washington carries a significant volume of traffic. Idaho and North Dakota carry the lowest volumes of automobile traffic; only New Hampshire and Alaska carry lower volumes (see Figure 7).

Truck

Trucks crossing the border (Figure 9) increased about 17 percent from 1985 to 1989, which translates to approximately 4.9 percent growth per year in truck traffic. From 1985 to 1989, truck traffic crossing the border into Canada increased by 204,000. Truck traffic increased during this time period but not as rapidly as did automobile traffic. A possible explanation of this is that the deregulation of the Canadian trucking industry caused truck traffic to show a sharp increase during the earlier part of the period, which has recently leveled off.

Michigan, New York, Washington, and Maine showed large volumes of trucks crossing into Canada (see Figure 10). This pattern is similar to that of automobile traffic, but whereas New York has the highest volume of auto traffic, Michigan has the highest volume of truck traffic. Washington carries substantially lower volumes of truck traffic than automobile traffic. The high volumes of truck traffic in Michigan and New York indicate that most of the commodities leaving the United States to go to Canada leave by these two states. The relatively high volumes in Maine may be caused by Canadian trucks crossing from New Brunswick to Quebec through Maine.

The most dramatic increase in truck traffic entering Canada is through Alaska (Figure 11). North Dakota and Idaho also show large increases in truck traffic, but these states carry relatively small amounts of the truck traffic volume. In the case of Alaska, the amount of truck traffic is extremely small.

PROBABLE TRANSPORTATION IMPACTS

The FTA will bring some transportation problems. As already discussed, both automobile and truck traffic are expected to

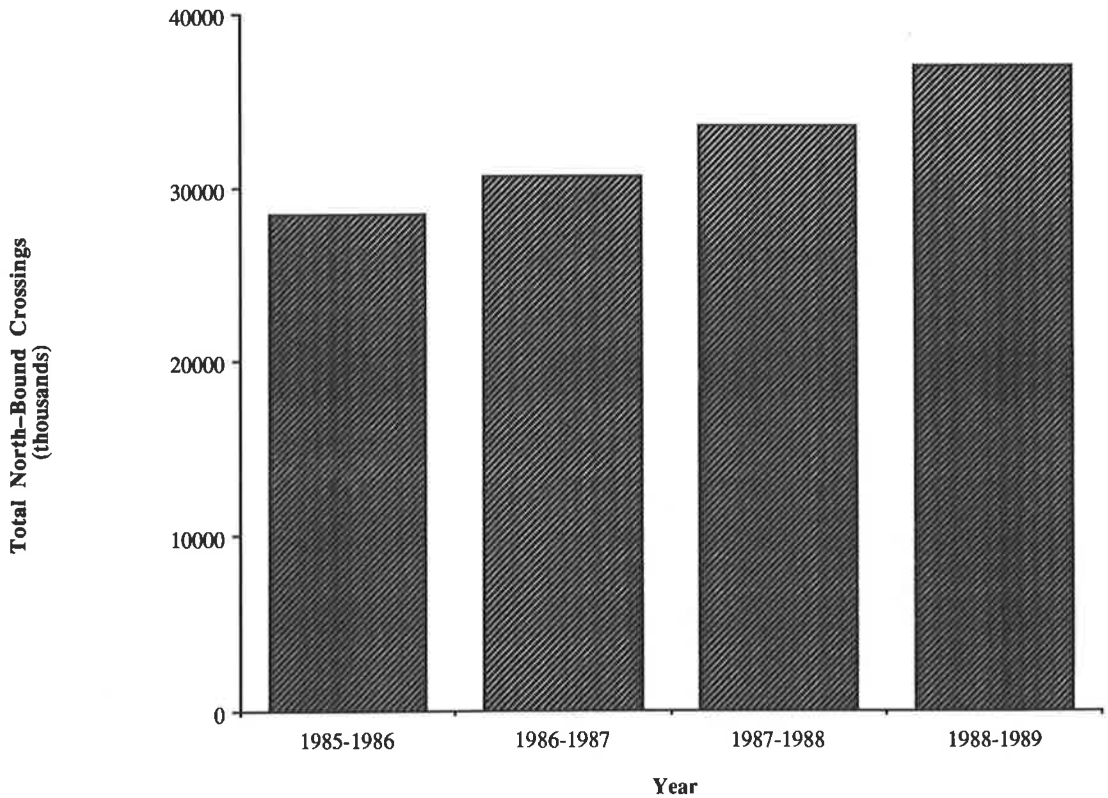

FIGURE 6 Total number of automobiles crossing from the United States into Canada, 1985–1989.

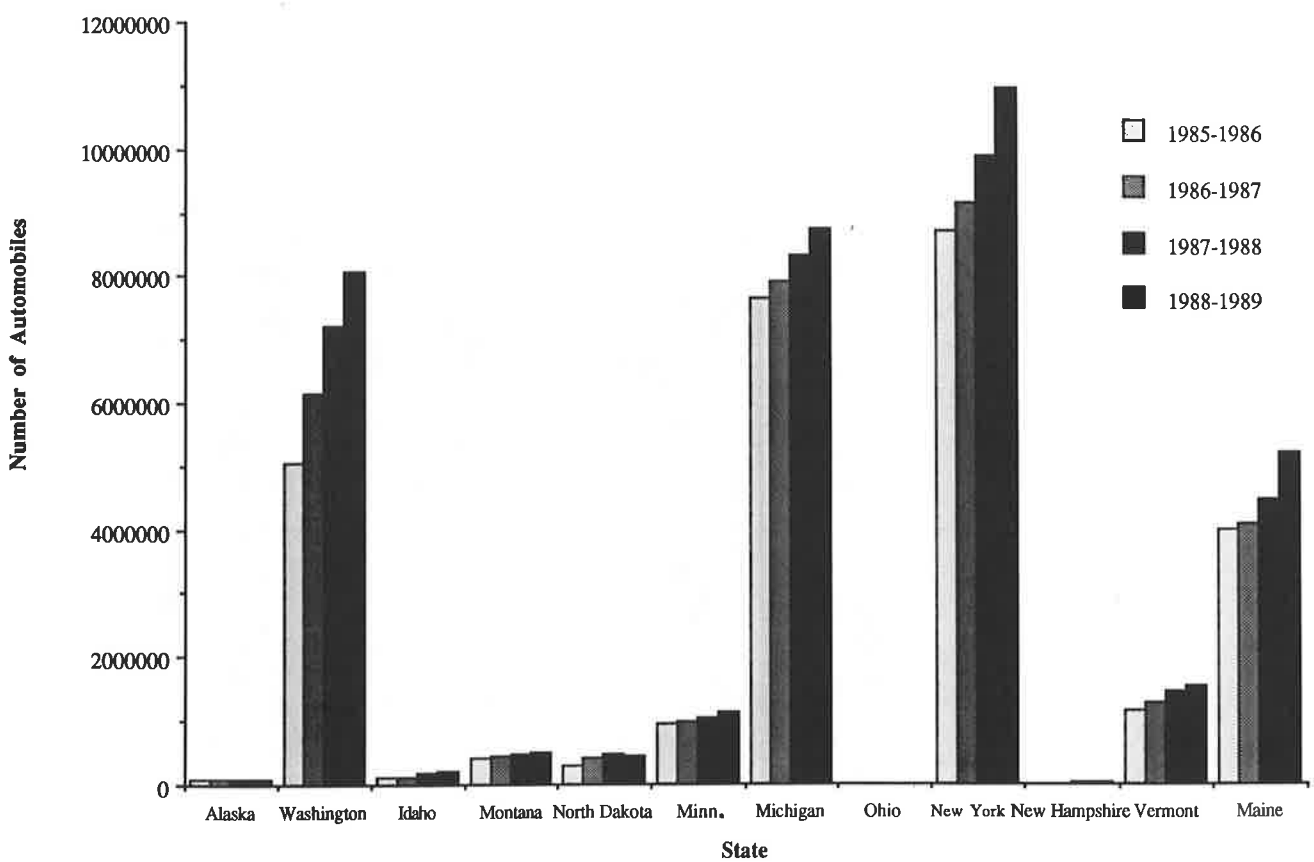

FIGURE 7 State breakdown of automobiles crossing the United States-Canadian border into Canada, 1985–1989.

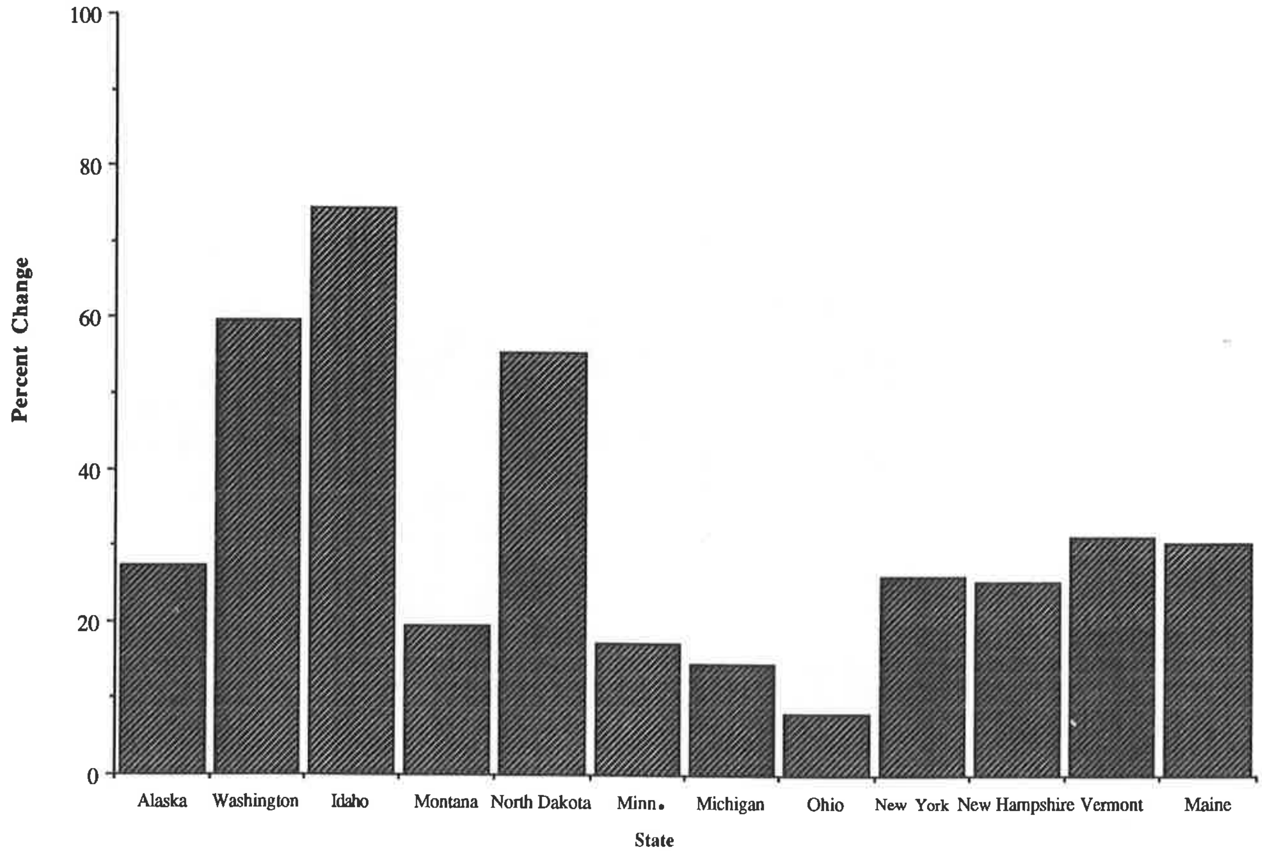

FIGURE 8 Percent change in automobiles crossing the United States-Canadian border into Canada, 1985–1989.

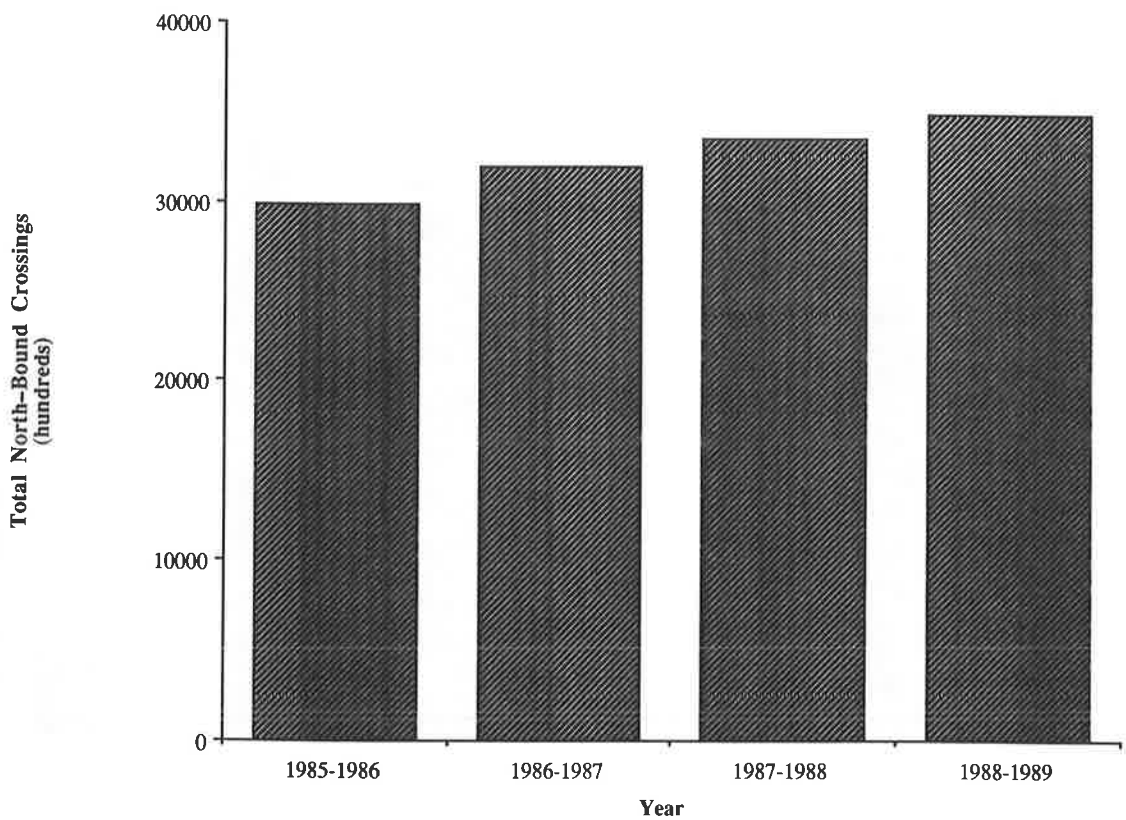

FIGURE 9 Total number of trucks crossing from the United States into Canada, 1985–1989.

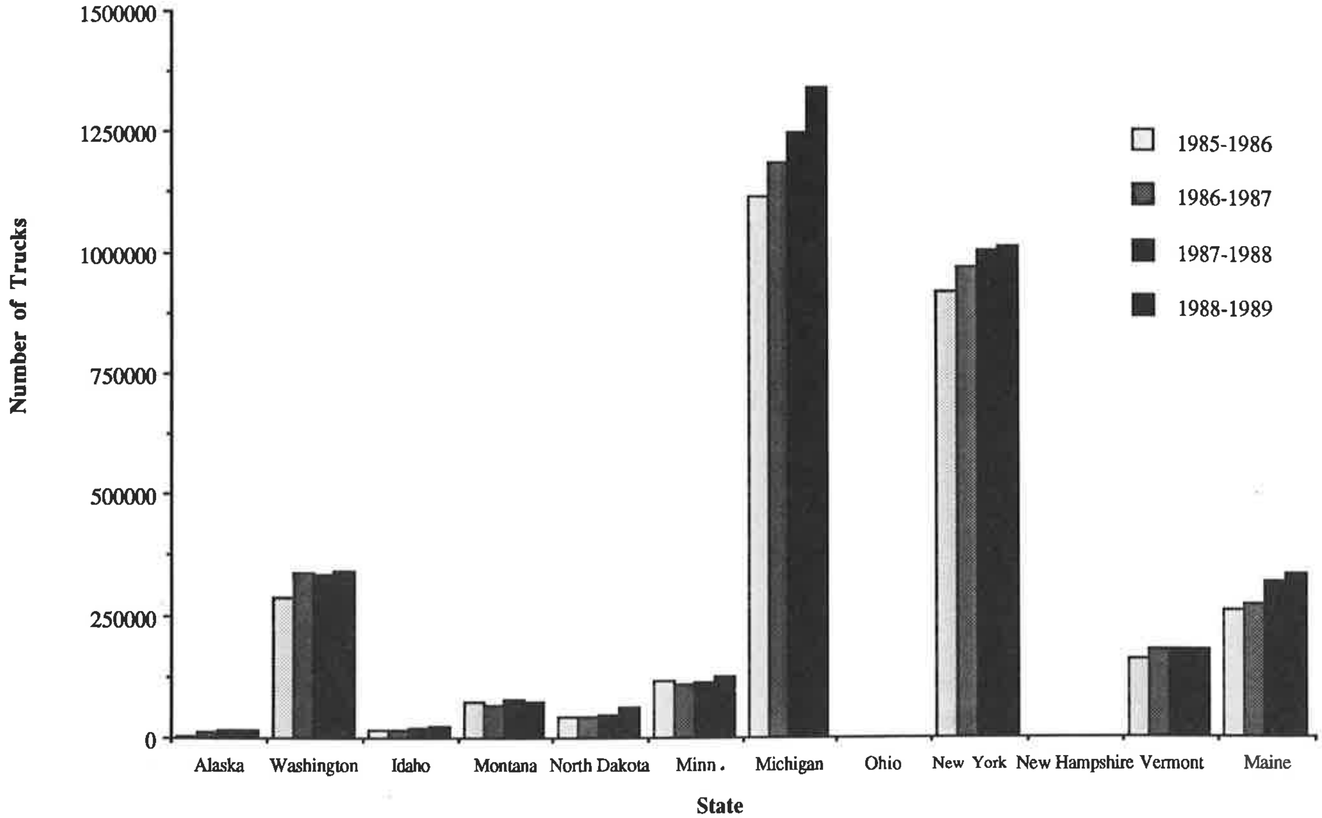

FIGURE 10 State breakdown of trucks crossing the United States-Canadian border into Canada, 1985–1989.

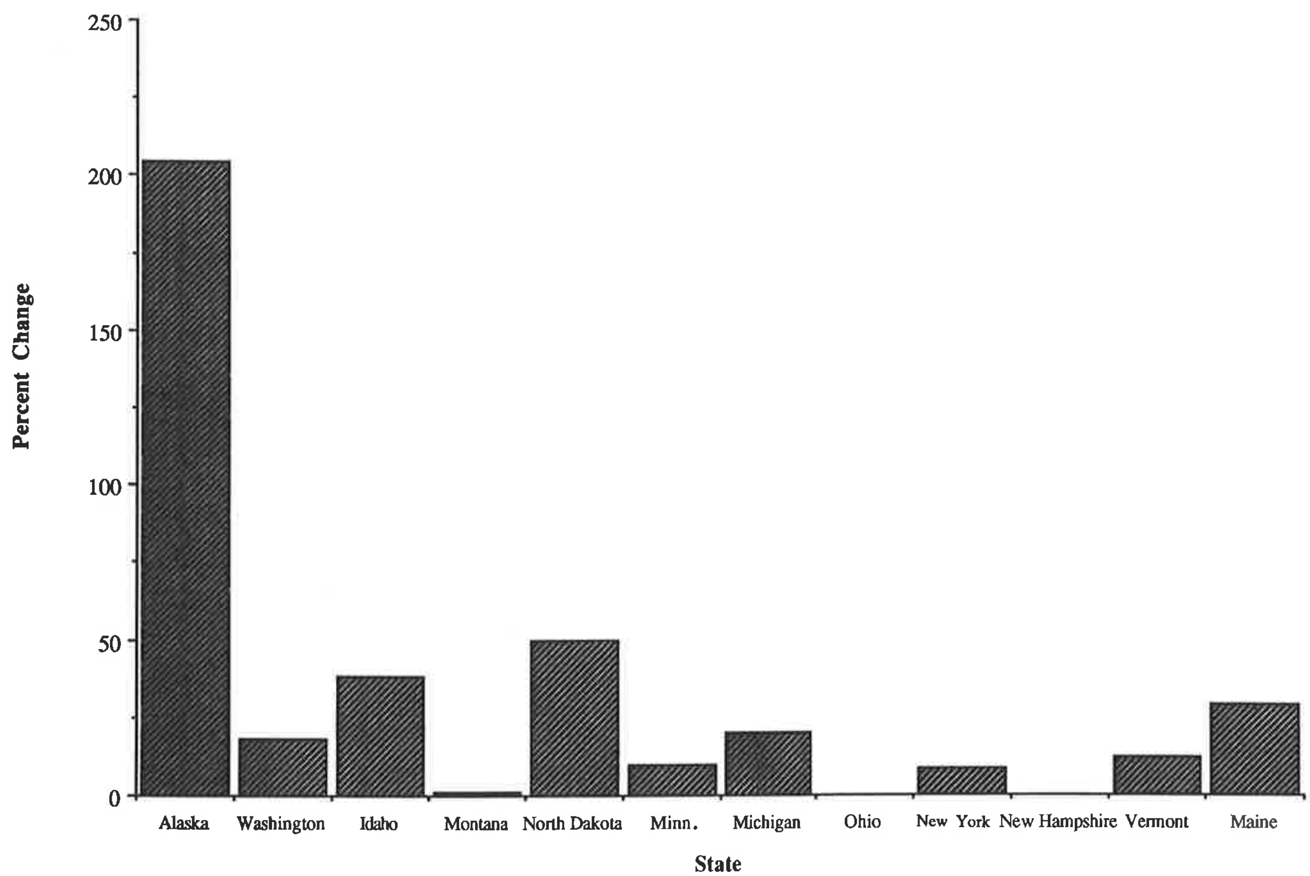

FIGURE 11 Percent change in truck traffic crossing the United States-Canadian border into Canada, 1985–1989.

continue to increase. Thus congestion at border crossings, which is already substantial, is expected to become worse, especially in the summer months. This will necessitate the need for road widening, particularly on Canadian routes close to the border. Road deterioration is also likely to increase because axle load damage increases as the ninth power of axle load itself. Thus a 2 or 3 percent increase in truck traffic will accelerate road deterioration by 20 to 30 percent.

As a result of the expected increase in traffic and road deterioration, a kind of "border tilt" may become apparent as the states and provinces focus on their borders. The result is likely to be a "southern tilt" in the focus of Canadian Ministries of Transportation, as road repair needs at the border increase. The U.S. side crossings are more adequate, but look for a similar "northern tilt" in border state attention toward the late 1990s, particularly in Washington, Michigan, and Maine, where traffic is expected to increase most rapidly. In Maine the possible trans-U.S. linkage of two Canadian provinces may generate pressure for a "Trans-Maine Highway," a possible new Interstate between New Brunswick and Quebec. Canadians will be expected to share the costs of the highway with the United States.

Increased attention to province-state reciprocity in truck axle and gross load limits and system improvements is also anticipated. Another impact is likely to be reciprocal use of empty trucks for return travel business (company interlining). As free trade barriers fall, companies will be on the lookout for ways to increase truck use efficiency through multiple-direction circles. Over the longer term, multistop truck companies are likely to be operating across the border and across states and provinces. A jointly owned United States-Canada company truck might deliver a load of furniture from North Carolina to Montreal, carry a load of cardboard boxes from Montreal to Ottawa, transport automobile parts to Detroit, and then convey office supplies to Charlotte—all in one long multistop journey.

The FTA is likely to accelerate the traffic growth rates in border crossings and the states that will feel the greatest effect will be

Washington: Expect an acceleration of truck growth from about 4–6 percent annually. Automobile travel will continue to grow by 15 percent annually.

Idaho, Montana, North Dakota: Present high growth rates should accelerate to the 10–15 percent range, particularly for truck traffic.

Minnesota, Michigan: Present automobile growth of 5 percent/year should increase to 6–7 percent/year. Truck traffic growth should slow if a recession slows automobile purchases.

New York: Present automobile and truck trends should continue.

Vermont, New Hampshire, Maine: Automobile traffic growth should hold in the 7 percent/year range and truck travel growth should accelerate to 10 percent/year.

In addition, other effects are likely. Professional business air travel should increase substantially, particularly between Toronto, Montreal, and the northeastern United States. Communication and telephone traffic should also accelerate. Summer recreational traffic to Canada should be only marginally affected. Some states have already shown tremendous growth patterns so the FTA may not trigger a significant increase in traffic. Traffic is expected to continue to increase but not as dramatically as in previous years.

CONCLUSION

Canada is presently upgrading and expanding its road network, but additional work may be necessary. Many U.S. multilane highways become two lanes when they cross into Canada. Roads in the United States may also need to be expanded. The bridges that span the border are also in need of expansion and repair because they were built at a time when traffic between the two countries was moderate and not expected to increase to the present levels that the FTA has facilitated.

The FTA will accelerate commerce and communications between the United States and Canada, which will be reflected in travel growth. Present growth patterns, in the 5+ range annually, are expected to accelerate to 6–7 percent, with some states and border crossings showing much more rapid growth. The agreement presents an opportunity for neighboring states and Canadian provinces to work together to solve problems of joint concern.

Further study will be necessary to examine these systems impacts more closely. The Canada to the United States data will need to be analyzed to see if there are any notable differences between the north and south traffic flows. Further study will also be necessary to determine whether the road networks that cross the border will be sufficient to handle the increasing traffic. These are challenges that both countries should approach cooperatively because each has so much to gain by their solution.

ACKNOWLEDGMENTS

Thanks are expressed to Jim Astlin of Canadian Customs for providing much of the data used in this study.

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Publication of this paper sponsored by Committee on International Trade and Transportation.

Highway Transportation Mode and Ontario's Trade with the United States, 1977–1987

JULIUS M. L. GORYS

The value of trade between the Province of Ontario, Canada, and the United States is currently approximately $130 billion. The purpose of this paper is to identify how the value of trade between the United States and Ontario changed from 1977 to 1987, focusing on the shift in modal share and in the type of major commodities traded. In particular, the reasons for the shift in modal share and subsequent actions by the provincial government will be documented.

The Ontario Ministry of Transportation has been keenly interested in information related to the movement of goods across its highway system in order to fulfill its highway protection and planning mandate.

The movement of goods has been the subject of increasing public attention caused by several factors; among them

1. Federal government initiatives on the signing of a free trade agreement with the United States and the implementation of regulatory reform of the transportation system;
2. Congestion and increasing volumes of larger and longer trucks on the highway system;
3. Economic considerations, which have meant that funds and support for new highway projects are based on an economic as well as a traffic rationale; and
4. Advanced deterioration of the highway network resulting from overloaded commercial vehicles.

The Municipal Transportation Policy Planning Branch is actively involved in goods movement data collection and analysis for its own purposes and in support of other policy offices in the Ontario Ministry of Transportation. For example, the branch

1. Undertakes major on-highway surveys of commercial vehicles at 5-year intervals;
2. Coordinates, funds, and directs municipal goods movement studies conducted periodically; and
3. Reviews data collection efforts by others. For example, much of the material in this paper is derived from Statistics Canada, a federal government agency.

The subject of this paper is the modal transport and trade relationship between the Province of Ontario and the United States during the period 1977 to 1987. The data represent Province of Clearance information (i.e., where the commodity clears customs).

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BACKGROUND

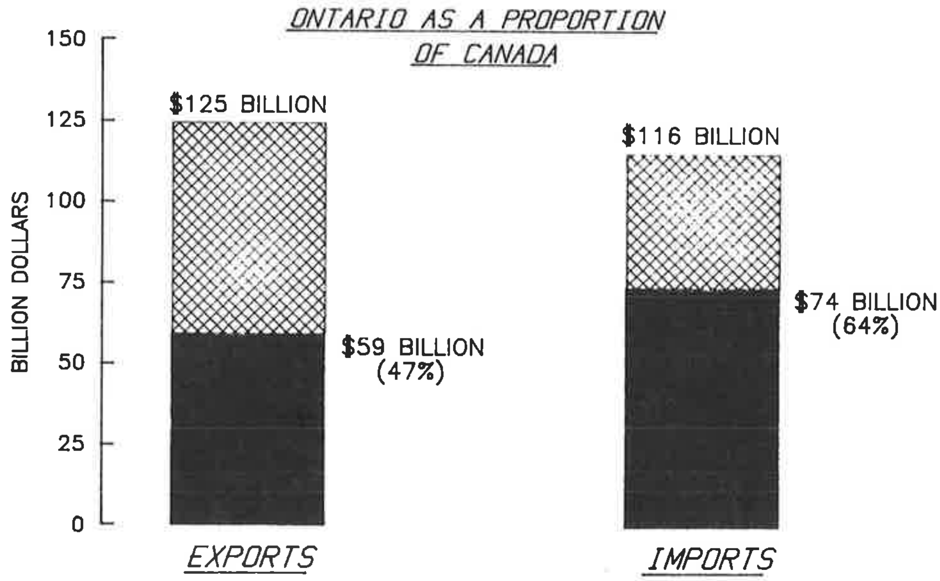
A review of 1987 data (Statistics Canada, International Trade Division, computer tapes, 1977 to 1989; unpublished import and export data) finds that Ontario is the principal importing and exporting province within Canada, accounting for 64 percent of Canada's import value, and 47 percent of Canada's export value (Figure 1).

The United States is Canada's most valued trading partner; the U.S. provides 68 percent of its imports, and is the consumer of 76 percent of its exports (Figure 2). Conversely, Canada is the most valued trading partner of the United States, with a trade value in 1986 of some $111.7 billion, 6 percent higher than that of Japan (*1*). Approximately 18 percent of U.S. imports come from Canada, whereas 21 percent of U.S. exports go to Canada. Although the United States imports more from Japan, it exports more to Canada (Figures 3 and 4). U.S. trade with Canada consistently exceeds its trade with the Federal Republic of Germany, Italy, the United Kingdom, and France combined.

Ontario's trading relationship is more closely linked to that of the United States than it is to that of the rest of Canada. About 89 percent of Ontario's exports go to the United States, whereas the United States supplies 80 percent of Ontario's imports (Figure 5). In contrast, 64 percent of exports from the rest of Canada are sent to the United States, and 48 percent of imports to the rest of Canada come from the United States.

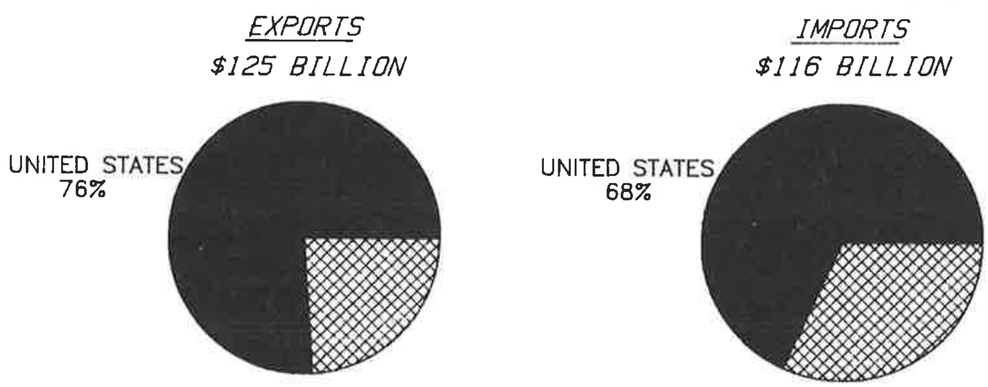
The bulk of Ontario's trade with the United States is, not surprisingly, with those American states in closest proximity to it. The East North Central region, containing the states of Michigan, Wisconsin, Ohio, Illinois, and Indiana, accounted for $22.4 billion, or 46 percent of Ontario's U.S. import total in 1987. This region also accounted for $28.1 billion, or 53 percent of Ontario's U.S. export total in 1987 (Figure 6).

The Mid-Atlantic states of New York, New Jersey, and Pennsylvania are also prominent traders with Ontario, and their importance has increased over the past decade. In 1987, these states generated $8.5 billion, or 18 percent of Ontario's U.S. imports, and $12.2 billion, or 23 percent of Ontario's U.S. exports. Generally, between 1977 and 1987, the trade relationship between Ontario and the various U.S. census



SOURCE: Statistics Canada International Trade Division

FIGURE 1 Distribution of Canadian trade, 1987.



SOURCE: Statistics Canada International Trade Division

FIGURE 2 Canada's trade relationship, 1987.

subdivisions became more diverse with proportionally less trade with the East North Central region.

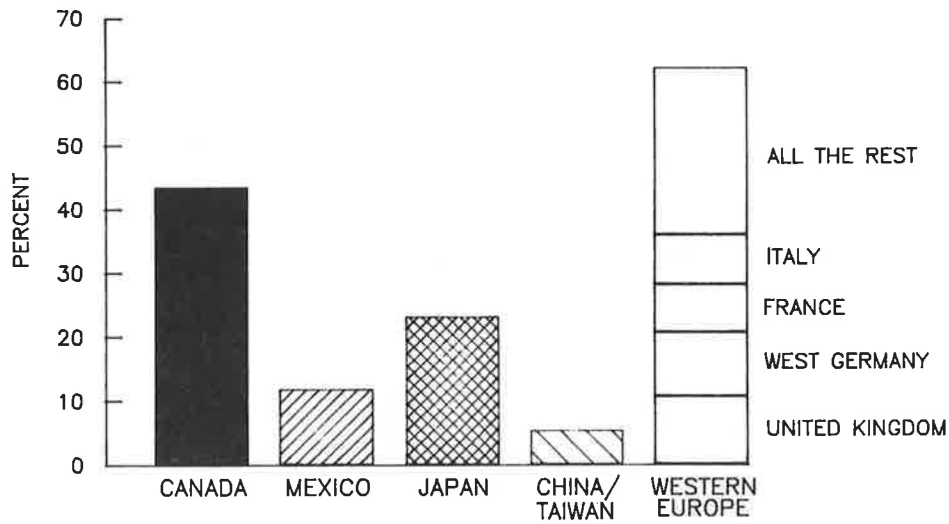
COMMODITY ANALYSIS

Import and export data collected by Statistics Canada also includes commodity information that is broken down into several large groups. Food and beverage-related items and special transactions are largely self-explanatory categories. Crude materials are broadly defined as unfinished goods: logs or nickel, for example. Fabricated materials are semi-finished goods such as lumber or steel, and end products are finished goods such as wood cabinets, furniture, or automobiles.

Increasingly, more of Ontario's exports are being processed to a finished product state. The proportion of Ontario's imports that were "end product"-related was already at a high level and exhibited little percentage change between 1977 and 1987 (Figure 7).

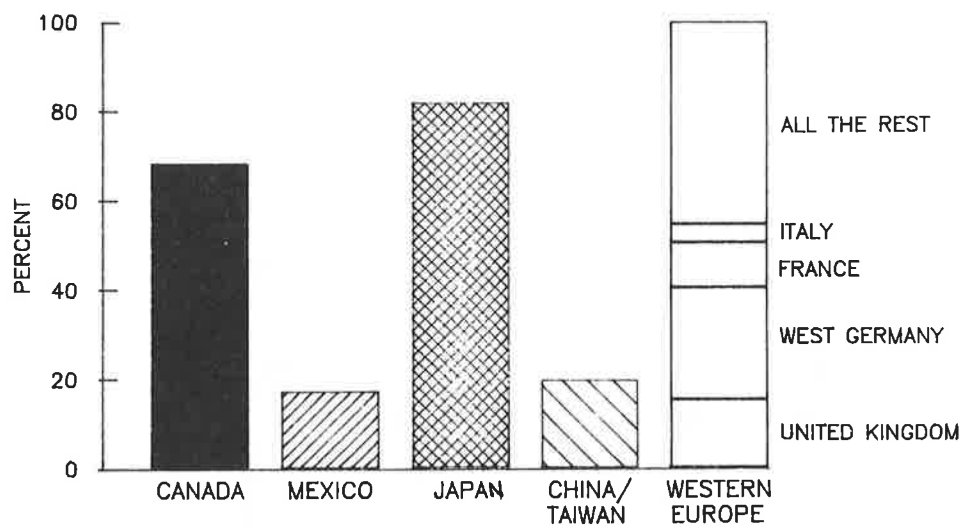
Not surprisingly, the automotive industry plays a pivotal role in the trade between Ontario and the United States. In 1977, 45 percent of Ontario imports from, and 50 percent of Ontario exports to, the United States were from this sector of the economy. In 1987, 42 percent of Ontario imports from, and 56 percent of Ontario's exports to, the United States were automotive industry products.

The automotive industry was particularly important in Ontario's trade to and from the states in the U.S. Midwest.



SOURCE: U.S. Bureau of the Census, Highlights of U.S. Export and Import Trade, Report FT990

FIGURE 3 Destination of U.S. exports, 1986.



SOURCE: U.S. Bureau of the Census, Highlights of U.S. Export and Import Trade, Report FT990

FIGURE 4 Origin of U.S. imports, 1986.

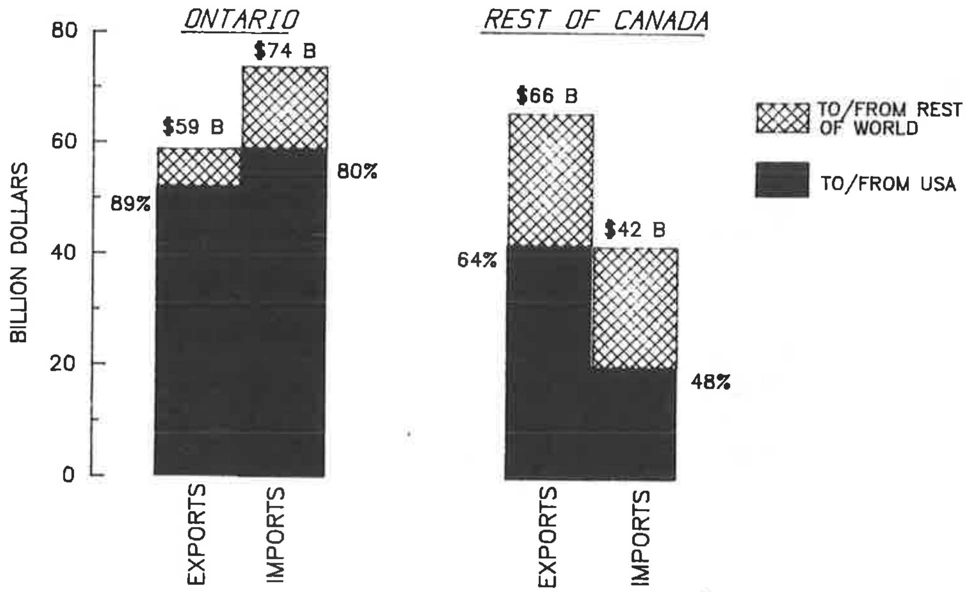
In contrast, trade with the mid-Atlantic and New England states was more diverse and proportionally contained more trade in fabricated materials.

MODAL SHARE ANALYSIS

The majority of the value of Ontario's trade with the United States is transported by truck/highway mode. In 1977, 59 percent of Ontario's exports to the United States were transported by the truck/highway mode; by 1987, its proportion had increased to 70 percent at the expense of the rail mode (Figure 8). For Ontario's imports, the truck/highway mode has an even greater share of transborder traffic. In 1977, 70 percent of the value of Ontario's imports from the United States were transported by the truck/highway mode; by 1987, this had risen to 85 percent of the total.

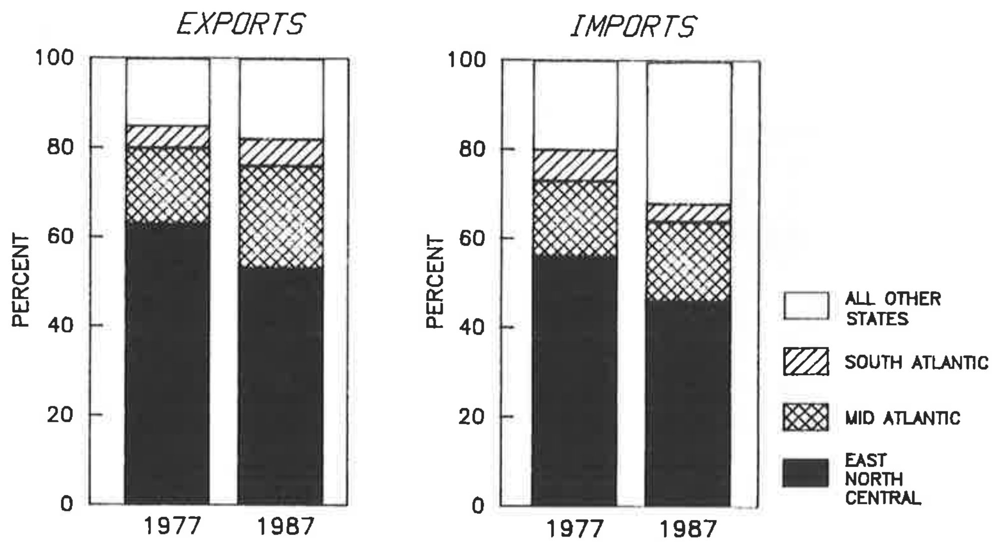
These changes were not merely a function of changes in value or currency fluctuations. There were significant declines in the amount of transborder rail traffic expressed in tonnage terms during this time period. The only components of rail traffic to increase appreciably between 1977 and 1987 were container on flatcar (COFC) and trailer on flatcar (TOFC) movements, which involved interfacing with the truck mode.

The transport modal share relationship varied considerably among the U.S. states. It was generally assumed that, all



SOURCE: Statistics Canada International Trade Division

FIGURE 5 United States trade emphasis, 1987.



SOURCE: Statistics Canada International Trade Division

FIGURE 6 Ontario/United States trade relationship, 1977 and 1987.

things being equal, the truck/highway mode would be less important in the transportation of Ontario's exports and imports to and from more distant states. This assumption did not always prove correct. For example, for Ontario's exports to points in the United States east of the Mississippi, the highway mode has become more dominant. This is true for the transportation of Canadian goods to the more southerly states, and less so for those transported to the mid-Atlantic and New England states, which are closer (Figures 9 and 10).

The modal share attained by rail to the East North Central states was found to be lower than anticipated, in light of the extensive trackage owned in that region by U.S. subsidiaries of both of Canada's national railways. Factors influencing the aforementioned trends will be discussed later in this paper.

OTHER EVIDENCE OF TRUCK/HIGHWAY DOMINANCE

There was additional evidence of a general shift in favor of the truck/highway mode from other data sources. Between 1977 and 1987, the number of inbound trucks crossing into Ontario from the United States rose from 1.3 million to 2.2 million, an average annual increase of 5.4 percent (Statistics

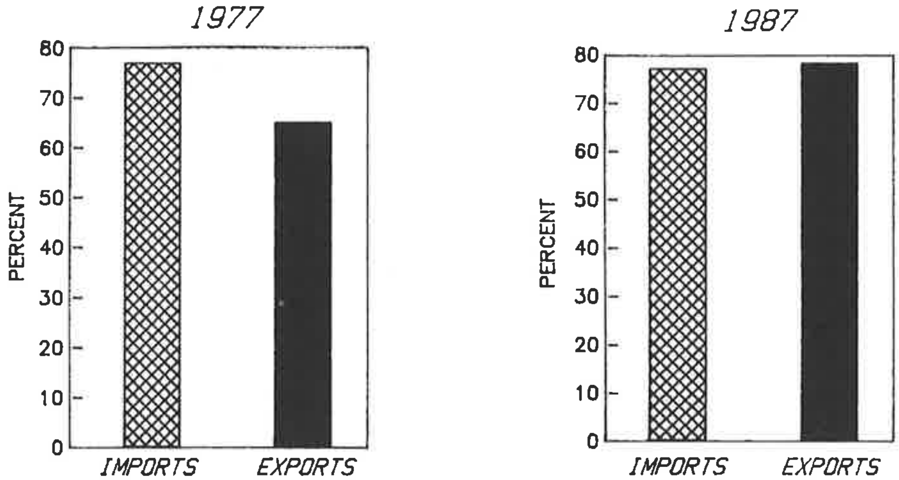


FIGURE 7 Proportion of trade value "end products," Ontario/United States, 1977 and 1987.

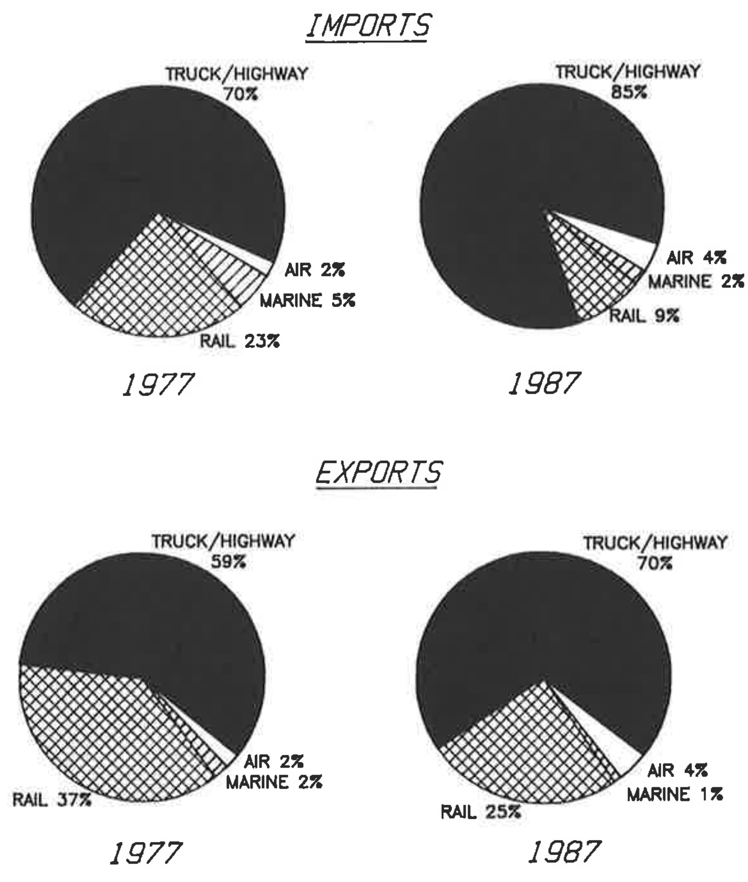
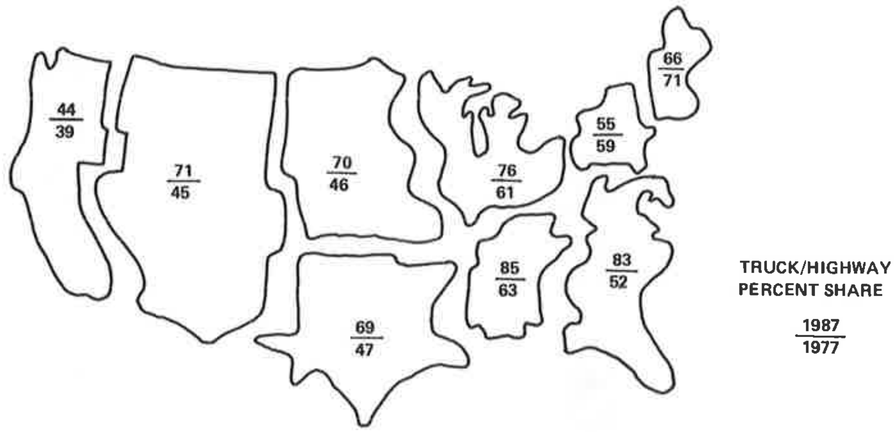


FIGURE 8 Ontario/United States trade relationship: mode used to cross customs, 1977 and 1987.

Canada, International Travel Division; unpublished data) (Figure 11). Truck movements via New York State gateways rose at a slightly higher rate: from 533,000 to 914,000, although the Ambassador Bridge at the Windsor-Detroit crossing continued to be by far the most heavily frequented border crossing, with 837,600 trucks traversing that crossing alone in 1987.

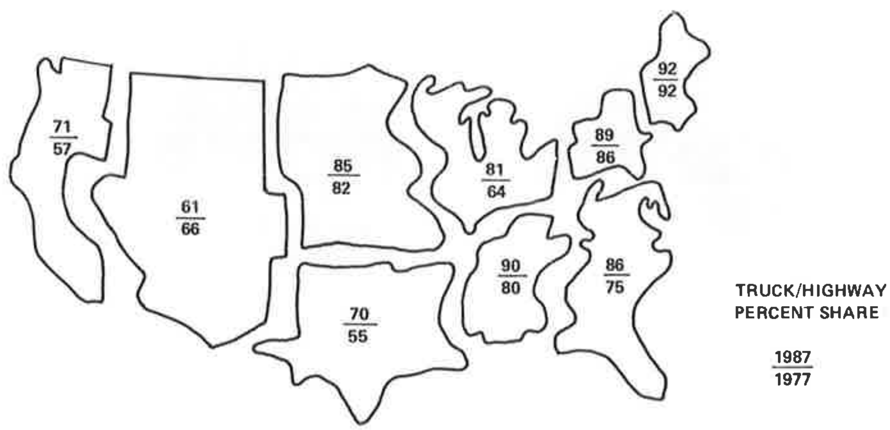
Preliminary information from the Ontario Ministry of Transportation's 1988 Commercial Vehicle Survey also suggests that the percentage of all international truck movements in Ontario is increasing at the expense of intraprovincial movements in particular.

Although truck volumes on the Ontario provincial highway system were also increasing in the 5 percent/year range, the degree of increase varied by highway; for example, they almost doubled between 1983 and 1987 on some segments of highways in the greater Toronto area. The highest truck volumes



SOURCE: Statistics Canada International Trade Division

FIGURE 9 Truck/highway modal share of Ontario/United States export trade value, 1977 and 1987.



SOURCE: Statistics Canada International Trade Division

FIGURE 10 Truck/highway modal share of Ontario/United States import trade value, 1977 and 1987.

were found among the 12-lane Highway 401 within Toronto, on which approximately 32,000 commercial vehicles passed per day.

REASONS FOR SHIFT IN MODAL SHARE

There are many reasons why the role of the truck/highway mode has been increasing in importance. First, the pattern of urban development is such that many new industrial areas are located along highways rather than rail lines.

Second, changes in regulations have permitted motor carriers to carry more weight, which has enabled them to be more competitive on longer distance trips. For example, in the early 1970s, a five-axle tractor trailer unit could carry a maximum weight of 80,000 lb; now the maximum weight permitted on Ontario highways is about 140,000 lb—greater than the amount that could be stored in the belly of a single 747 jumbo aircraft.

Third, the commodity mix has changed. More of both Ontario's imports and exports in particular are end products that are lighter and have a higher intrinsic value. Such goods are more favorably distributed by truck or air mode.

Fourth, the manner of production has changed with the introduction of the just-in-time inventory processing system by the automotive industry. There is less stockpiling of inventory; rather, both inputs and the final output must be delivered more promptly. The truck/highway mode is most suited to that type of scheduling. Somewhat surprisingly for the exporting of automotive products, however, the truck/highway proportion of modal traffic changed only marginally and was approximately 64 to 65 percent in both 1977 and 1987.

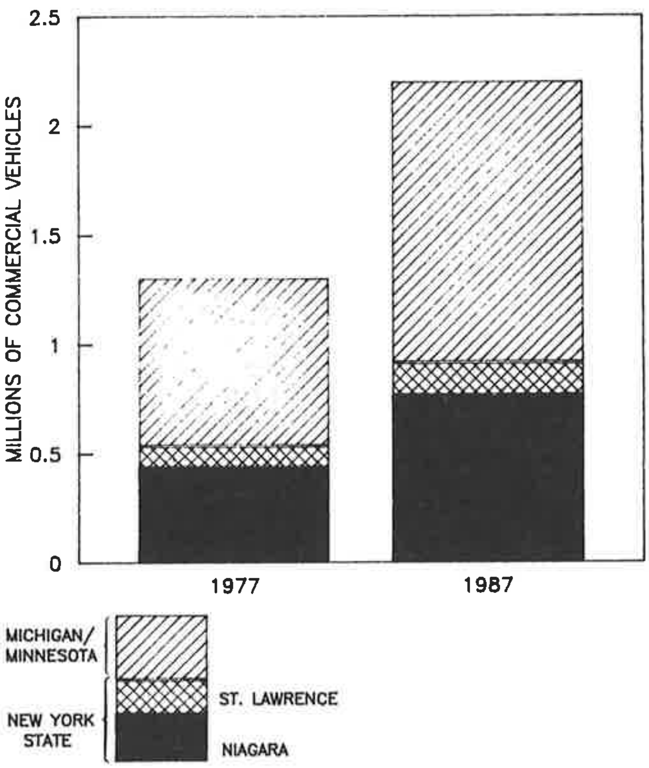
Fifth, the structure of the transportation industry, by definition, favors greater use of the truck/highway mode because there are far more carriers who offer greater flexibility in transporting goods with superior prices and service than can be found with the other modes. Even bulk commodities, such as lumber, that have been traditionally moved by the rail mode are now increasingly being handled by the truck/highway mode. For example, in 1977, only 20 percent of the value of Ontario's lumber exports to the United States were transported by the truck/highway mode; by 1987, 92 percent were transported by that mode (Figure 12).

The reason why the truck/highway mode was not as prominent in the trade relationship between Ontario and the mid-Atlantic and New England states is twofold: (a) there is a higher proportion of trade in fabricated materials rather than end products; in that particular class of commodity, rail transport can be (and obviously is) quite competitive, and (b) contrary to the national trend, the rail mode has been successful in maintaining or retaining a significant share of the exporting of automotive products from Ontario through aggressive marketing. Three-quarters of all rail export traffic to the mid-Atlantic/New England states is made up of one commodity: passenger automobiles and their chassis. The rail mode transports 86 percent of Ontario's exports of this commodity to those two U.S. census subdivisions, but only 27 percent of this commodity to the remainder of the United States.

The inability of the rail mode to attract or maintain transborder traffic during this decade, particularly in the East North Central region, is a function of many complex factors. Among them are the short distance of haul to and from destinations north of the border and the predominant commodity traffic mix, but also the perceived reluctance to adopt double-stack technology and more actively solicit intermodal traffic by Canadian rail carriers.

Sixth, there are continual additions and enhancements to the highway infrastructure system on both sides of the border. This is at a time when the rail network is shrinking through branch line abandonment, the St. Lawrence Seaway is still constrained by weather and the size of its locks, and the air mode is hampered by airports that do not have enough runways and terminals and whose ability to move goods is affected by the existence of curfews on night flights, insufficient numbers of customs clearance personnel (given the demand), and bilateral restrictions.

For example, a major U.S. air cargo carrier is permitted to fly into Toronto, Canada's principal air passenger and cargo hub, to unload goods but is not allowed to fly goods out. Instead, it is forced to have them sent by truck to Buffalo, where they are flown to its central U.S. sorting hub in Ohio for distribution (*2*).



SOURCE: Statistics Canada International Travel Division

FIGURE 11 Inbound border truck movements, Ontario/United States, 1977 and 1987.

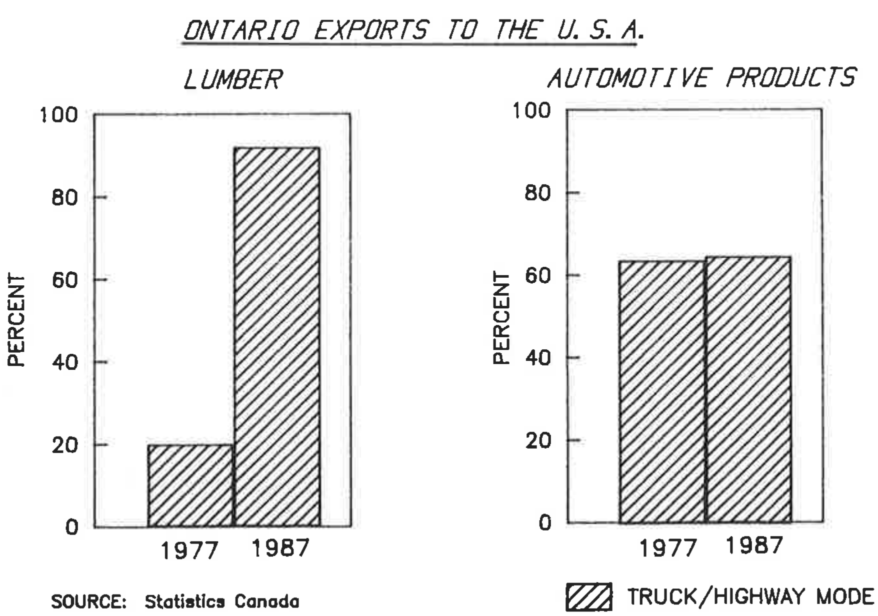


FIGURE 12 Modal share changes, 1977 to 1987.

Yet another firm finds airport customs facilities in Toronto so busy that it is actually faster to fly instead to Buffalo and to truck goods to Toronto. Because of such constraints and flight infrequency to some destinations, it is estimated that almost 15 percent of air cargo traffic at Pearson International Airport in Toronto is trucked to its final destination.

Seventh, because of such physical or operational considerations, there is greater use of American gateways to move a considerable proportion of Ontario's trade to and from other continents. For example, Canada Post recently made a decision to forward mail to Europe using trucks to transport it first to New York and then to Europe by U.S. air carriers, rather than by Air Canada via Canadian gateways at Toronto and Montreal, as it had done previously (*3*). Flights were discovered to be more frequent and cheaper by using that route. This has led to further increases in truck traffic on Ontario's highways.

A review of trade data found that approximately 29 percent of Ontario's imports from other continents and 21 percent of Ontario's exports to other continents are transported by the truck/highway mode, using an American port or airport such as Port Elizabeth, Detroit, Miami, or New York (Figure 13).

IMPLICATIONS

Some problems have been associated with the shift in modal share in favor of the truck/highway mode. First, although increases in truck volumes on the provincial highway system and at the border have largely been commensurate with those of automobiles, expansion and enhancement of the network and border crossings have not kept pace with this degree of increase. As a result, there has been increased congestion at border areas and during the peak hour in major municipalities.

Trucks generally deliver during the off-peak hour in urban locations to minimize the effects of congestion; typically, they account for 10 to 15 percent or less of peak hour travel. During the course of the conduct of the Ontario Ministry of Transportation's 1988 Commercial Vehicle Survey, classification counts indicated that truck activities were far less oriented to the peak hour than were those of automobiles (Ontario Commercial Vehicle Survey, to be published in 1990) (Figure 14).

The expansion of the peak hour has, however, affected truck scheduling so much that a recent goods movement study in Toronto estimated that close to 30 percent of the cost of moving goods—or almost $2 billion per year—was directly attributable to congestion (*4*) and could be expected to increase to 50 percent of the cost of moving goods if no mitigating measures were undertaken. Because of the larger size and operational characteristics of trucks, they are increasing viewed by commuters as contributors to congestion and there have been calls in some circles for their movement to be restricted, for example, most recently in Charleston and Los Angeles (*5,6*).

Second, trucks have been increasing in size and length, whereas automobiles are becoming smaller and less powerful, raising concerns about safety, particularly given the perceived effects of deregulation in both Canada and the United States.

Third, because trucks are now carrying heavier and denser commodities such as lumber, greater pressure is being borne by pavement surfaces, requiring increased and more frequent rehabilitation.

Fourth, the increase in both truck movements and the proportion of those movements that are related to dangerous goods has resulted in the desire of some communities to have truck bypass routes constructed by the province in order to minimize the perceived risk of an incident. The economic cost of providing such routes, given general fiscal restraint measures, is, however, increasingly prohibitive.

PROVINCIAL AND OTHER ACTIONS

In recognition of the broader economic role of highways and the need to make a long-term commitment to transportation

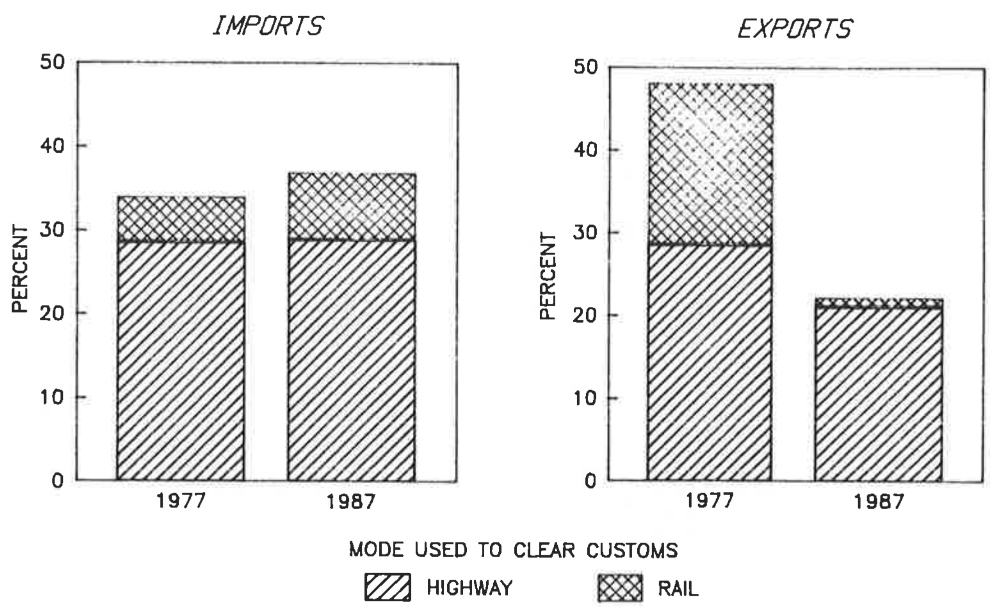


FIGURE 13 Role of United States gateways: Ontario's trade to all other countries, 1977 and 1987.

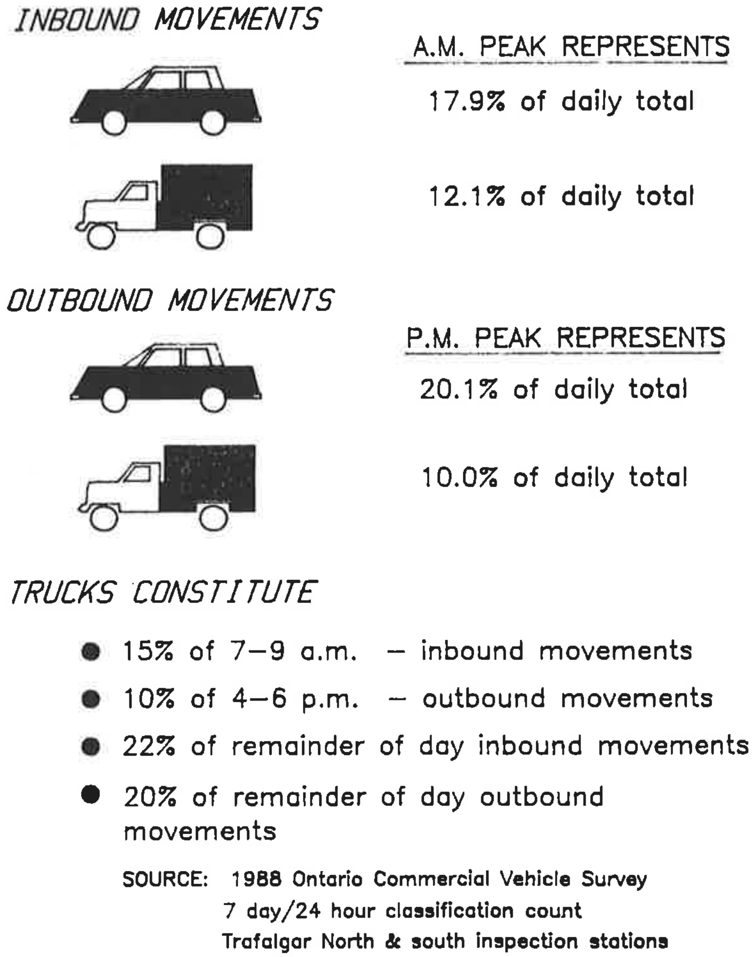


FIGURE 14 Peak hour characteristics.

investment to support sustained economic growth, a number of measures and initiatives have been adopted to deal with the subjects of congestion, the increase in truck volume, and the shift in modal traffic to the truck/highway mode.

First, the cornerstone of provincial action in this regard was a recent announcement of a $2 billion, 5-year transportation capital program by the provincial treasurer in his May 1989 budget (*7*). In the fastest-growing regions of the province, the following major improvements are planned:

- Expansion and accelerated construction of the provincial highway network,
- Considerable financial commitment for major municipal arterial roads and connecting links,
- Increases in capital spending for municipal transit projects, and
- Expansion of provincially operated commuter rail service.

These actions would have the effect of enhancing mobility on both the highway and transit networks, enabling goods to be moved more expeditiously by truck. To improve service levels and safety in other areas of the province, freeway capacity would be increased by widening some highways, constructing new highways, and adding more truck climbing lanes on selective facilities.

Second, measures are being implemented to improve the operational efficiency of highways with the expansion of the freeway traffic management network.

Third, because responsible decisions cannot be made in a vacuum, there is an increase in research to better quantify goods movement considerations for highway planning and protection purposes. As indicated previously, major commercial vehicle surveys are undertaken on the provincial network every 5 years, the province funds and provides direction for municipal studies on the subject, participates on task forces organized by other levels of government, and undertakes related research.

Fourth, to enhance safety and protect the pavement surface, enforcement of weight restrictions and safety standards on commercial vehicles has been added. This has been accomplished through periodic enforcement blitzes and altering the hours of operation of the province's truck inspection stations. Since 1985 in Ontario, the Ministry of Transportation highway enforcement personnel and the Ontario Provincial Police have laid over 2,000 charges for on-highway offenses.

Constructive efforts have been undertaken by both the private and public sectors as well. To minimize the effects of congestion, both manufacturers and motor carriers are resorting to evening and weekend deliveries. Measures have been adopted by Canada Customs to reduce inbound border truck traffic by permitting goods to proceed without inspection in bond to inland "suffrage" customs warehouses and by placing additional truck booths at customs areas for through truck traffic.

As this paper illustrates, monitoring and accounting for the movement of goods is a complex undertaking, but it should provide worthwhile insights for transportation planners and engineers for use in capital planning, maintenance staging, and enforcement deployment. It is hoped that the results of this paper would be to encourage further work to be undertaken in this field of research.

ACKNOWLEDGMENTS

The author greatly appreciates the assistance in the preparation of this paper provided by the staff at the Ministry of Transportation and at Statistics Canada, particularly the contributions of K. Pask, A. Banik, E. Cheung, P. Dimitriou, O. Soucy, and A. Gerlewych.

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The opinions expressed in this paper are solely those of the author and in no way reflect the position of the Ontario Ministry of Transportation.

Publication of this paper sponsored by Committee on International Trade and Transportation.

Ship Impact Risk Analysis of the Tappan Zee and Castleton-on-Hudson Bridges, Hudson River

PAIK-KEE LOW AND RICHARD WILSON

The exposure to risk of ship-bridge collisions at the Tappan Zee and Castleton-on-Hudson bridges on the Hudson River in New York State is evaluated in this paper. Provided are a description of the major factors affecting the potential for ship-bridge collisions and an estimate of the observed and potential frequency of ship-bridge accidents at the two bridges. A statistical analysis is used in this paper to predict the probability of a ship-bridge collision based on accident rates obtained for each class of bridges, defined here as the set of bridges over navigable waters in the United States of similar characteristics to the bridge of interest. The probability of an accident occurring at each of the two study bridges represents the average number of accidents that could occur each year. This can also be represented by the number of years between two consecutive accidents (or the return period). This is calculated by taking the direct inverse of the probability of occurrence of a ship-bridge accident. The return period found for the Tappan Zee Bridge was 55 years, and for the Castleton-on-Hudson Bridge the return period was 268 years. These results serve as indicators for precautionary measures to reduce the risk and severity of a ship-bridge collision.

Recent years have seen an increase in serious accidents involving ship collisions with major bridges. These accidents have claimed many lives and resulted in millions of dollars in damages, lost transportation services, repair and replacement costs, and spills and releases from the ships. Various factors have contributed to this increase, including the rapid growth in size and tonnage of the world fleet of merchant vessels during the last 25 years. In addition, bridges are not always designed with attention to the waterborne traffic that passes beneath them. As a result, they may be poorly located for ship maneuvering, lack sufficient navigational clearance, or have piers that may be placed so that vessels that stray from the main navigational channel would collide with them before running aground. Moreover, most bridges are not designed to withstand the horizontal impacts of these vessels. Hence, protection systems for them may need to be provided.

Evaluated in this paper is the potential of ship-bridge collisions at the Tappan Zee and the Castleton-on-Hudson bridges on the Hudson River in New York State. Provided is a description of the major factors affecting the potential for ship-bridge collisions, analysis of the considerations regarding the natural setting and general river conditions at the two bridges, and an estimate of the predicted frequency of ship-bridge accidents.

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The first section of the paper contains a description of the study approach and identifies the data used. In the second section, the ship-bridge collisions on the Hudson River are described, and a brief survey of international bridge accidents is presented that identifies their nature and the factors that contributed to their occurrence. The third section provides a description of the Tappan Zee and the Castleton-on-Hudson Bridges, the characteristics of the river within their vicinity, weather conditions, and types of vessels that pass beneath each bridge. In the fourth section, the results of the study are presented and the risks to the two bridges assessed.

APPROACH AND DATA SOURCES

Although no national standards defining acceptable levels of risk for ship-bridge collisions exist, a risk analysis identifies the risk of ship-bridge collisions for the Tappan Zee and Castleton-on-Hudson Bridges. This information can be used to evaluate methods to reduce such risks.

The model adopted in this risk assessment conforms to the simple, general equation:

$$TR = 1/(N \times PC)$$

where

TR = the number of years between two accidents (return period),
N = the number of annual vessel transits beneath a bridge, and
PC = the ship-bridge collision rate at a bridge.

When a vessel strays from the main navigational channel, it could hit a bridge pier or superstructure. The probability that a collision would occur is dependent on such variables as the geometry and depth of the waterway, the location of the bridge piers, the density of the waterborne traffic on the waterway, human error, mechanical failure, or unfavorable or adverse environmental conditions such as fog or storm.

In this paper, the probabilities of a ship-bridge collision occurring at either the Tappan Zee or Castleton-on-Hudson Bridges are estimated by analyzing national maritime traffic and accident statistics for the period 1981 to 1986 for the appropriate classes of bridges, and the traffic profiles of the vessels and ships that pass beneath the two bridges.

A class of bridges is defined here as the set of bridges of similar horizontal clearance to the study bridge. The Tappan

Zee Bridge has a horizontal clearance in the main navigational channel of 1,098 ft, whereas the Castleton-on-Hudson Bridge has a horizontal clearance of 552 ft. The classes were established for horizontal clearance ranging from 900 to 1,300 ft for the Tappan Zee class, and 500 to 600 ft for the Castleton-on-Hudson class. Each class of bridges is analyzed for the total number of ship-bridge collisions that occurred from 1981 to 1986, and the total vessel traffic that passed beneath each bridge within that class for the same period. Therefore, the average annual rate of ship collisions, *PC*, is obtained for that class of bridges by dividing the total number of accidents by the total number of vessel transits.

After obtaining the number of ships and barges (*N*) that transit beneath each bridge, the probability or chance of a ship-bridge collision occurring at that bridge ($N \times PC$) can then be established. Hence, the smaller the return period, the greater the risk that a ship-bridge collision could take place.

The data on national maritime accidents were primarily obtained from the marine accident files maintained by the United States Coast Guard (USCG); the United States Army Corps of Engineers (USACE) provided data on vessel movements (*1*). Only data on movements by self-propelled vessels were considered relevant, as barges are accompanied by tugboats. The two classes of bridges were determined through a search of data included in the USCG *Bridges Over the Navigable Waters of the United States*, all volumes, 1984 (*2*). The traffic profile (*N*) of the Hudson River was obtained from the USACE Waterborne Commerce Statistics Center, the Maritime Association of the Port of New York and New Jersey, and the Hudson River Pilots Association (HRPA). Relevant bridges and accidents obtained through the data search are listed in Tables 1 through 4.

TASKS UNDERTAKEN

A vessel listing for the Hudson River [see Appendix *B* in the Parsons Brinckerhoff study (*4*)] was created by combining information from the Maritime Association on ship movement with data from Lloyd's Register of Ships (*3*) and then resorted according to vessel types and classes. A data base for bridges of the United States over navigable waters was also created according to size of horizontal span. This was done to obtain bridges of similar sizes and characteristics (i.e., class) for comparison with the proposed bridges. Accident statistics were then compiled by sorting the accident data base according to the horizontal clearances of two classes of bridges. The results can be found in Appendix *C* in the Parsons Brinckerhoff study (*4*).

National accident statistics were obtained from the USCG Office of Marine Safety in Washington, D.C. (records pertaining to ship/bridge collisions for the years 1980 to 1988). These records provided a listing of all accident cases that involved ship-bridge collisions. From this list, an accident data base was compiled that included the name of the waterway and the bridge where each accident took place. By making correlations with information contained in *Bridges Over the Navigable Waters of the United States* (*2*), the type and horizontal clearance of these bridges were also included. The data base is presented in Appendix *D* in the Parsons Brinckerhoff study (*4*).

Telephone interviews were also conducted with various organizations to obtain information on vessel traffic and navigation on the Hudson. The organizations contacted included the

- U.S. Coast Guard
- Maritime Association of the Port of New York and New Jersey
- Towboat and Carriers Association of New York and New Jersey
- U.S. Army Corps of Engineers
- Hudson River Pilots Association
- Albany Port District Commission
- Barge/Tug Transportation Companies
  - –New York Trap Rock Corporation
  - –Reinauer Transportation Company
  - –Red Star Marine Services, Inc.
  - –Berman Enterprises, Inc.
  - –Bouchard Transportation Company
  - –Buchanan Marine Corporation
  - –Eklof Marine Corporation
  - –Gallagher Brothers Sand & Gravel Corporation

HISTORICAL ACCIDENT EXPERIENCE

Discussed in this section are the nature and causes of accidents on the Hudson River and around the world that involved ship-bridge collisions.

Ship-Bridge Collisions on the Hudson River

A review of the files maintained by the First Coast Guard District at Governor's Island, New York, for all bridges crossing the Hudson River north of Yonkers to Albany, New York, indicated that there was only one reported maritime accident involving a bridge on the Hudson River. This was confirmed by a search of the records of national maritime accidents (according to regional water-body designations) maintained by the USCG at its Office of Marine Safety. The accident at the Tappan Zee Bridge occurred on December 31, 1975. A tugboat pushing a tank barge northbound at reduced speed with visibility impaired by fog made contact with the west pier of the west pass after difficulties with its radar equipment. Although there was a lookout stationed at the bow of the barge, communications were insufficient to give timely warning of the impending collision to the tugboat's pilothouse.

The bridge sustained minor damage to its fendering system. The barge was punctured, resulting in the discharge of oil into the river. A copy of the accident report is given in *Ship Impact Risk Analysis* (*4*).

Ship-Bridge Collisions Around the World

Although none of the bridges across the Hudson River has been involved in major ship-bridge collisions, such accidents have occurred nationally and internationally. A *Ship Collision Risk Assessment* by COWIconsult for the Sunshine Skyway Bridge in Tampa, Florida, in 1981 (*5*), gives a list of examples

TABLE 1 TAPPAN ZEE CLASS BRIDGES (900–1,300 ft)

SEQ	WATERWAY	CITY	ST NAME AND LOCATION OWNER	MILEPOST	TYPE	LENGTH	LW	HW	USE
1	EAST RIVER	NEW YORK CITY	NY QUEENSBORO BR W CHANNEL NY CITY-NYC	5.5	F	900	138	131	HWY
2	MISSISSIPPI-LOWER	CARUTHERSVILLE	MO CARUTHERSVILLE I 55-MO AND TN	838.9	F	900	96	52	HWY
3	ST. JOHNS RIVER	JACKSONVILLE	FL DAME PT JACKSONVILLE FL-JACKSONVILLE	9.8	F	906		160	HWY
4	WILLAMETTTE RIVER	PORTLAND	OR FREEMONT BR	10.9	F	928	163	147	HWY
5	MISSISSIPPI-UPPER	ST LOUIS	MO VETERANS MEMORIAL BRIDGE	180.2	F	940	102	65	HWY
6	WHITE RIVER	NEWPORT	AR LOUISIANA GAS COMPANY	243.5	SUS	944	67	42	PL
7	HUDSON RIVER	NEWBURGH	NY NEWBURGH & BEACON NY I 84-NY	62.0	F	960		139	HWY
8	HUDSON RIVER	NEWBURGH	NY NEWBURGH-BEACON NY-NY	62.0	F	960	185	181	HWY
9	NIAGARA RIVER	NIAGARA	NY UPPER STEEL ARCH-NIAGARA FALLS	13.0	F	960	189		HWY
10	ST. JOHNS RIVER	JACKSONVILLE	FL JACKSONVILLE EXP COMMODORE PT	22.1	F	960	143	141	HWY
11	NIAGARA RIVER	LEWISTON	NY LEWISTON NY-NIAGARA FALLS	7.1	F	980	200	195	HWY
12	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN NORTH PIER	0.2	F	998	151	145	HWY
13	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN SOUTH PIER	0.2	F	998	141	135	HWY
14	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN NORTH PIER	0.2	F	1000	157	151	HWY
15	CARQUINEZ STRAIT	VALLEJO-UPSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN SOUTH PIER	0.2	F	1000	152	146	HWY
16	COOPER RIVER	CHARLESTON	SC CHARLESTON SC US 17-SC	3.0	F	1000	155	150	HWY
17	OHIO RIVER	MAYSVILLE	KY MAYSVILLE-ABERDEEN US 60	408.4	SUS	1000	80	38	HWY
18	SAN FRANCISCO BAY	SAN RAFAEL	CA RICHMOND SR 17 (MAIN CHANNEL-CTR SPAN)	13.0	F	1000	190	185	HWY
19	OHIO RIVER	COVINGTON	KY COVINGTON-CINCINNATI	470.5	SUS	1004	74	27	HWY
20	COLORADO RIVER	BLYTHE	CA BLYTHE	121.1	F	1020		48	PL
21	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN NORTH PIER	0.2	F	1030	162	156	HWY
22	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR NORTH(RIGHT) SPAN SOUTH PIER	0.2	F	1030	153	147	HWY
23	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN NORTH PIER	0.2	F	1030	150	144	HWY
24	CARQUINEZ STRAIT	VALLEJO-DNSTRM	CA VALLEJO BR SOUTH(LEFT) SPAN SOUTH PIER	0.2	F	1030	140	134	HWY
25	CLEARWATER RIVER	OROFINO	ID OROFINO DENT BR - CLEARWATER CO	17.0	F	1035	30		HWY
26	WILLAMETTE RIVER	ST JOHNS	OR ST JOHNS-MULTNOMAH	5.9	SUS	1068	189	174	HWY
27	COLUMBIA RIVER	ASTORIA	OR ASTORIA TO PT ELLICE (MAIN CHANNEL)	13.5	F	1070	193	186	HWY
28	EAST RIVER	NEW YORK CITY	NY TRIBOROUGH BR	7.8	F	1070	143	138	HWY
29	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN B-C PIER B	8.9	SUS	1072	224	218	HWY
30	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN B-C PIER C	8.9	SUS	1072	227	221	HWY
31	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN C-D PIER C	8.9	SUS	1079	226	220	HWY
32	SAN FRANCISCO BAY	SAN FRANCISCO	CA SF/OB W SPAN C-D PIER D	8.9	SUS	1079	224	218	HWY
33	COLORADO RIVER	TOPOCK	AZ TOPOCK	233.7	F	1080	72	53	HWY
34	COLUMBIA RIVER	LONGVIEW	WA LONGVIEW (RAINIER)	66.0	F	1085	187	176	HWY
35	HUDSON RIVER	NYACK	NY TAPPAN ZEE BR	27.0	F	1098	144	139	HWY
36	PATAPSCO RIVER	BALTIMORE	MD SOLLERS PT-HAWKINS PT I 395	6.0	F	1100		185	HWY
37	MISSISSIPPI-LOWER	BATON ROUGE	LA BATON ROUGE-PORT ALLEN	229.3	F	1120	165	125	HWY
38	LONG BEACH HARBOR	LOS ANGELES	CA VINCENT THOMAS BR	3.0	SUS	1150	189	185	HWY
39	EAST RIVER	NEW YORK CITY	NY MANHATTAN BR	1.1	F	1200	144	134	HWY-RR
40	MISSISSIPPI-LOWER	LULING	LA LULING AND DESTREHAN	121.7	F	1200	154	133	HWY
41	RED RIVER	RED RVR PARISH	LA TENNESSEE GAS TRANSLINE	205.5	SUS	1250	76	51	PL

SOURCE: PARSONS BRINCKERHOFF

of ship-bridge collisions that took place between 1960 and 1980 in the United States and around the world.

The causes of such collisions are often a complex combination of various factors that fall into three main categories:

1. Human error (e.g., lack of experience; misjudgment; negligence; misunderstanding between captain, pilot, and helmsman; incorrect interpretation of chart or notice to mariners; violations of rules of the road; incorrect evaluation of current and wind conditions; and so on);

2. Mechanical failure (e.g., engine, steering, radar equipment); and

3. Environmental conditions (e.g., strong winds and storm, fog, rough current conditions, heavy traffic, narrow river channel width and shape, poor navigational aids).

The nature and impact characteristics of these collisions have also been categorized:

1. The hull of the ship hits a bridge pier and moves, overturns, or breaks it;

TABLE 2 CASTLETON-ON-HUDSON CLASS BRIDGES (500–600 ft)

SEQ	WATERWAY	CITY	ST NAME AND LOCATION OWNER	MILEPOST	TYPE	LENGTH	LW	HW	USE
1	ALLEGHENY RIVER	CHESWICK	PA CHESWICK PA I 80-PA	14.2	F	500	64	53	HWY
2	ALLEGHENY RIVER	CHESWICK	PA CHESWICK PA-BLE	14.2	F	500	89	78	RR
3	ARKANSAS RIVER	LITTLE ROCK	AR LITTLE ROCK AR 440-AR	112.9	F	500	57	52	HWY
4	ARTHUR KILL	STATEN ISLAND	NY STATEN ISLAND NY-ELIZABETH NJ-BO	11.6	VL	500	35	31	RR
5	CAPE COD CANAL	BOURNE	MA BOURNE MA-BUZZARDS BAY	0.7	VL	500	11	7	RR
6	CAPE COD CANAL	BOURNE	MA BOURNE MA SR 28-US ARMY COE	2.0	F	500	139	135	HWY
7	CAPE COD CANAL	SAGAMORE	MA SAGAMORE MA US 6-US ARMY COE	5.2	F	500	142	135	HWY
8	CHSPKE & DLWR CANAL	CANAL	DE CANAL DE-CR	7.7	VL	500	50	45	RR
9	COLUMBIA RIVER	KENNEWICK	WA KENNEWICK WA-WA	330.0	F	500	61		HWY
10	COLUMBIA RIVER	PORTLAND	OR PORTLAND I 205 (MAIN CHANNEL)	112.7	F	500	136	119	HWY
11	DELAWARE RIVER	BRISTOL	PA BRISTON PA-BURLINGTON NJ-BURLINGTON CO	117.8	VL	500	68	62	HWY
12	DELAWARE RIVER	DELAIR	NJ DELAIR NJ-CR	104.6	VL	500	55	49	RR
13	GASTINEAU CHANNEL	JUNEAU	AK JUNEAU AK-AK		F	500	66	50	HWY
14	HOUSTON SHIP CANAL	HOUSTON	TX TEXAS TURNPIKE AUTHORITY	40.0	F	500		175	HWY
15	HOUSTON SHIP CHANNEL	HOUSTON	TX HOUSTON TX-TEXAS-TURNPIKE AUTH	40.0	F	500		175	HWY
16	ILLINOIS RIVER	CREVE COUER	IL CREVE COEUR IL I 474(TWIN)-IL	158.0	F	500		54	HWY
17	KANAWHA RIVER	POINT PLEASANT	WV POINT PLEASANT WV US 35-WV	0.1	F	500	69	30	HWY
18	KOOTENAI RIVER	BONNERS FERRY	ID BONNERS FERRY ID-BONNERS FERRY	152.1	SUS	500	36	32	PL
19	LOS ANGELES RIVER	LONG BEACH	CA QUEENS WAY	2.7	F	500	50	45	HWY
20	MISSISSIPPI-LOWER	NEW ORLEANS	LA PARIS ROAD SR 47-US GOVT	13.0	F	500	140	137	HWY
21	MISSISSIPPI-UPPER	MUSCATINE	IA MUSCATINE SR 92-IA	455.9	F	500	64	52	HWY
22	MISSISSIPPI-UPPER	ROCK ISLAND	IL ROCK ISLAND I 280-IL	478.3	F	500	62	52	HWY
23	MISSISSIPPI-UPPER	ST LOUIS	IL MCKINLEY BR	182.5	F	500	95	58	HWY-RR
24	OHIO RIVER	BROOKVILLE	IL IRVIN COBB BR US 45	937.3	F	500	91	46	HWY
25	OHIO RIVER	CAIRO	IL CAIRO IL-ICG	977.7	F	500	104	44	RR
26	OHIO RIVER	CINCINNATI	OH CINCINNATI OH-SOU	472.3	F	500	78	25	RR
27	OHIO RIVER	KENOVA	WV KENOVA WV-NW	315.7	F	500	74	30	RR
28	OHIO RIVER	MARTINS FERRY	OH MARTINS FERRY	89.0	F	500	80	32	RR
29	ROGUE RIVER	AGNESS	OR NEAR AGNESS OR - LARRY LUCAS	26.0	SUS	500	80	6	PL
30	SAN DIEGO BAY	SAN DIEGO	CA CORONADO BAY BRIDGE SPAN 20/21	7.8	F	500	179	175	HWY
31	ST LOUIS RIVER	DULUTH	MN I 535 RICES POINT	5.4	F	500	123	120	HWY
32	SUSQUEHANNA RIVER	HAVRE DE GRACE	MD HAVRE DE GRACE MD-BO	2.0	F	500	88	86	RR
33	TENNESSEE RIVER	CALVERT CITY	KY CALVERT CITY I 24-KY	21.1	F	500	87	45	HWY
34	MISSISSIPPI-UPPER	HASTINGS	MN HASTINGS MN US 61 10	813.9	F	502	63	47	HWY
35	MONONGAHELA RIVER	DONORA	PA DONORA PA-PA	36.3	F	502	54	25	HWY
36	OHIO RIVER	CINCINNATI	OH CINCINNATI OH-KY	469.9	F	502	78	23	HWY
37	MISSISSIPPI-UPPER	ST LOUIS	IL MERCHANTS BR	183.2	F	503	92	55	RR
38	ATCHAFALAYA RIVER	SIMMESPORT	LA SIMMESPORT LA S I-LA	132.7	F	504	102	50	HWY
39	MONONGAHELA RIVER	RANKIN	PA RANKIN SR 837-ALLEGHENY CO	9.6	F	505	75	40	HWY
40	MONONGAHELA RIVER	BROWNSVILLE	PA BROWNSVILLE US 40-PA	56.2	F	506	46	18	HWY
41	MISSISSIPPI-UPPER	SAVANNA	IL SAVANNA-SABULA US 52	537.8	F	508	64	57	HWY
42	OHIO RIVER	AMBRIDGE	PA AMBRIDGE-ALIQUIPPA SR 18 65	16.8	F	510	78	58	HWY
43	SNAKE RIVER	CENTRAL FERRY	WA CENTRAL FERRY WA SR 127-WA	83.2	F	510	60	58	HWY
44	MISSOURI RIVER	SOUTH OMAHA	NE SOUTH OMAHA NE US 275	612.2	F	514	62	52	HWY
45	COOS BAY	NORTH BEND	OR US 101-OR	9.8	F	515	126	120	HWY
46	MISSISSIPPI-UPPER	ROCK ISLAND	IL CENTENNIAL BR US 67	482.1	F	515	65	45	HWY
47	MONONGAHELA RIVER	HOMESTEAD	PA HOMESTEAD SR 837-ALLEGHENY CO	7.3	F	516	51	18	HWY
48	MISSISSIPPI-UPPER	ST LOUIS	IL EADS BR	180.0	F	517	79	42	HWY-RR
49	KENTUCKY RIVER	TYRONE	KY TYRONE KY-SOU	84.0	F	518	196	156	RR

TABLE 2 (*continued*)

SEQ	WATERWAY	CITY	ST NAME AND LOCATION OWNER	MILEPOST	TYPE	LENGTH	LW	HW	USE
50	PASSAIC RIVER	NEWARK	NJ NEWARK NJ PULASKI SKYWAY-NJ	2.0	F	520	140	135	HWY
51	SNAKE RIVER	RAPARIA	WA RAPARIA WA US 12 LYONS FERRY BR-WA	59.2	F	520		52	HWY
52	ALLEGHENY RIVER	EMLENTON	PA EMLENTON PA I 80-PA	90.6	F	521	162	140	HWY
53	CHSPKE & DLWR CANAL	CHESAPEAKE CITY	MD CHESAPEAKE CITY MD US 213-US GOVT	13.9	F	523	137	135	HWY
54	CHSPKE & DLWR CANAL	ST GEORGES	DE ST GEORGES DE US 13-US GOVT	4.5	F	523	139	135	HWY
55	ICWW ALT. ROUTE	MORGAN CITY	LA BERWICK BAY US 90-LA	0.7	F	525		73	HWY
56	LK WSHG SHP CANAL	SEATTLE	WA US 99 GEO. WASHINGTON MEMORIAL BRIDGE	2.7	F	525	74	73	HWY
57	DELAWARE RIVER	EASTON	PA EASTON PA-DEL RIVER JT TOLL BR COMM	183.7	F	526		28	HWY
58	ILLINOIS RIVER	BEARDSTOWN	IL BEARDSTOWN IL US 67 SR 100-IL	87.9	F	526	69	49	HWY
59	OHIO RIVER	METROPOLIS	IL METROPOLIS IL-PI	944.1	F	530	98	44	RR
60	MERRIMACK RIVER	TYNGSBORO	MA TYNGSBORO BRIDGE SR 3A 113	47.4	F	533		18	HWY
61	MISSOURI RIVER	ROCHEPORT	MO ROCHEPORT I 70	185.0	F	533	67	55	HWY
62	OHIO RIVER	LOUISVILLE	KY LOUISVILLE KY-JEFFERSON IN-CR	602.9	F	537	77	36	HWY
63	MISSISSIPPI-UPPER	HANNIBAL	MO MARK TWAIN BR US 36 61-MO&IL	309.2	F	546	66	57	HWY
64	OHIO RIVER	STEUBENVILLE	OH STEUBENVILLE	66.7	F	546	72	38	RR
65	DELAWARE RIVER	FLORENCE	NJ FLORENCE NJ-PA & NJ TURNPIKE COMM	121.2	F	550	141	135	HWY
66	OHIO RIVER	HUNTINGTON	WV WEST END SR 94-WV	310.7	F	550	74	29	HWY
67	HUDSON RIVER	CASTLETON	NY CASTLETON NY-NY	135.7	F	552	139	135	HWY
68	ILLINOIS RIVER	MEREDOSIA	IL MEREDOSIA SR 104-IL	71.3	F	554	72	47	HWY
69	OHIO RIVER	WHEELING	WV 9TH ST I 70-WV	90.2	F	554	76	29	HWY
70	MONONGAHELA RIVER	PITTSBURGH	PA GLENWOOD SR 885-PA	5.9	F	557	50	17	HWY
71	MISSISSIPPI-UPPER	CLINTON	IA CLINTON US 30	518.1	SUS	568	63	53	HWY
72	BERWICK BAY	MORGAN CITY	LA MORGAN CITY LA US 90-LA	17.7	F	571	73		HWY
73	MISSOURI RIVER	KANSAS CITY	MO PASEO BR US 69 71	364.8	SUS	573	69	55	HWY
74	MUSKINGUM RIVER	BEVERLY	OH BEVERLY OH-OHIO POWER CO	29.0	SUS	575	68	30	CB
75	MYSTIC RIVER	CHELSEA	MA TOBIN MEMORIAL BR	0.1	F	575	144	135	HWY
76	MISSISSIPPI-UPPER	ST LOUIS	IL POPLAR ST BR	179.2	F	580	97	55	HWY4
77	OHIO RIVER	EVANSVILLE	IN EVANSVILLE IN-HENDERSON KY US 41	786.8	F	580	84	42	HWY
78	BERWICK BAY	MORGAN CITY	LA MORGAN CITY LA US 90-LA	17.7	F	583	50		HWY
79	GIWW MGN CITY	MORGAN CITY	LA SR 75-LA LWR GRAMD RVR BAYOU SORREL	38.4	F	583		50	HWY
80	ICWW ALT. ROUTE	BAYOU SORREL	LA LOWER GRAND RIVER SR 75-LA	38.4	F	583		50	HWY
81	CHSPKE & DLWR CANAL	REEDY POINT	DE REEDY POINT DE SR 19-US GOVT	1.0	F	584		135	HWY
82	MOUNT HOPE BAY	BRISTOL	RI BRISTOL-PORTSMOUTH RI-MT HOPE BR COMM	0.0F	(SUS	585	139	135	HWY
83	NEWARK BAY	NEWARK	NJ NEWARK & BAYONNE NJ-NJ	4.0	F	585	139	135	HWY
84	CHSPKE & DLWR CANAL	CANAL	DE SUMMIT BRIDGE DE US 301-US GOVT	9.7	F	586	138	135	HWY
85	MONONGAHELA RIVER	MONESSEN	PA MONESSEN PA-PA	38.0	F	594	47	19	HWY
86	AMERICAN RIVER	SACRAMENTO	CA SACRAMENTO CA	7.1	SUS	600	39	10	FB
87	HOOD CANAL	PORT GAMBLE	WA HOOD CANAL FLTG BR CENTER SPAN	5.0	P	600			HWY
88	KOOTENAI RIVER	PORTHILL	ID PORTHILL - US GOVT	105.9	SUS	600		16	HWY
89	MISSOURI RIVER	ST CHARLES	MO ST CHARLES MO-NW	27.1	F	600	72	56	RR
90	NARRAGANSETT BAY W.	NORTH KINGSTON	RI RI-JAMESTOWN BR COMM	5.7	F	600	138	134	HWY
91	NECHES RIVER	PORT ARTHUR	TX PORT ARTHUR SR 87-TX	1.5	F	600	176	172	HWY
92	OHIO RIVER	METROPOLIS	IL METROPOLIS IL-PADUCAH KY I 24	940.8	F	600	70	15	HWY
93	OHIO RIVER	NEW ALBANY	IN NEW ALBANY I 64-KIT	607.4	F	600	98	21	HWY-RR
94	SACRAMENTO RIVER	SACRAMENTO	CA SACRAMENTO CA WATT AVE-SACRAMENTO CO	7.1	SUS	600	39	10	FB
95	SAN DIEGO BAY	SAN DIEGO	CA CORONADO BAY BRIDGE SPAN 19/20	7.8	F	600	199	195	HWY
96	ST CLAIR RIVER	PORT HURON	MI BLUEWATER BRIDGE	39.1	F	600	135		HWY
97	TOWN CREEK	CHARLESTON	SC CHARLESTON SC US 17-SC	3.0	F	600	140	135	HWY
98	TOWN CREEK	CHARLESTON	SC CHARLESTON SC US 17-SC	3.0	F	600	140	135	HWY

SOURCE: PARSONS BRINCKERHOFF

TABLE 3 ACCIDENTS IN CASTLETON-ON-HUDSON CLASS BRIDGE, 1981–1986

RECORD#	CASE	TYPE	CY	HORZ	PERIODAY WATER	MILEPOST	CAUSE	VSLNAME	USE	LENGTH	BRIDGE NAME
1	0029PAD82	F	82	500 N	02XIRO	977.7	PERRJDG	ACBL 1791	BSLD	200	CAIRO IL-ICG
2	0035PAD84	F	84	500 N	02XIRO	977.7	PFALACW	BARGE M 76	UNK	135	CAIRO IL-ICG
3	0044PAD82	F	82	500 N	02XIRO	937.3	PERRJDG	DK 107	BSLD	195	IRVIN COBB FR IL US45-KY
4	2883PHI81	VL	81	500 D	03AIRD	104.6	PCRLSNS	CERRO BOLI	BSLD	753	DELAIR NJ-CR
5	MC86001974	F	86	500 T	02XIRO	472.4	POPERER	SHE 8046	BSLD	195	CINCINNATI OH-SOU
6	0150SLM83	F	83	503 D	02XIRU	183.0	PERRJDG	LAWRENCE C	TOW	69	MERCHANTS BR - ST LOUIS
7	0283SLM83	F	83	503 N	02XIRU	183.2	PERRJDG	CAPT CARL	TOW	68	MERCHANTS BR - ST LOUIS
8	MC86004099	F	86	503 N	02XIRU	183.2	POPERER	SG 578 B	BSLD		MERCHANTS BR - ST LOUIS
9	MC86005938	F	86	515 D	13PIXN	9.8	PIMPSFP	ELGAREN	RORO	709	US 101 NORTH BEND-OR
10	0729NEW82	F	81	525 D	08GIXI	0.7	VINHRSP	NMS 1403	OIL	195	BERWICK/MORGAN US 90-LA
11	1623NEW83	F	83	525 D	08GIRQ	0.7	PERRJDG	PBR 358	OSV	178	BERWICK/MORGAN US 90-LA
12	MC85007133	F	85	530 N	02XIRO	944.0	PERRJDG	R 6317	BSLD	195	METROPOLIS IL-PI
13	0004LOU84	F	84	537 D	02XIRO	603.0	PIMPSCR	PORT OF MO	TOW	93	BIG 4 RAILROAD BRIDGE
14	0009LOU83	F	83	537 N	02XIRO	603.0	POPERER	CC 57	BSLD	195	BIG 4 RAILROAD BRIDGE
15	2659LOU81	F	81	537 D	02XIRO	603.0	POPERER	RL 1401	BSLD	195	BIG 4 RAILROAD BRIDGE
16	0144SLM82	F	82	546 D	02XIRU	309.2	POPERER	RUTH BRENT	TOW	103	MARK TWAIN MO US36/61
17	MC85007702	F	85	554 N	02XIRI	71.0	POPERER	USL 475	OIL	118	MEREDOSIA IL SR104-IL
18	MC86005626	F	86	554 N	02XIRI	71.0	POPERER	MSS 678	OIL	195	MEREDOSIA IL SR104-IL
19	0012SLM84	F	84	580 D	02XIRU	179.2	VFLDMOT	B 242	BSLD	195	POPLAR ST ST LOUIS
20	0020SLM83	F	83	580 N	02XIRU	179.0	PFALATR	MPC 70	UNK	195	POPLAR ST - MO ST LOUIS
21	0072SLM84	F	84	580 N	02XIRU	179.2	PERRJDG	BRENDA J	TOW	113	POPLAR ST ST LOUIS
22	0120SLM84	F	84	580 N	02XIRU	179.2		CC 7705B	BSLD	200	POPLAR ST ST LOUIS
23	0171SLM82	F	82	580 D	02XIRU	179.0	PFALACW	ARTHUR J D	TOW	117	POPLAR ST - MO ST LOUIS
24	0171SLM84	F	84	580 N	02XIRU	179.2	PERRJDG	CIA 170	BSLD	195	POPLAR ST ST LOUIS
25	MC84000220	F	84	580 D	02XIRU	179.0	PERRJDG	MEM 407 B	BSLD	200	POPLAR ST - MO ST LOUIS
26	0059NEW84	F	84	583 D	08GIRZ	37.5	PFALACW	AS 105	OIL	246	BAYOU SORREL SR 75-LA
27	MC87002079	F	86	585 D	09XIRMU	4.0	PLCKKNO	CYSTAL KIN	BSLD	521	NEWARK & BAYONNE NJ
28	0032PAD84	F	84	600 N	02XIRO	940.9	POPERER	ACBL 712	BSLD	200	I24-KY METROPOLIS IL
29	0120PAD83	F	83	600 N	02XIRO	941.0	PERRJDG	OR 4134	BSLD	195	METROPOLIS IL/KY I24

TABLE 4 ACCIDENTS IN TAPPAN ZEE CLASS BRIDGES, 1981–1986

Record#	CASE	TYPE	CY	HORZ	PERIODAY WATER	MILEPOST	CAUSE	VSLNAME	USE	LENGTH	BRIDGE NAME
1	MC85002672	F	85	900 D	02XIRL	838.9	PERRJDG	M 6621	BSLD	195	CARUTHERSVILLE I55-MO&TN
2	MC86006063	F	86	900 N	02XIRL	838.9	POPERER	BUNGE 56	BSLD	195	CARUTHERSVILLE I55-MO&TN
3	0013SLM84	F	84	940 T	02XIRU	180.2	PERRJDG	BILL HENRY	TOW	110	VERERANS MEM BR ST LOUIS
4	0014SLM84	F	84	940 D	02XIRU	180.2	PFALACW	USL 477	UNK	236	VERERANS MEM BR ST LOUIS
5	0047SLM82	F	82	940 D	02XIRU	180.0	PFALACW	GWG-207	OIL	264	VETERANS MEM IL US40/66
6	0071SLM84	F	84	940 D	02XIRU	180.2	PFALACW	MEM 392 L	UNK	195	VERERANS MEM BR ST LOUIS
7	0162SLM82	F	82	940 D	02XIRU	180.0	PFALACW	RUSTY FLOW	TOW	140	VETERANS MEM IL US40/66
8	0322SLM84	F	84	940 N	02XIRU	180.2	PERRJDG	ACBL 1840	BSLD	200	VERERANS MEM BR ST LOUIS
9	1696SLM81	F	81	940 N	02XIRU	180.0	PERRJDG	X-913	BSLD	195	VETERANS MEM IL US40/66
10	4513SLM81	F	81	940 N	02XIRU	180.0	POPERER	AT 191	BSLD	195	VETERANS MEM IL US40/66
11	0271SFC82	F	82	1000 D	12PIBS	0.2	POPERER	ORIENTAL H	BBLK	556	CARQUINEZ BRIDGE
12	3549NEW81	B	81	1000 D	08GIXI	3.1	PUNKNOW	JOSEPHINE	WORK	165	DANZIGER BR US 90-LA
13	0085SFC83	SUS	83	1079 D	12PIBS	8.9	PFALACW	SILETZ	UNK	198	BAY BRIDGE (D BAY)
14	2753NEW81	P	81	1250 D	08GIXN	478.5	PFALRUL	DUNCAN L H	TOW	132	PORT ALLEN CANAL SR77-LA
15	3520NEW81	B	81	1250 N	08GIXI	59.0	PERRJDG	USL 604	CHEM	236	BAYOU DULARGE BRIDGE
16	3522NEW81	SW	81	1260 N	08GIXI	134.0	PINATT	ARAPAHO	TOW	55	CYPREMORT(LOUISA)SR319LA
17	0769NEW83	SW	83	1290 D	08GIRQ	95.0	PIMPMOT	ING 581	BSLD	195	KROTZ SPRINGS LA-MP

2. The stem of the ship or the deck house hits a bridge column or other supporting structure above the pier top;
3. The stem of the ship, deck house, or cargo hits the superstructure of the bridge.

A list of 19 accidents that were cited in the study previously mentioned as being significant examples of major accident scenarios is presented in Table 5.

In addition, a major ship-bridge collision occurred in 1981 when the main tower of the 1,600–ft Newport suspension bridge in Rhode Island was struck head-on by a fully laden 45,000–ton tanker. The ship was shortened 12 ft through bow crushing, but the bridge pier suffered only superficial damage. The majority of these accidents were caused by a combination of environmental factors such as adverse weather conditions (resulting in reduced visibility or loss of control), followed by

TABLE 5 SHIP COLLISIONS AGAINST BRIDGES, 1960–1980

		Category of main cause/Impact
1960	OLD SEVERN RAILWAY, ENGLAND Ship: Two oil barges hooked up together Accident: Broadside collision with a pier Damage : Two spans fell down Cause: Tugskipper's negligence in rough weather	C/I
1963	SORSUND, NORWAY Ship: 5,000 DWT cargo boat Accident: Stem of ship hit the bridge columns above the foundations Damage: Bridge column broke Cause: Helmsman's faulty maneuver	A/II
1964	MARACAIBO, VENEZUELA Ship: 36,000 DWT tanker Accident: Broadside collision with two piers more than 2000 feet from the navigational spans Damage: Three spans fell down Cause: Failure of electrical system affecting steering gear	B/II
1964	PONTCHARTRAIN, LOUISIANA Ship: Tug towing two barges Accident: Three trestles were hit by the tug and barges Damage: Two spans fell down Cause: Helmsman's lack of attention	A/I
1967	CHESAPEAKE, VIRGINIA Ship: Coal barge Accident: Battering against the bridge deck Damage: Six spans damaged Cause: Barge torn loose in storm	C/III
1970	CHESAPEAKE, VIRGINIA Ship: 14,000 t.disp. US-navy ship Accident: 1-1/2 hours battering against the bridge Damage: Five spans knocked down and 11 others damaged Cause: Ship torn loose in the storm	C/III
1972	CHESAPEAKE, VIRGINIA Ship: Empty barge Accident: Gouging the deck and knocking down several piles Damage: Five spans damaged Cause: Towline from tug snapped in rough weather	C/III
1972	SIDNEY LANIER, GEORGIA Ship: 13,000 DWT freighter Accident: The superstructure was hit by the bow of the ship Damage: Three spans fell down Cause: The helmsman misunderstood the pilot's instructions	A/III

(continued on next page)

1974	PONTCHARTRAIN, LOUISIANA Ship: Tug pulling four empty barges Accident: Two supports destroyed (high piling) Damage: Three spans fell down Cause: The tug pilot fell asleep	A/I
1975	NEW WESTMINSTER, CANADA Ship: Empty barge Accident: Hit the superstructure Damage: One span fell down Cause: Barge torn loose in the storm	C/III
1975	TASMAN, AUSTRALIA Ship: 7,200 DWT bulk carrier Accident: Head-on and broadside collision with two piers Damage: Three spans fell down Cause: Loss of steering ability due to engine stop (Captain's careless navigation)	A/I
1976	PASS MANHAC, LOUISIANA Ship: Barge loaded with oyster shells Accident: An intermediate support destroyed (high piling) Damage: Three spans fell down Cause: Strong current (tug skipper's responsibility)	A/I
1977	PASSAIC, NEW JERSEY Ship: Empty oil/barge Accident: Collision with a pier Damage: Two spans fell down Cause: Broken towline to tug	C/I
1977	HOPEWELL, VIRGINIA Ship: 25,000 DWT tanker Accident: The stem of the ship destroyed a pier bent about 400 feet from the navigational span centreline Damage: Two spans fell down Cause: Fault in steering gear	B/II
1977	SAN FRANCISCO-OAKLAND, CALIFORNIA Ship: Barge-mounted marine crane towed by tug Accident: The crane hit the superstructure in side span Damage: Structural damage to the superstructure Cause: Tug skipper's careless navigation	A/III
1978	BERWICK BAY, LOUISIANA Ship: Tug pushing four barges Accident: The lead barge hit the side span bridge superstructure Damage: The 232-foot steel span fell into the water and sank Cause: Tug skipper's careless navigation	A/III
1979	VANCOUVER, CANADA Ship: 22,000 DWT bulk carrier Accident: Stem of ship hit the superstructure in side span about 300 feet from navigational span center Damage: One span fell down Cause: Captain's misjudgment of landmarks due to dense fog	C/II
1980	SUNSHINE SKYWAY, FLORIDA Ship: 35,000 DWT bulk carrier Accident:Stem of Ship hit bridge column above pier top about 800 feet from navigational channel Damage: Almost three spans fell down Cause: Pilot's careless navigation in rough weather with reduced visibility	C/II

TABLE 5 (*continued*)

1980	ALMOSUND, SWEDEN Ship: 27,000 DWT Accident: Deck house of ship hit the arch construction near the foundation on shore about 300 feet from the navigation channel Damage: Total collapse of arch span Cause: Steering difficulties in rough weather due to reduced engine power in dense fog	C/II

Note:
- A Human Error
- B Mechanical Failure
- C Environmental Conditions
- I Hull of ship hits bridge pier
- II Stem of ship or deck house hits bridge column
- III Stem of ship, deck house, or cargo hit superstructure

Source: COWIconsult, "Ship Collision Risk Assessment," Sept. 1981

human errors in judgment in conjunction with mechanical failures. These factors result in varying degrees of vessel aberrancy. Vessels then run aground or are involved in collisions or rammings. For example, in a river of high traffic density or reduced visibility caused by foul weather, a vessel may enter the domain of another vessel, increasing the probability of panic maneuvers, so that a vessel, in trying to avoid another, may collide with a bridge pier.

Other factors that contribute to the probability of occurrence of a ship-bridge accident include the geometry of the waterway, its depth, the location of bridge piers, span clearances, angle of rudder at time of failure, and the size, width, length, draft, shape, and velocity of vessels. In addition, daytime and nighttime conditions, reduced visibility, and poor navigational aids affect vessel navigation. It is, however, the draft of a ship that determines whether it runs aground or reaches the bridge if it deviates off course from the navigational channel; that is, becomes aberrant. A ship in ballast has a variable draft determined by the master of the ship according to many factors. These include weather conditions, air draft constraints, depth of the waterway, and duration of the journey. The faster a ship in ballast travels, the more stable it is. However, its impact in a collision increases when moving at greater speeds. Fully loaded ships have drafts that are dictated by the load line rules. Such information on the vessel can be found in *Lloyd's Register of Ships* (*3*). The rate of aberrancy has been reported to be two to three times greater for barges than that measured for ships on the same waterway.

ENVIRONMENTAL RISK FACTORS: Castleton-on-Hudson and Tappan Zee Bridges

The environmental risk parameters affecting the Tappan Zee and Castleton-on-Hudson Bridges are examined in the following section.

Geometrical Conditions

The Tappan Zee Bridge is located at milepost 23.5 on the Hudson River and crosses from South Nyack to Tarrytown. Its fixed main span has a horizontal clearance of 1,098 ft and a vertical clearance of 139 ft at mean high water. There are three navigational channels designated for passing beneath the bridge. The controlling depth is approximately 32 ft. Ships generally use only the center channel, whereas barges may also travel the east and west passes.

The Tappan Zee Bridge is about 3 mi long, with 188 bents located in the river. There are three types of foundations used to support the bents. The locations along the bridge of the different kinds of foundations are shown in Figure 1. The western portion of the bridge is made up of rigid-frame reinforced concrete bents on timber piles. The bents are spaced 50 ft apart. The pile caps are typically 91 ft long and 4 ft deep, ranging in width from 11 to 19 ft. At the north end of each pile cap there is an ice breaker structure, and on the south is a pile cluster. Along the eastern portion and a section about midriver west of the navigational channels, the bridge is supported on 12 bents that have two pier shafts, each supported on a solid circular concrete footing with steel H-piles.

Across the three navigational channels and at four bents to the west, the bridge is supported by eight floating caissons on piles. Cylinder piles are used under the caissons supporting the 1,200-ft main span. H-piles were used for the two 500-ft flanking spans and the four caissons to the west spaced 250 ft apart. At the upriver side there are ice breakers. A fendering system encompasses the rest of the structure.

The Castleton-on-Hudson Bridge is located at milepost 135.7 on the Hudson River. It has a fixed main span with a horizontal clearance of 552 ft and a vertical clearance of 135 ft at mean high water. There is one navigational channel designated for passing beneath the bridge. Controlling depth of the channel is also about 32 ft. A location plan is shown in Figure 2.

At Castleton-on-Hudson only two of the 42 bridge piers are located in the Hudson River. One of the piers is in shallow water near the east side and the other is near the middle of the river. The midriver pier, along with another pier located at the west shoreline 600 ft away, supports the main span across the 360–ft channel. The foundations for these bridge piers are massive concrete placed down to rock. About 350 ft downriver there is a railroad bridge. The bridge piers of

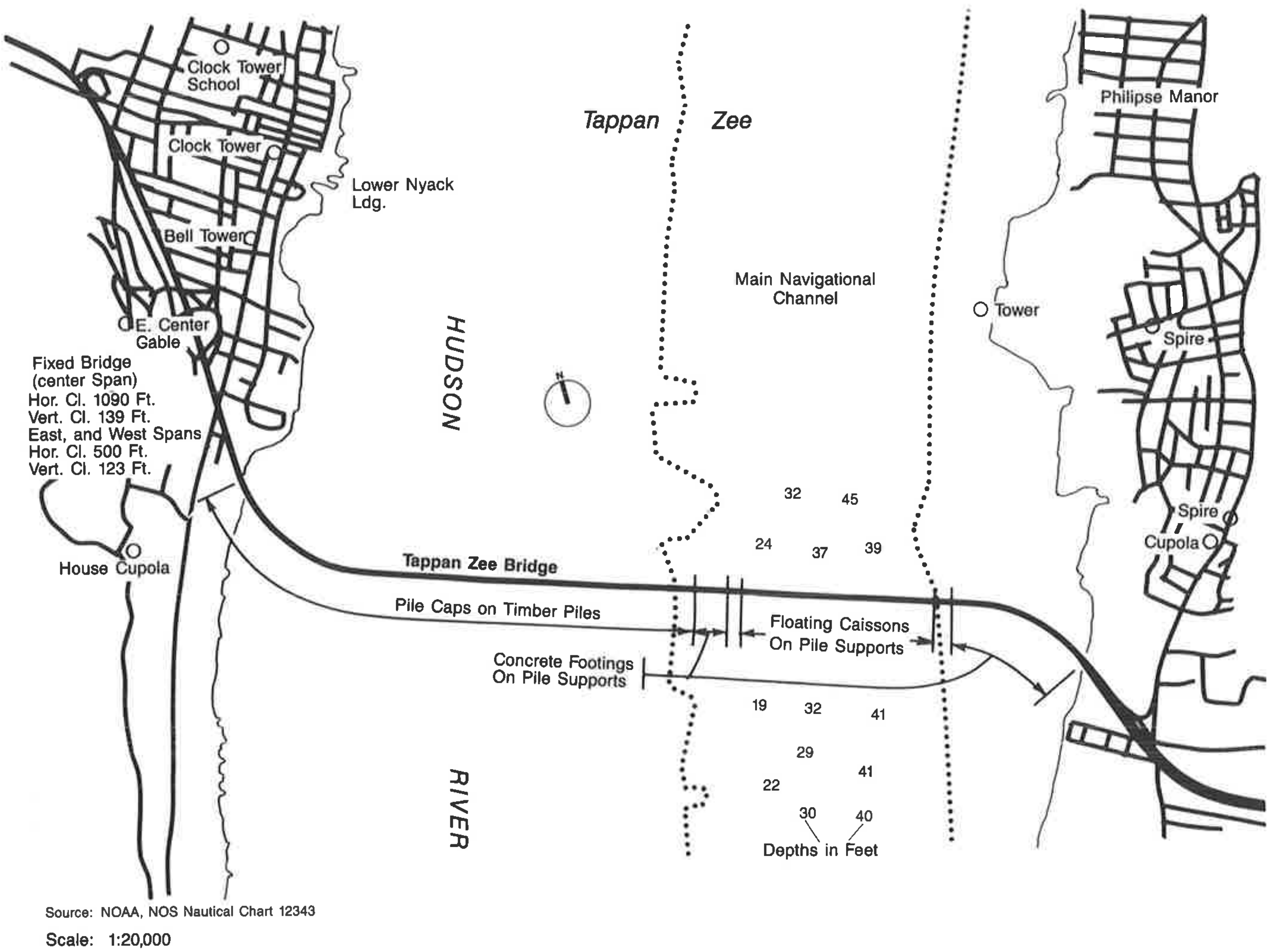


FIGURE 1 Tappan Zee Bridge location plan.

the railroad bridge are similar in size and position within the river.

Thus the foundations of the two bridges are significantly different. The Castleton-on-Hudson Bridge has a stronger type of foundation, whereas the Tappan Zee Bridge's foundation is more vulnerable.

Navigational Conditions

The following information on navigational conditions comes from the *U.S. Coast Pilot*, Vol. 1 (*6*):

> Navigation along the Hudson as far north as Kingston is easy; above Kingston numerous steep-to shoals and middle grounds make navigation trickier. Tides in the Hudson River are affected by freshets, winds, and droughts. The mean range of tide is 4.5 ft at The Battery, 3.7 ft at Yonkers, 2.8 ft at Newburgh, 3.1 ft at Poughkeepsie, 3.7 ft at Kingston, 4.6 ft at Albany, and 4.7 ft at Troy. The velocities of currents are 1.4 knots flood and 1.4 knots ebb northwest of The Battery, 1.6 and 2.2 knots at the George Washington Bridge, 0.9 and 1.1 knots at Newburgh, 1.1 and 1.2 knots at Poughkeepsie, 1.3 and 1.6 knots at Kingston, and 0.3 knot flood and 0.8 knot ebb at Albany. In even extremely severe winters, Coast Guard icebreakers and continuous river traffic maintain an open channel to Albany. The ice season usually starts in early January and ends in mid-March.
>
> Normally shipping is affected most seriously in the Hudson River between Tappan Zee and Albany. Modern vessels experience little difficulty maneuvering through the ice, but may be slowed by other river traffic. In addition to the problem of getting through the ice, aids to navigation are covered or dragged off station by moving ice.

According to comments by the Hudson River Pilots Association (HRPA), navigation at the Castleton is considered more difficult than it is at the Tappan Zee because ships must maneuver to begin the turn just north of the bridge. Also the channel is narrower at Castleton. HRPA noted that none of the bridges crossing the river has radar reflectors or radar markers, the use of which could be helpful during times of reduced visibility.

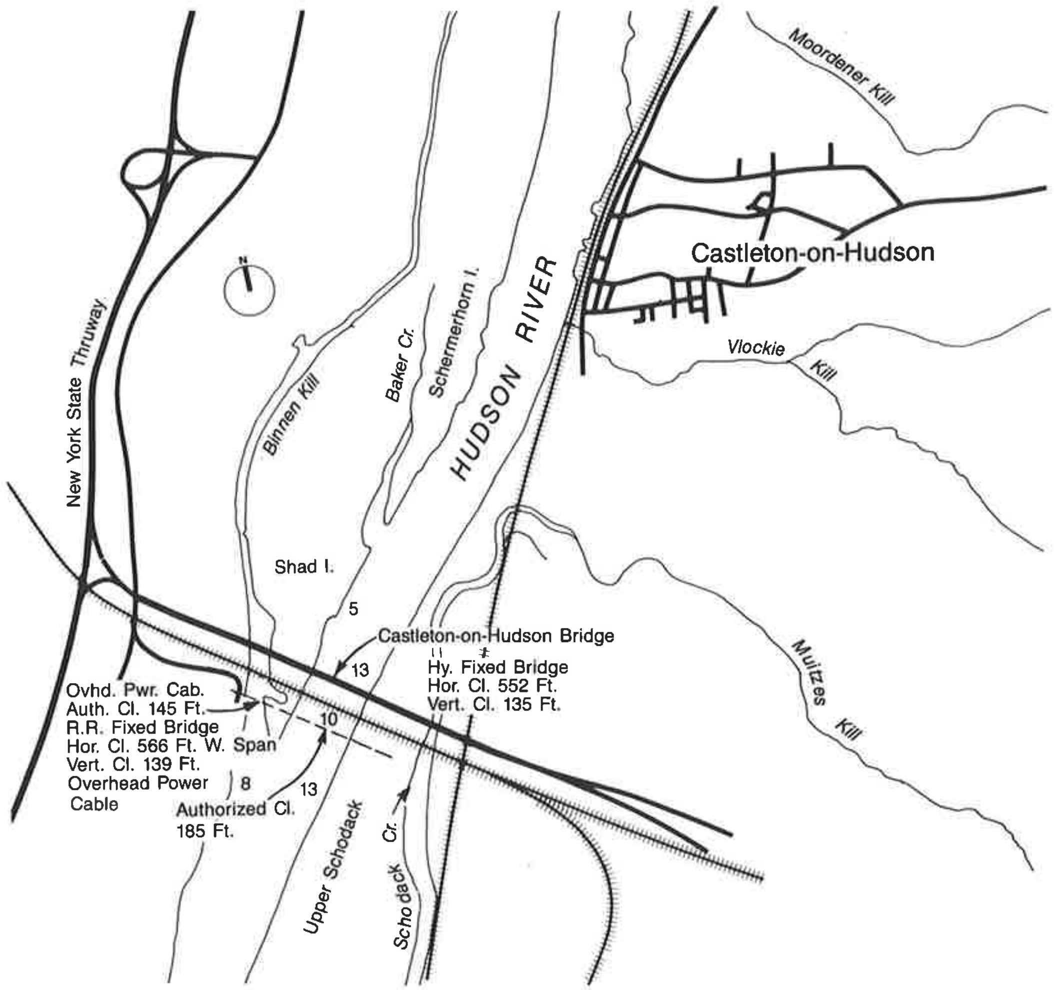


FIGURE 2 Castleton-on-Hudson Bridge location plan.

Weather Conditions

The following information on weather conditions is obtained from USACE, the Port of Albany, and ports on the Hudson River, New York 1984 (*7*).

> The climate at Albany and the lower Hudson River Valley is primarily continental in character, but is subject to some modification from the maritime climate which prevails in the extreme southeastern portion of New York State. The moderating effect on temperatures is more pronounced during the warmer months than in the cold winter season when outbursts of cold air sweep down from Canada with greater vigor than at other times of the year. In the warmer portion of the year temperatures rise rapidly during the daytime to moderate levels. As a rule, temperatures fall rapidly after sunset so that the nights are relatively cool.
>
> Winters are usually cold and occasionally fairly severe. Maximum temperatures during the colder winter months often are below freezing, and nighttime low temperatures frequently drop to 10 degrees or lower. Sub-zero temperatures occur rather infrequently, about a dozen times a year. Snowfall in the area is quite variable and over some of the higher nearby areas ranges up to 75 inches or more for a season. Snow flurries are quite frequent during the cold months.
>
> Precipitation is sufficient to serve the economy of the region in most years, and only occasionally do periods of drought become a threat. A considerable portion of the rainfall in the warmer months is from showers associated with thunderstorms, but hail is not usually of any consequence.
>
> On the whole, wind velocities are moderate. The north-south Hudson River Valley has had a marked effect on the lighter winds, and the warm months usually average out as a south wind. Destructive winds occur infrequently.
>
> The area enjoys one of the highest percentages of sunshine that can be found in the State. This is true of the Hudson Valley area from Albany southward to the coast with slightly more sunshine progressively southward. Seldom does the area experience extended periods of cloudy days or extended periods of smog. Occasionally during the warm months there are short periods when high humidity associated with temperatures above 85 degrees is rather uncomfortable. Tornadoes are rather rare in the Albany area; six have been reported since 1826. The days of heavy fog average twenty-three a year.

Although climate and currents do not seem to offer any major obstacles to navigation, the occasional fog or storm resulting in reduced visibility has, at least in part, brought about an accident and an oil spill on the Hudson at the Tappan Zee. In addition, the HRPA indicated that transverse winds from the west can sometimes cause difficulty with navigation around Tappan Zee. Weather conditions are continuously reported on radio by the National Oceanic and Atmospheric Administration for the upper and lower Hudson areas.

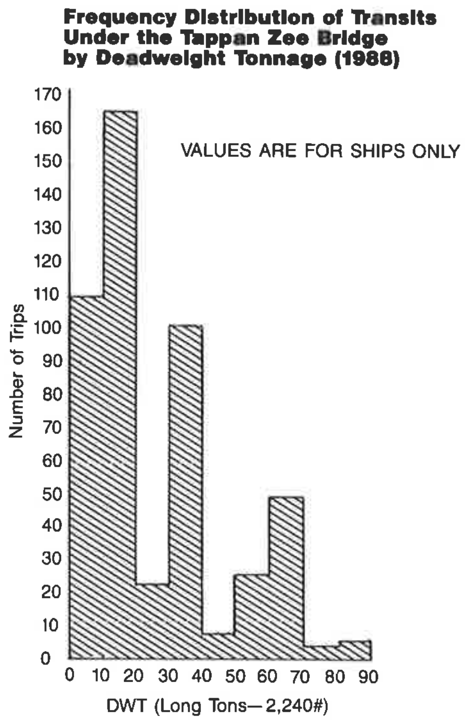
Vessel Types and Traffic Load

Piloted ships and barges propelled by tugs are the two basic types of maritime traffic navigating the Hudson River. Data on ship movements obtained from the Maritime Association of the Port of New York and New Jersey indicate that about 125 ships travel annually upriver under the Tappan Zee Bridge to call at ports along the Hudson. Approximately 100 of these ships travel to the Port of Albany, passing also beneath the Castleton-on-Hudson Bridge.

Many of the ships that are listed make more than one call at a particular port along the river during the year. In 1988, almost half of the ships returned within the calendar year on several occasions, and one bulk carrier was recorded as having made 18 trips. A review of the information on stopovers shows that the vessels travel to a single destination on the river. As ships do not exit via the canal system, each call on a river port generally represents two transits (upriver and downriver) beneath any bridge passed. The vessels travel at speeds ranging from 8 to 12 knots.

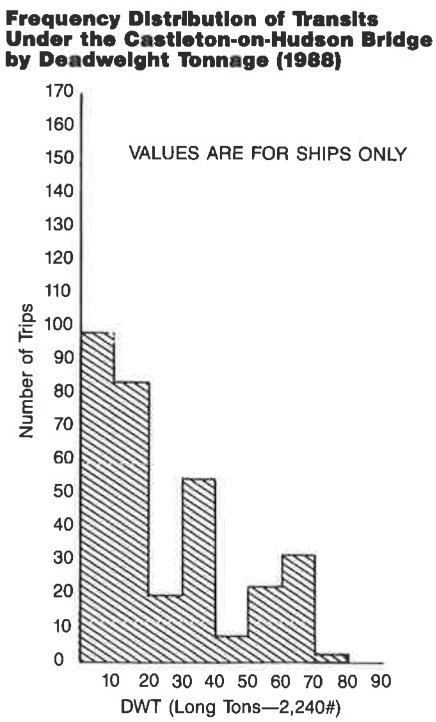
According to the Maritime Association of the Port of New York and New Jersey, about 328 and 488 total ship transits were made in 1988 by ships passing the Castleton-on-Hudson and Tappan Zee Bridges, respectively. These numbers represent the relative exposure of the bridges to potential ship collisions. The deadweight tonnage frequency distribution in Figure 3 shows that many of the ships are in the 50,000 to 70,000 tonnage range, or are less than 20,000 tons. Tankers are the heaviest vessels that transit the Hudson.

The Towboat and Harbor Carriers Association of New York and New Jersey has identified more than 30 companies that offer towing or barge services, or both, for the Hudson River.



Range	Trips
0<10	108
10<20	164
20<30	22
30<40	100
40<50	8
50<60	26
60<70	50
70<80	4
80<90	6
Total	488

Source:
Maritime Association of the Port of New York and New Jersey



Range	Trips
0<10	100
10<20	86
20<30	20
30<40	58
40<50	8
50<60	22
60<70	32
70<80	2
80<90	—
Total	328

Source:
Maritime Association of the Port of New York and New Jersey

FIGURE 3 Frequency distribution of transits.

Unlike ships, which are subject to compulsory pilotage, barge movements are not routinely monitored by a central agency. General information on barge traffic and operation on the Hudson was obtained primarily through telephone interviews. The U.S. Army Corps of Engineers' statistics on waterborne commerce in the United States are a limited source of assumptions on barge traffic information. The HRPA and the barge operators confirmed a ratio of 1 to 8 for traffic volume between ships and barges on the Hudson River, indicating total vessel transits of 3,000 annually. However, the USACE's *Waterborne Commerce of the United States* (*1*) indicates an estimated average annual total number of transits of 4,500 on the Hudson River.

For the purposes of this study, barges were categorized as either oil or traprock types. Tank (oil) barges are used to deliver oil to terminals on the Hudson River as far north as Albany. These barges vary in size from 9,000 to 25,000 DWT (approximately 25,000- to 70,000-barrel capacity). The drafts of these barges when loaded range from 10 to 30 ft. Tank barges are generally pushed one at a time at speeds of 6 to 9 knots. Barges do not require pilots under the Compulsory Pilotage Regulation, as there is an exclusion for barges below a gross weight tonnage of 10,000 GWT (about 180,000-barrel capacity). As shown in Table 6, all barge traffic on the Hudson River does not require pilots.

There are two barge operators on the river dealing in traprock. Unlike oil barges, sand and rock barges do not vary in size or capacity. They generally have a 1,200–ton capacity. Loaded barges are moved downstream in fleets of 8 to 15 barges/trip at about 5 knots. Empty barges are brought upriver in a similar fashion at approximately 8 knots. The quarries are located south of Castleton; consequently, only the Tappan Zee Bridge is subject to such traffic. These barge operations are seasonal and take place from April through December. Earlier trips in the spring are contingent on temperature and ice conditions. Each barge flotilla makes an average of five trips downstream per week.

Vessel Impact Force

Although the size of vessels navigating the Hudson is limited by the depth of the channel, it should be noted that the larger the vessel (in terms of its weight) and the faster it sails, the greater the collision impact. For example, a vessel of 5,000 DWT traveling at a design speed of 16 knots can produce an impact force of about 7,100 tons based on the method of estimation by Woisin and Gerlach (*8*). Most of the ships traveling on the Hudson have design speeds in excess of 15 knots. A vessel of 40,000 DWT traveling at a speed of 12 knots can

TABLE 6 TYPICAL BARGE SIZES ON HUDSON RIVER

OIL BARGES

Dimensions (Feet)	Capacity/Approx. DWT (Barrels/Long Tons)
240x43x14	20,000 / 3,500
330x39x15.5	30,000 / 5,700
330x56x21.5	57,000 / 10,300
300x64x21.5	60,000 / 11,700
320x64x23	68,000 / 13,400
230x52x24	41,000 / 8,200
295x45x16	25,000 / 6,000
316x60x24	65,000 / 13,000
302x90x24	85,000 / 17,000
316x60x24	70,000 / 13,000
446x74x30	140,000 / 28,000

Average DWT = 11,800 Tons

SAND & STONE BARGES

Dimensions (Feet)	Approx. DWT (Long Tons)	
120x40x12	1,100	
130x40x12	1,200	
130x36x18	1,300	(1500 Max)

Average DWT = 1,200 Tons

Source: Telephone Interviews with Local Marine Transporters result in a collision impact of 12,000 tons. Impacts can vary from a mere glancing of the piers to a full head-on collision, with their energy increasing exponentially with ship speed. Ships in light ballast are considered the most dangerous vessels under these circumstances. Having considerable impact force, they are a danger to bridge piers, and because they also float high in the water are equally a danger to the bridge superstructure. Small vessels and barges generally travel at slower speeds. Wind affects empty barges particularly, impairing their directional stability. Barges, being the most weakly constructed vessels, have significantly lower impact forces than most other vessels. The kinetic energy of a ship is a function of its effective mass and the velocity at which it travels. In a collision, this energy is absorbed through the crushing of the ship and the deformation and displacement of the pier, the pier fenders (if they exist), and then the water resistance. If a ship strikes a pier at an angle, a considerable amount of the energy is dissipated through the rotation and displacement of the ship off its original course. In a head-on collision, the ship's center of gravity is not shifted and maximum impact is encountered by either the ship or the pier. (The exact prediction of deformational consequences is extremely complex and beyond the scope of this paper.) Bridge pier strengths vary greatly among bridges and even among piers of the same bridge. The latter case is illustrated by the various types of foundations used to support the numerous spans of the Tappan Zee Bridge.

To redesign a bridge pier to increase its ability to withstand such vessel impact forces would be prohibitively expensive. Hence, reasonable protective systems should be provided while accepting a certain level of risk. (There are several categories of risk: owner's, bridge user's, and third party. Third party risk refers to the risk to ships and persons on ships caused by collision with a bridge.) The next section presents the assessment by this study of the levels of risk that each of the two bridges faces.

RISK ASSESSMENT

The results of the data search and analysis are presented in Table 7. The accuracy of these numbers is directly related to the accuracy of the available data. The estimated average annual vessel transits per class of bridges was based on traffic activity for self-propelled vessels at each reach of the related river (*1*). The estimated annual Hudson River vessel transits per bridge are given for Tappan Zee and Castleton-on-Hudson bridges as adjusted values, taking into account traffic information received from the USACE Waterborne Commerce Statistics Center, the Maritime Association of the Port of New York and New Jersey, and the Hudson River Pilots Association.

The return periods were calculated to be 55 years and 268 years, respectively, for the Tappan Zee and Castleton-on-Hudson Bridges. For example, in the Tappan Zee class, there are 41 bridges ranging from 900 to 1,300 ft in horizontal clearance in the United States. Within this class of bridges, there were 17 ship-bridge accidents from 1981 to 1986, inclusive. The total number of vessel transits beneath all 41 bridges from 1981 to 1986 was 4,222,920. Therefore, the accident rate (PC) was $17/4,222,920 = 0.000004$. This is the probability or chance that any one vessel that transits beneath a bridge in the Tappan Zee class has an accident at the bridge. Because the estimated annual number of vessel transits on the Hudson that pass beneath the Tappan Zee Bridge is $N = 4,500$, the annual probability or chance of an accident occurring at the Tappan Zee Bridge or ($N \times$ PC) is 0.0181. Recalling the first equation, the return period is then 55 years. It should be noted that the estimated annual transits may overstate the actual number of transits, as that reflects traffic on a reach; thus the return periods may be lower. The Tappan Zee has a higher risk of an accident, and both of the return periods are small compared with the Scandinavian risk-acceptance standard of 10,000 years. The orders of magnitude indicate

TABLE 7 RESULTS OF STUDY DATA SEARCH AND ANALYSIS

Period of study: 1981-1986	Castleton-on-Hudson	Tappan Zee
Horizontal Clearances	552 feet	1098 feet
Class of Horizontal spans	500-600 feet	900-1300 feet
Number of Bridges in Class	98	41
Number of Accidents per Class	29	17
Estimated Average Annual Vessel Transits per Class	1,947,236	703,820
Estimated Total Vessel Transits per Class	11,683,416	4,222,920
Estimated Annual Hudson River Vessel Transits per Bridge	1,500	4,500
Probability of Occurrence of Vessel Accidents	0.0037	0.0181
Return period for Vessels	268 years	55 years

Source: Parsons Brinckerhoff

the possibility of ship-bridge accidents at these two bridges and warn of the dangers that could occur in the event of such an accident on the Hudson.

Although the Tappan Zee Bridge crosses a straight part of the Hudson, its exposure to collisions by maritime vessels is enhanced by the increased length and number of piers required by the width of the river. The major or catastrophic events following impacts by a large vessel are of concern in the case of the occurrence of the following situations:

Scenario 1: A ship striking a floating caisson-type foundation, breaching the watertight buoyancy chambers.

Scenario 2: A ship striking either the superstructure or the pier shaft supports for the span.

Under the present conditions, the floating caissons on pile supports lack adequate protection from the large vessels. Hudson River traffic data indicate that a large majority of the vessels have hull designs that include bulbous bows. Although the mass concrete ice-breaker structure at the north of the caisson might deflect an aberrant vessel, the pile clusters and fendering system do not have sufficient energy-absorbing capacity or strength to prevent impact. In the event of damage to the caisson, the caisson may lose its buoyancy and overstress the pile supports, causing catastrophic failure of the bridge. The threat of such severe damage exists for large ships in ballast as well as ships fully loaded because the caissons are located in the deeper waters within the navigational channel.

Another problem with collisions by the heavier vessels with the caissons arises because the buoyant structure cannot develop sufficient frictional forces along its base at the river bottom and there are no batter piles to transfer lateral loads. Large horizontal loads might cause lateral displacements affecting the integrity of the superstructure. Hence, some of the larger oil tanker barges could disrupt the deep-water foundations.

A ship accident as described in Scenario 2 can happen almost anywhere along the length of the bridge. As shown in Figure 1, minimum water depths along the alignment at mean low water are generally better than 6 ft. Because mean high water is about 3 ft more, aberrant vessels with drafts up to 9 ft would collide with most places along the bridge. A typical vessel in the 16,000 DOT class transiting in ballast has a minimum draft of about 9 ft. However, to avoid air draft problems with the bridges, the larger vessels take on substantial ballast. According to the Hudson River Pilots Association, the ballasted vessels have bow drafts of 10 to 15 ft and stem drafts ranging 20 to 28 ft.

Unlike the Tappan Zee, the Castleton-on-Hudson Bridge does not have extensive physical exposure. Besides crossing a narrower stretch of river, the bridge piers are shielded on the downstream side by the supports of the adjacent railroad bridge.

The span over the entire crossing at the Castleton-on-Hudson Bridge remains high, providing a vertical clearance of 135 ft, and therefore an aberrant vessel primarily represents a threat only for collisions with the substructure. Considering the massiveness of the footings founded on rock, it appears that the smaller vessels might cause damage but would not cause catastrophic failures. The fendering system for the mid-river pier is suitable for dealing with smaller vessels should there be a mishap. The maximum depth of water around the piers varies from about 10 to 21 ft. Larger vessels traveling light or in ballast could stray from the channel and reach the bridge piers. It is these vessels that are a concern for risk and would require protective structures at the Castleton-on-Hudson Bridge.

It should be noted that the risk of oil spills resulting from vessel-bridge collisions is always there, whether a bridge pier or structure is damaged or not.

CONCLUSION

In conclusion, this study has found that the vessel traffic density is fairly low on the Hudson River and that navigational conditions are generally good. The climate and river currents do not pose any serious obstacles to safe navigation.

Risk of a ship-bridge collision at the Tappan Zee and Castleton Bridges on the Hudson River were analyzed in this study. The return period for the Tappan Zee Bridge was 55 years. The return period for the Castleton-on-Hudson Bridge was 268 years. The results serve merely as indicators for precautionary measures. As indicated in the section on risk assessment in this paper, the disasters that could occur at the Tappan Zee Bridge in particular would result in significant consequences. For example, damage to any of the hollow caissons of the main piers would lead to the probable collapse of the pier and, consequently, to the superstructure. The other smaller piers of the Tappan Zee Bridge are also highly vulnerable to relatively large aberrant vessels in light ballast, as the water depths allow for their passage without running aground. Given the relatively small return periods for the Tappan Zee Bridge, it is recommended in this study that further studies be undertaken to find appropriate measures to reduce the risk and severity of a ship-bridge collision. One of the piers of the Castleton-on-Hudson Bridge is particularly vulnerable, although it is relatively sturdy in comparison to the main piers of the Tappan Zee Bridge. It requires protection against large vessels. It is noted that 85 percent of all ship-bridge accidents in the United States between 1981 and 1986 resulted from pilot navigational error. It is recommended that preventive measures such as improved navigational aids be considered in addition to structural solutions.

ACKNOWLEDGMENTS

The permission of the New York State Thruway Authority to present and publish this paper is gratefully appreciated. The authors acknowledge the kind assistance provided by the Marine Safety Evaluation Branch of the U.S. Coast Guard and particularly thank T.W. Purtell and Thomas Pettin, together with William C. Heming of the First Coast Guard District Office, and Joyce McIlroy, Marine Intelligence, Maritime Association of the Port of New York. The authors wish to personally thank Waisum Alain To for his help with the data base system, and David Atkin, Jim Brown, Tom Kuesel, and Mike Abrahams for their frank and timely reviews of the text of the paper.

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Publication of this paper sponsored by Committee on Ports and Waterways.

Supplemental Freight on Ferries: Case Study of Operations and Cost Comparisons

JOHN G. SCHOON, PETER G. FURTH, AND ROBERT C. LIEB

Presented in this paper is a case study conducted in the Boston, Massachusetts, area that describes existing and required operational features of potential supplemental freight scenarios associated with passenger ferries. A basic, approximate comparison of economic costs associated with each scenario is presented to assist in developing more detailed marketing and demand analyses and possible implementation of a pilot project. Despite technological advances in waterborne transportation and, in many cases, a considerable passenger demand for ferry travel, provision of services frequently needs to be subsidized by public agencies so that fares remain competitive with alternative modes. In Boston, recently inaugurated shuttle and commuter passenger ferry services are currently meeting a significant portion of their operating costs, and other important transportation system advantages are evident in terms of modal diversity. However, in order to augment farebox revenues and reduce passenger fare subsidies, other sources of revenue are being investigated. Supplemental freight items that can be carried aboard regular passenger ferries so that passenger service is not disrupted or made less attractive are seen as a possible means of obtaining this additional revenue.

The potential for passenger ferry services in a number of metropolitan areas of the United States appears to be growing as congestion of land-based transportation increases. Yet, despite technological advances in waterborne transportation and, in many cases, a considerable passenger demand for ferry travel, provision of services frequently needs to be subsidized by public agencies so that fares remain competitive with alternative modes. In Boston, Massachusetts, recently inaugurated shuttle and commuter passenger ferry services are currently meeting a significant portion of their operating costs, and other important transportation system advantages are evident in terms of modal diversity.

However, in order to augment fare box revenues and reduce passenger fare subsidies, other sources of revenue are being investigated. Supplemental freight items that can be carried aboard regular passenger ferries in such a way that passenger service is not disrupted or made less attractive are seen as a possible means of obtaining this additional revenue.

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OVERVIEW OF EXISTING FERRY AND TRANSPORTATION CHARACTERISTICS

Passenger Ferry Services in the Boston and South Shore Areas

Extensive interest in passenger ferry services in the Boston Harbor area and South Shore communities has given added impetus to provision of commuter, shuttle, and excursion services, and cruises and charters (*1–8* and various internal studies, Massachusetts Port Authority, Boston, 1970–1985). Key features of the area and route locations are shown in Figures 1 and 2. The inner harbor is connected with the South Shore communities by services operating from either Rowes Wharf or Long Wharf in Boston to Hingham, Hull, and Quincy, south of the city. These services operate predominantly during the peak periods on weekdays, with travel lengths of up to approximately 10 mi, travel times of approximately 40 min, and 30-min headways. The ferries used on the Boston-Logan Airport shuttle are typically 20-seat vessels of 40-ft length, and those on the South Shore commuter routes have a capacity of more than 150 passengers and may be more than 100 ft long.

Of the two scheduled shuttle services within the inner harbor, the Boston-Logan Airport service has been very successful and carried more than 350,000 passengers in 1986. This service operates at a 15-min headway during daylight hours year-round. A private service operates to and from the World Trade Center and Long Wharf. A service has recently been inaugurated between Boston and Charlestown (Pier 4) during peak hours. Four round trips are made in the a.m. peak period and three in the p.m. peak period.

Other ferry services include private ferries used by contractors for the transfer of personnel, materials, and equipment associated with construction projects. These ferry services are not included in this study because they would not typically be associated with supplemental freight transport.

In terms of future development, various agencies, including those of the Commonwealth of Massachusetts and the City of Boston, are promoting ferry services within the inner harbor area, particularly as a means of alleviating current traffic congestion and improving access and environmental conditions. Although many of these plans are tentative, approximately 15 additional sites are under consideration.

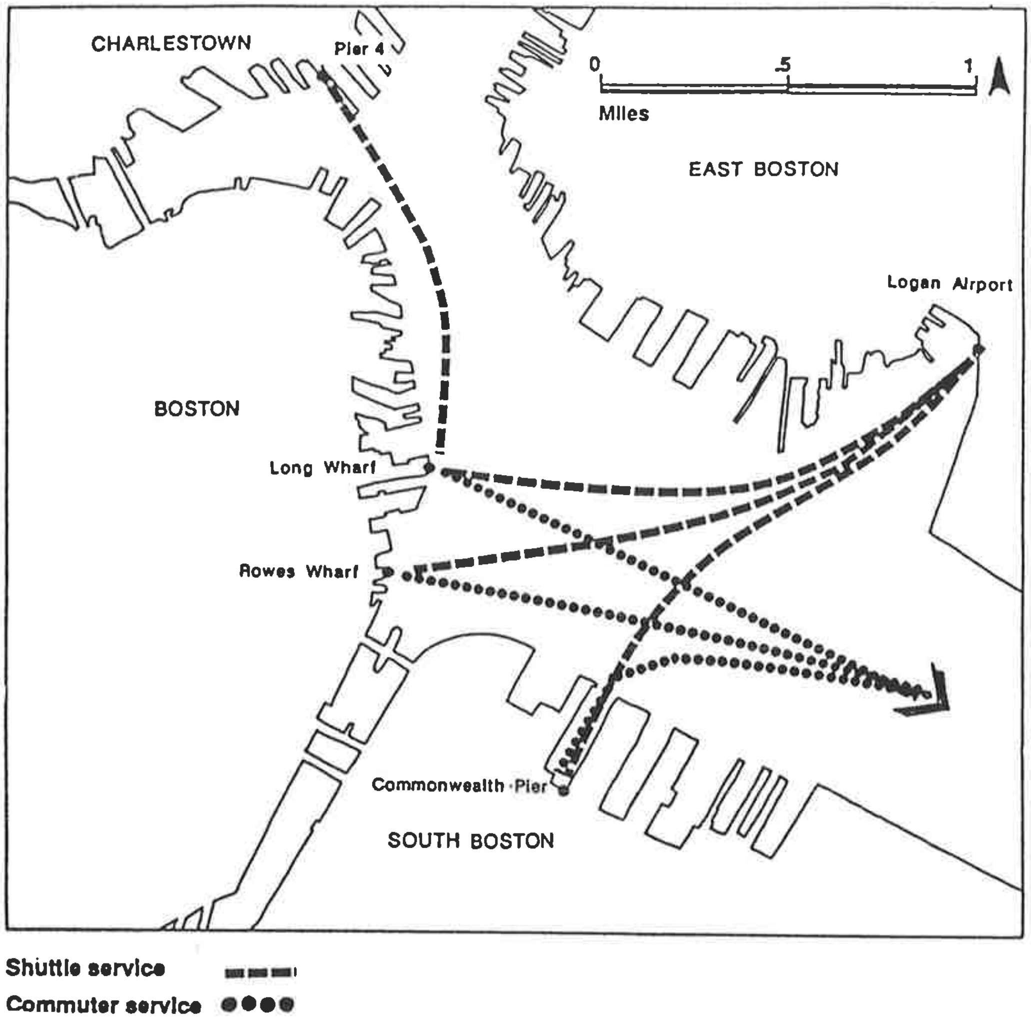


FIGURE 1 Existing Inner Harbor ferry routes (9).

Waterborne Facilities: Screening

Essentially, the type of freight would consist predominantly of packages weighing up to about 20 to 30 lb and capable of being carried by one person. Screening of the ferry services was conducted to concentrate the investigations on the ferry service and competing facilities that are relevant to carrying this type of supplemental freight.

Accordingly, a number of criteria were developed and applied in a three-stage screening process.

Initial Screening by Type of Ferry Services

The major categories of ferry services were identified as follows:

1. Commuter service: Operates between downtown Boston and suburban localities.
2. Shuttle service: Terminal locations predominantly within Boston's inner harbor. May include on-demand (taxi) service between mainland terminals.
3. Excursion services: Predominantly recreational trips, including fixed-schedule trips between the harbor islands and other places of interest such as the USS *Constitution*.
4. Cruises and charters: Primarily specialty trips, including dinner and concert trips as well as recreational trips such as whale watches and trips to Provincetown and Gloucester.

The criteria considered important in this initial screening were:

1. Physical facilities. These must be suitable for carrying light freight. Unless the wharf and vessel characteristics appear to be suitable for transporting freight of the kind described earlier, or appear to be fairly readily adaptable to this purpose, the service would not be a candidate for further investigation at this stage.
2. Year-round service. If only seasonal service were offered, the disruption, rescheduling, and lack of continuity would be unacceptable for consistent supplemental freight transportation.
3. Schedule. Scheduled operation—or the potential for it—should be evident, otherwise the logistics of carrying supplemental freight, and possible gaps in the service, are likely to result in unsatisfactory operating service.
4. Time and cost advantages. Unless a clear time or cost advantage over land transportation is evident from the use of waterborne transportation, it is unlikely that the freight services will be acceptable.

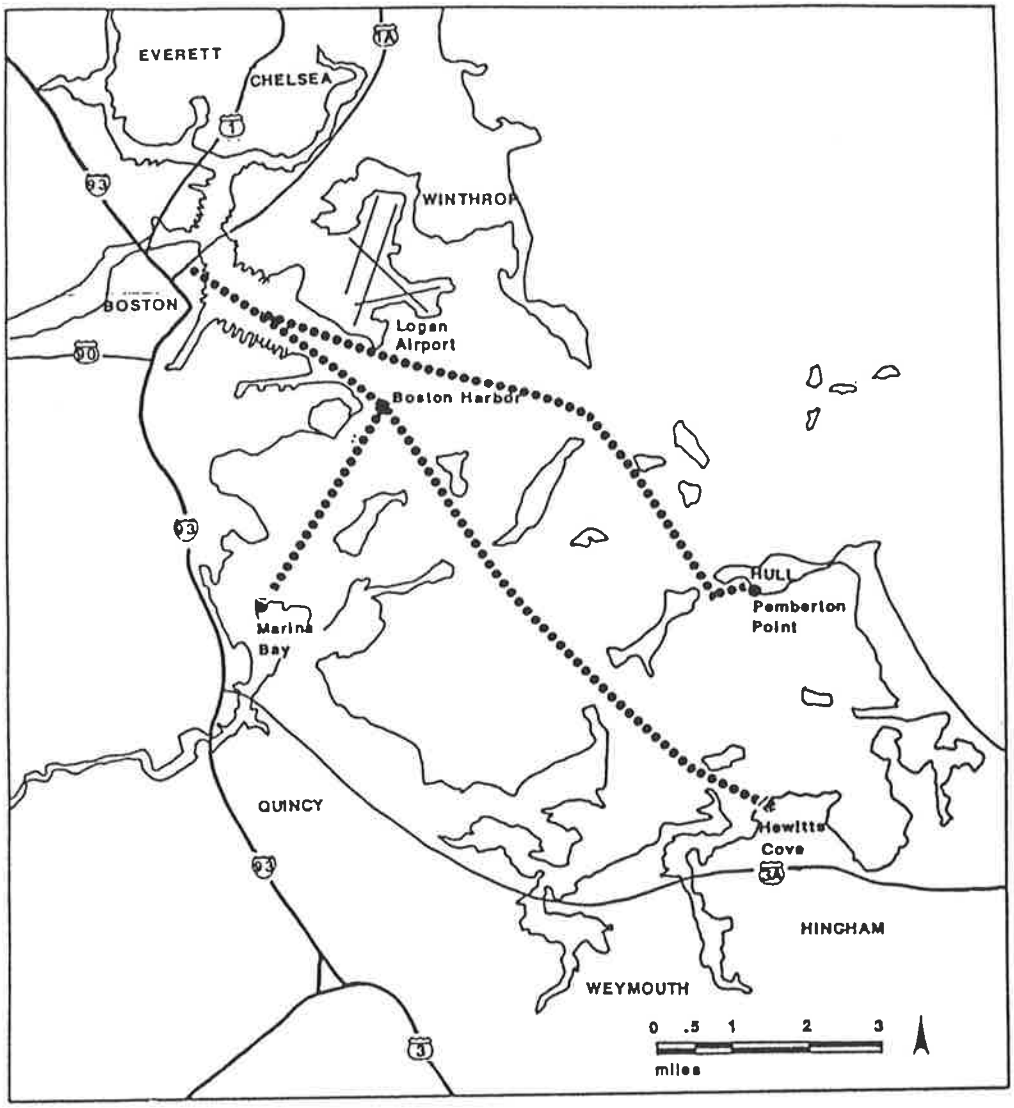


FIGURE 2 Existing commuter ferry routes (*9*).

The results of this initial screening were to include only commuter transportation and shuttle-taxi services in the inventory and ensuing analysis.

Second Screening of Existing Ferry Services

The commuter and shuttle services were next examined for their specific physical and operating characteristics, including

1. Terminal locations,
2. Schedule,
3. Land access, and
4. Approximate travel time advantage over land routes,

Most services offer frequent travel during the peak periods. Only the Boston airport shuttle, however, offers full service throughout the day. Land access in general is adequate but some improvements may be needed in several instances (see later evaluations of specific land terminals). In most cases the travel times by ferry appear to be within the same approximate range as those for corresponding land routes, based on approximate evaluation of existing modal options. More detailed travel time and cost studies for alternative modes are described later in this paper.

Final Screening

Two services were eliminated from further consideration because of uncertain future service and a varied schedule of the service for private commercial activities. As a result of the final screening, the following services were considered in the subsequent analysis for the case study:

1. Boston-Hingham (Hewitts Cove),
2. Boston-Hull (Pemberton Point),
3. Boston-Quincy,

4. Boston-Logan Airport, and
5. Boston-Charlestown (Pier 4).

Categories of Freight Examined in This Study

The package freight movements throughout the study area are differentiated by a wide array of service options for customers. A review of these options and the associated charges provides a major basis, together with considerations of future development, for identifying and structuring a service within which passenger ferries might play a useful and financially feasible role.

Freight Service Categories

Several categories of potential freight of the type described earlier in this paper are of interest in ferry freight operations in the Boston Harbor area: package delivery ("for hire" carriers), private goods transportation, and air cargo. The main points concerning their selection for consideration in this study are discussed as follows.

Package Delivery

Several types of package delivery are offered by commercial operators. Their main features are

- Overnight package delivery. This service offers "next day" delivery for packages of a size similar to those in the "same day" category. In some cases, however, packages may be deposited in each firm's pick-up boxes, using the appropriate package and labeling supplied by the firm. The United States Post Office and private firms handle a considerable volume of this type of package transportation. Another feature of this kind of service is that the predominant movement of the packages is to and from other cities by dedicated aircraft, thus necessitating a local destination (for purposes of this study) to be Logan Airport.
- Same-day package delivery or courier service. Packages are typically picked up and delivered by means of one or a combination of modes, which include pedestrian, bicycle, van, taxi, subway, or bus. The packages are usually of a size that can be easily transported by one person, and range in size from letters to small boxes averaging 20 to 30 lb, which can be moved by means of a small handcart if necessary. This form of package service operates throughout the Boston area.

Because of the physical characteristics of the packages and the fact that the delivery routes coincide with current and future possible ferry routes (discussed in more detail later in this paper), this type of service is of considerable interest in this study.

Private Freight Carriage

Many firms carry their own freight in and around the Boston area and conduct their own pickup and delivery service between a variety of origins and destinations. Typically, these organizations use a van or truck, and the origins and destinations tend to be fairly constant as a result of providing service to a large proportion of established customers. Often, the use of the firm's own vehicles and labor force ensures that the firm has continuous control over the movements of the goods and that their shipping costs are minimized. Examples of the kind of goods shipped include small boxes of high unit-cost such as seafood being shipped by air package services, and small machinery and electronic equipment for air shipment and for local customers.

Although the characteristics of the current freight movements being made by private carriers appear to have some disadvantages from the point of view of control over the shipment, the potential for using ferries for a certain portion of the trip may be possible, and this type of movement is considered to have the potential for supplemental ferry freight services.

Air Cargo

A considerable amount of air cargo originates in and is destined for the Boston area. However, it is considered that the potential for ferries participating in portions of the total air cargo movement (except for the overnight service already mentioned) would be insignificant. The main reasons for this are that

- Individual items of freight would be of a size and weight that would render handling without the use of special equipment difficult and time-consuming. This could have an adverse effect on ferry schedules, with resulting lower levels of service to passengers and consequent reductions in fare revenues.
- Time differential between land and ferry routes is not as important as it is with the time-sensitive delivery of packages for same day or express mail services mentioned previously.

Types of Freight Not Included

Because the focus of this paper is on supplemental freight only, it does not include consideration of large items of freight that may require special loading equipment or roll-on, roll-off operations. These activities are likely to interfere with frequent, timely passenger service.

Summary

From these considerations of the various types of freight, the most appropriate services suitable for detailed investigation are

- Same-day delivery services in which a time or cost advantage over the equivalent land route can be demonstrated.
- Certain segments of the overnight package delivery service in which time and cost are competitive with equivalent land routes.
- Private delivery of freight in which cost and control factors are advantageous.

Transportation Elements: Route Evaluations

The suitability of the existing ground and waterborne transportation facilities for supplemental freight movement was examined in this inventory to identify existing conditions and provide a guide for identifying improvements. To do this, each of the selected routes was observed from the place of origin of the freight through to its destination, including all land- and water-based transportation elements. Many of the main features that were considered are illustrated conceptually in Figure 3.

Road Access

The characteristics of the street and highway access to and from the vicinity of the wharf area are important because of the effects on travel times, costs, and convenience. In general, the name, functional classification, number of lanes, availability of curb parking, and an indication of traffic volumes and speeds were noted for off-peak and peak travel periods.

Vehicle Loading and Unloading Facilities

For the freight to be loaded or unloaded from a van or other vehicle, adequate parking or waiting areas must be available for periods of up to 15 min or longer. A possible means of carrying small freight items is by use of bicycle courier services using the ferries. To facilitate this, areas for temporary storage of bicycles at the wharf, or facilities for carrying bicycles on the ferries, or both, would be required. The observations addressed parking regulations, potential availability of spaces, parking rates, and other factors that might affect the ease and safety of vehicle parking and waiting.

Access Between Parking and Wharf

For the freight to be either carried manually or transported on a handcart between the parking areas and the wharf, adequate facilities suitable for pedestrian movement must be available. In some cases, it is possible to bring the van or other delivery vehicle to the wharf where freight can be loaded

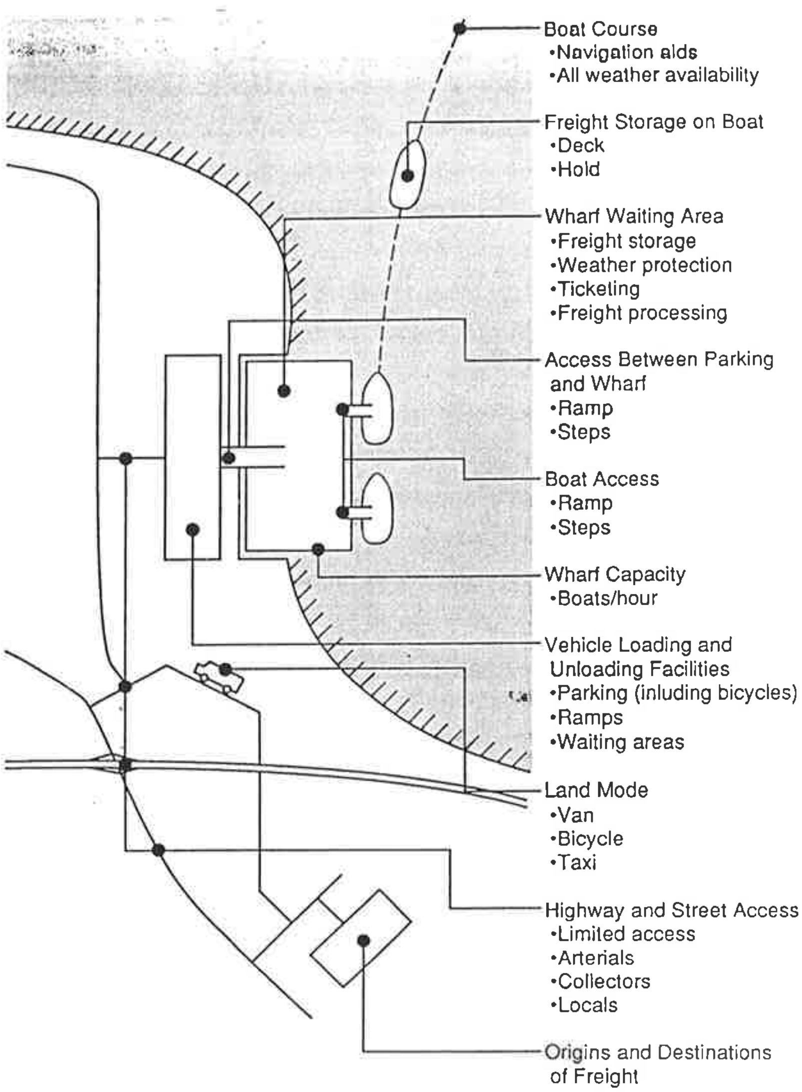


FIGURE 3 Key factors in supplemental freight route feasibility analysis: generic diagram (*9*).

or unloaded directly. However, this situation is infrequent. It appears more likely that small packages will be delivered by hand or by using a handcart, implying the need for a ramp with suitable grades, adequate widths, and other features that permit easy movement along this segment of the total trip.

Wharf Waiting Area

In most cases, goods must be delivered to the wharf to make use of ferry services with minimal delay. Thus, some form of storage or waiting area is useful. This area may range in extent from 2yd^2 to 3yd^2 to larger areas, depending on the expected freight traffic. Also noted, in addition to a description of the available space, were the presence and type of protection from inclement weather for the courier, handler, and the freight itself. Also, that some form of security should be provided if the freight is left unattended for any length of time.

Ticketing or Check-In Facilities

Unless some form of prior payment is employed, such as a contract for a specific number of trips or freight items, payment and checking of the freight at the embarkation point may be necessary. The extent of ticketing available was noted for each of the inventoried routes.

Wharf-to-Ship Movement

Moving the freight between the surface of the wharf and the deck of the vessel may be achieved in several ways. Some form of ramp may be available or, as was sometimes evident, several steps may be used to make up the difference between the levels between the wharf and the deck. Difficulties in carrying out this maneuver with various kinds of freight or handcarts may be an important source of delay or may cause safety problems. Therefore, an indication of the currently available method was included as part of the evaluation.

Shipboard Facility for Freight

Once the freight is aboard the vessel, there must be adequate space for its storage during the trip. In many cases, only limited space is available on passenger ferries, and this must sometimes be shared with passengers or crew. In the evaluation, an indication was given of the amount of deck space available, together with any other obvious problems in using it.

In general, because no unusual problems such as depth and navigation were apparent with the waterborne segments of the services selected in earlier screening, they are not discussed further in this overview.

Results of Wharf and Related Land Access Inventory

The following comments summarize the relevant findings for all but the Logan Airport wharf:

- Road access and parking/waiting areas range from moderately good and accessible to instances such as that at Rowes and Long wharfs where access and parking are likely to be adversely affected by peak-hour traffic and restricted parking areas.
- Access between parking/waiting areas and the wharf almost always requires negotiation of a ramp, the grade of which may be excessive during low tides. Also, ramps often have a step at one end, making movement of a handcart difficult.
- Wharf waiting areas are in general not protected from weather, which presents serious disadvantages during rain, snow, and icy conditions, particularly when these result in slippery, unsafe surfaces.
- Ticketing, except at Long Wharf and for some cases at Hingham, is conducted aboard the ferry. A ticket booth is used at Long Wharf. This procedure may have to be further examined because of possible delays during busy periods.
- Boarding and alighting between the boat and the wharf surface are accomplished largely by means of one or two steps and sometimes by use of a short ramp. This could cause delays, especially if a handcart is used for transporting the freight.
- Most of the boats currently used on passenger ferry service have no special area for freight carrying. Usually, however, there is sufficient space on deck for a limited amount of freight, and additional space may be available during periods of light passenger traffic.

At the Logan Airport wharf, most of the waiting areas for vehicles are adequate; a passenger shelter is provided at the parking/shuttle stop; ramps to the wharf are approximately 4 ft wide, although the grades may be excessive during low tides; treads on the ramps appear to give good traction; and the waiting area on the wharf is covered but not enclosed.

CHARACTERISTICS OF CURRENT (1988) FREIGHT MOVEMENT

Transportation of current land mode freight that could be a candidate for supplemental freight aboard ferries is affected by various factors. These include travel times, costs, reliability, and availability of the modal elements involved in the total trip, as well as the shipper's control over the security and level of service offered to customers. Outlined in this section are some of the major characteristics of existing freight movement in the Boston area, including routes, charges, and modal combinations, to assist in the formulation and evaluation of the scenarios described later in this paper.

Market Characteristics of Freight Services

Within the categories of freight described above, the existing route structure and service characteristics reflect the demand, prices, infrastructure, and modal options that may be assumed to be the most efficient available under current conditions. To explore further the nature of the services offered, a comparison was made for selected origin and destination pairs of the modal elements involved and the associated prices. This provided a useful basis for comparison with the future service scenarios.

Current Service Characteristics

Six major origin and destination pairs were selected as being representative of the current and likely future needs, based on their observed existing activity or future potential. These are

- Boston-Airport
- Boston-Inner Harbor
- Boston-South Shore
- Airport-South Shore
- Airport-Inner Harbor
- Inner Harbor-South Shore

For each of the service categories (same day, overnight, and private), the modes considered included pedestrian, bicycle, automobile, bus, subway, and ferry. It is assumed that any movement within Logan Airport that relies on ferry or subway will also include use of the internal airport shuttle buses or vans.

The service characteristics are summarized in Table 1 and Figure 4. The usual mode is the van or truck, with a significant involvement of pedestrian couriers in the downtown-airport-inner harbor area. Charges to customers for these deliveries range from approximately $3 for areas within the downtown and inner harbor areas to $28 for an individual package transported between the South Shore and the airport. It should be noted that overnight charges (express mail) of $14 include the cost of delivering a package nationwide but also apply if the package is being delivered locally, and that discounts for certain types and quantities of mail may reduce the customer's cost to about 65 percent of the basic charge. Some of these characteristics are discussed briefly in the following section.

Several features often distinguish the types of freight service, and have been mentioned as part of the preceding profiles. They include

- Price to customer. A regular rate for occasional customers may be charged or discount rates may be offered to regular customers or for higher volumes of freight shipped. Charges will also vary depending on the items described later in this paper.
- Time for delivery. These features may include same day, rush, overnight, or guaranteed time delivery.
- Type of collection and delivery. The shipping firm may pick up the package at the customer's premises or the customer may deliver the package to a collection box or to offices of the shipping firm.
- Security. Special security precautions may be taken with valuable freight, together with appropriate insurance arrangements if necessary.

In addition to these considerations, which apply directly to customer options, a delivery firm itself will adapt its opera-

TABLE 1 CHARACTERISTICS OF SELECTED CURRENT (1988) FREIGHT MOVEMENT OF POTENTIAL INTEREST AS SUPPLEMENTAL FREIGHT (*9*)

ORIGIN (2) DESTINATION	TYPE OF SERVICE	USUAL LOCAL TRANSPORTATION ELEMENTS								EXAMPLES OF CHARGES TO SENDER (4)
		Pede-strian	Bic-ycle	Auto	Van Truck	Taxi	Bus	Sub-way	Ferry (5)	
Boston - Airport	Same-day	●		○	●	●		●	○	$10.00 Delivered to airline package office
	Overnight				●					$14.00 regular charge
	Private (3)			○	●	○		○	○	Cost is part of sender's operations
Boston - Inner harbor area	Same-day	●	●	○	●	●		○		$6.00 - $10.00, approximately
	Overnight				●					$14.00 regular charge
	Private (3)			○	●	○			○	Cost is part of sender's operations
Boston - South shore	Same-day	○		○	●	○		○	○	$20.00 - $24.00, approximately
	Overnight				●					$14.00 regular charge
	Private (3)			○	●	○			○	Cost is part of sender's operations
Airport - South shore	Same-day			○	●	○				$24.00 - $28.00, approximately
	Overnight				●					$14.00 regular charge
	Private (3)			○	●	○			○	Cost is part of sender's operations
Airport - Inner harbor area	Same-day	●		○	●	○		●	○	$10.00 - $13.00, approximately
	Overnight				●					$14.00 regular charge
	Private (3)			○	●	○				Cost is part of sender's operations
Inner Harbor - South shore	Same-day	○		○	●	○		○	○	$20.00 - $24.00, approximately
	Overnight				●					$14.00 regular charge
	Private (3)			○	●	○				Cost is part of sender's operations

Key: ● Frequent use ○ Occasional use

Source : Discussions with courier and express mail firms in the Boston area

1) Freight included in this table includes letters, small packages and items of a size and weight suitable for possible transportation as supplemental freight on ferries.

2) "Boston" refers to downtown, Rowes, Long Wharf area; "Inner harbor" refers to other parts of the Boston, Charlestown, Revere, South and East Boston areas; "South Shore" refers to points south of approximately Dorchester Bay.

3) "Private" means transportation provided by the sender's own organization. Costs are not detailed because of their wide variation due to freight volume variations and joint use of equipment and personnel.

4) Discounts for volume and customer service agreements may reduce these charges to as little as approximately 65% of the of the charges stated here.

5) This service is often based upon verbal understandings between the sender, ferry operator and receiver. Usually, the sender transports the goods to the ferry terminal and the pick-up is made by the recipient. Charges may typically be the cost of one passenger fare.

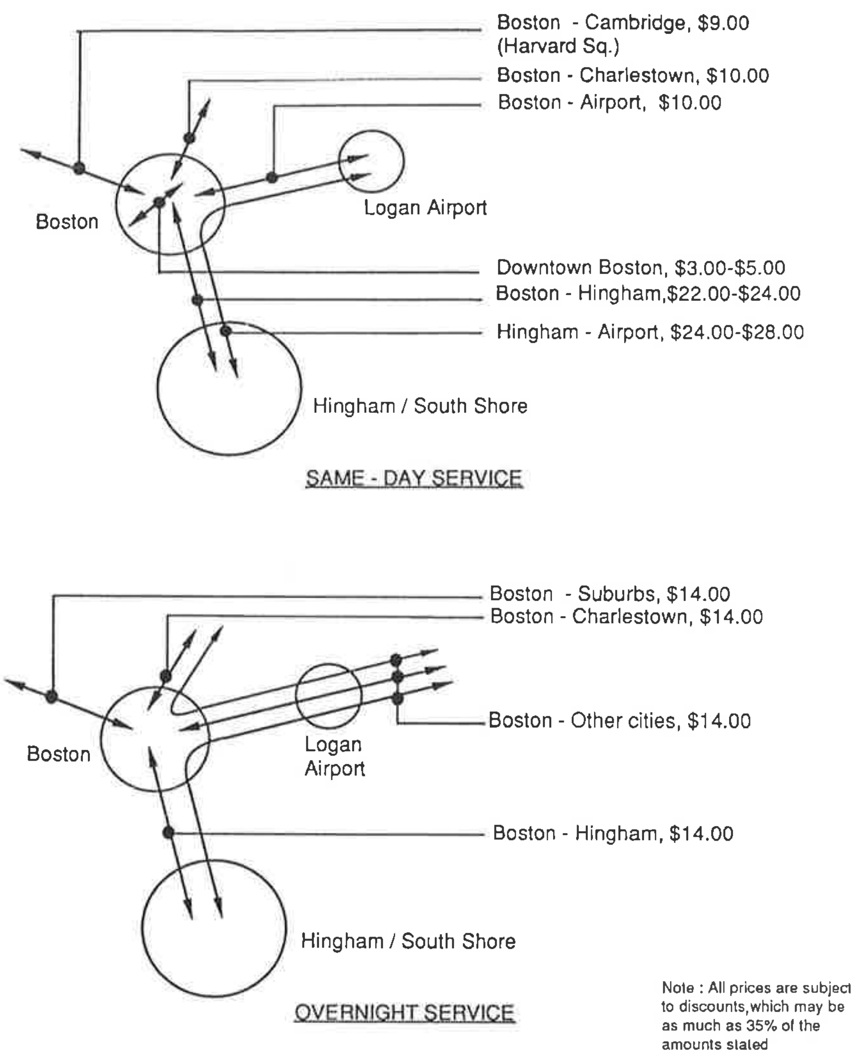


FIGURE 4 Examples of package delivery prices in the Boston area (9).

tions to the transportation environment. A typical example is one in which several firms that handle overnight mail ensure that most of their movements avoid peak-hour traffic congestion.

Travel Time and Cost Considerations

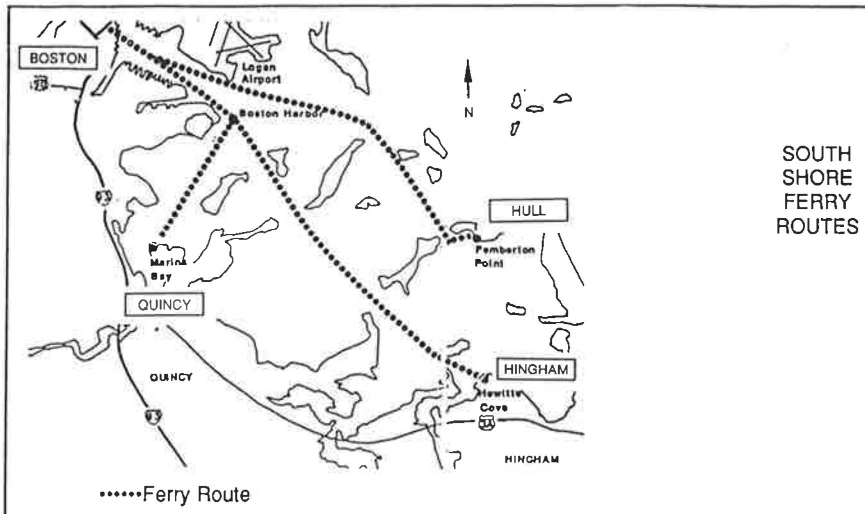
Two primary determinants of the feasibility of providing ferry freight services, in terms of the competitiveness with land-based facilities, are travel time and cost. Unless these factors combined can be shown to be superior to land-based services, it is unlikely that any significant demand for ferry freight services can be expected. Although the other features of the service are important, it is usually the case that these less-crucial determinants can be accommodated within certain limits once the essential determinants are established.

In examining the existing conditions, therefore, the major emphasis was placed on the travel time and cost characteristics associated with current ferry transportation in and around the Boston Harbor area. The times are examined here in greater detail to identify the elements of importance in structuring potential ferry services, together with comparative costs.

Example of Travel Time and Cost Comparison: Boston-South Shore

These routes are between Boston and Hingham, Hull and Quincy. The comparison of routes was made between ferry and automobile, the latter being representative of van and bus service, as shown in Figure 5. For the ferry trip, an automobile element (also representative of a van) was included at both ends of the trip to simulate the fact that packages typically would originate at some point other than the ferry terminal itself. All of the runs took place during the morning peak-traffic period, experience having shown that approximately the same total travel times obtained during the afternoon peak.

The results of these observations indicate that for each of the origin-destination pairs, the use of the automobile resulted in the least overall travel time. The greatest time difference resulted for the Hingham route, for which the ferry time of 73 min contrasted with the 48 min by automobile. The Hingham route is the longest of the three. For the Quincy route—the shortest—the difference was smaller: 44 min by ferry versus 29 min by automobile. From Hull, the ferry distance is about the same as that from Hingham, whereas the land distance is



Major Mode(s)	Observed Travel Times (minutes) by Trip Element (6)					**Total one-way fares ($) (5)**
	Walk (3)	Wait	Ferry	Auto	**Total**	
Hingham (2) - Boston (1) (4)						
Ferry	9.0	1.0	56.0	7.0	73.0	3.00
Auto	---	---	---	48.0	48.0	---
Hull (2) - Boston (1) (4)						
Ferry	12.0	2.0	45.0	8.0	67.0	2.50
Auto	---	---	---	52.0	52.0	---
Marina Bay (Quincy) (2) - Boston (1) (4)						
Ferry	13.0	1.0	17.0	13.0	44.0	4.50
Auto	---	---	---	29.0	29.0	---

Notes:
1) Boston destination is the intersection of Federal and Franklin Streets.
2) •Hingham origin is the intersection of Main and South Streets.
•Hull origin is the intersection of Nantasket Avenue and Kenberra Street.
•Quincy origin is the intersection of Sea Street and Southern Artery (Rte. #A).
3) Walking time at Boston destination only is about 6 - 8 minutes.
4) Rowes Wharf is used for the Hingham ferry terminal in Boston, Long Wharf for the Hull and Quincy ferries.
5) Fares are based upon one-way, regular adult fare.
6) Travel times shown above are the result of a single run, and should not be considered to be average values. Each run was made during the AM peak traffic period, inbound to Boston.

FIGURE 5 Travel time and fare comparisons, South Shore communities to downtown Boston (1988) (*9*).

longer. The quicker Quincy trip is caused in part by a shorter distance and also by the use of a smaller and much faster boat that is possible because its route is better protected than the Hingham and Hull routes.

Summary of Findings

The results of the these observations show that nowhere in the existing transportation system in the Boston area is ferry transportation a superior mode (in terms of travel time and cost) to normal day-to-day land-based operations, and would be unlikely to offer any appreciable advantages in direct route competition with the available land modes. In considering the use of ferries for transporting supplemental freight, however, several points are pertinent to future possibilities; these include the following:

- It is possible that, for a limited number of origins and destinations in close proximity to a ferry terminal, the ferry may be superior.
- Some types of freight movement are not time sensitive within a range of several hours, and ferry service may be advantageous where the cost of transportation may be reduced for these types of freight.
- Future changes in the frequency, speed, and routing of a ferry may render the service more attractive.
- If land-based transportation becomes excessively congested or disrupted, ferry services may be appropriate.

Future Ferry Services

Although tentative at present, several proposals have been made for improvements to the existing ferry services. From the standpoint of supplemental freight transportation, these are important for the following reasons:

1. Ferry operations would continue throughout the day between the South Shore and Boston, thus offering the possibility of reduced travel costs over land-based vehicle transportation.
2. Direct, all-day service between the South Shore and the airport would be inaugurated, thus reducing peak hour and daytime travel times between these points over that required by land vehicles, and introducing possible cost savings.

POTENTIAL FERRY FREIGHT SCENARIOS AND ECONOMIC ANALYSIS

Outlined in this section, using the information about current and future freight transportation discussed earlier, are the relative merits of supplemental freight services that would be competitive with land-based services. Also included is a description of an initial economic analysis to estimate likely cost savings of using ferry transportation.

Identification of Candidate Freight Services

Examination of existing and improved ferry services indicates that reductions in travel time and identification of cases for which travel time may not be crucial between certain limits for the various origins and destinations may assist the feasibility of carrying supplemental freight. Furthermore, because of the potential improvements in ferry service and terminals, it is probable that some cost reductions in freight movement may be made by using ferries instead of land-based modes in selected cases. The routes on which potential savings exist, based on the travel time and approximate cost analyses, are summarized in Table 2. Key points are presented as follows to identify specific origin/destination pairs for more detailed examination.

Boston-Airport

Although future plans describe more frequent ferry service between Boston and the airport, it is unlikely that significant time or cost savings may be expected. For example, for the downtown Boston-Airport route, the Blue Line subway connection was shown to be faster and much less expensive than the airport shuttle operation. Similarly, a future ferry connection between North Station and the airport would not be expected to be significantly faster than that of the Green and Blue Line subway connection, and plans for the former do not yet include tentative schedules.

However, for certain kinds of priority or "rush" services, this route may have some potential, but is not considered further here.

TABLE 2 POTENTIAL SAVINGS OVER CURRENT (1988) FREIGHT CHARGES FOR SPECIFIC ORIGIN-DESTINATIONS (*9*)

ORIGIN (2) DESTINATION	TYPE OF SERVICE	EXAMPLES OF CHARGES TO SENDER[4]	POTENTIAL SAVINGS RESULTING FROM IMPROVED FERRY SERVICE
Boston - Airport	Same-day	$10.00 Delivered to airline package office	No significant savings - land routes better, except for special or priority service
	Overnight	$14.00 regular charge	
	Private [3]	Cost is part of sender's operations	
Boston - Inner harbor area	Same-day	$6.00 - $10.00, approximately	Some possible savings due to more frequent service
	Overnight	$14.00 regular charge	
	Private [3]	Cost is part of sender's operations	
Boston - South shore	Same-day	$20.00 - $24.00, approximately	Some possible savings due to more frequent service
	Overnight	$14.00 regular charge	
	Private [3]	Cost is part of sender's operations	
Airport - South shore	Same-day	$24.00 - $28.00, approximately	Good possibility of savings due to considerable reduction in travel time
	Overnight	$14.00 regular charge	
	Private [3]	Cost is part of sender's operations	
Airport - Inner harbor area	Same-day	$10.00 - $13.00, approximately	Some possible savings due to new routes and more frequent service
	Overnight	$14.00 regular charge	
	Private [3]	Cost is part of sender's operations	
Inner Harbor - South shore	Same-day	$20.00 - $24.00, approximately	Same as for Boston - South Shore
	Overnight	$14.00 regular charge	
	Private [3]	Cost is part of sender's operations	

1) Freight included in this table includes letters, small packages and items of a size and weight suitable for possible transportation as supplemental freight on ferries.

2) "Boston" refers to downtown, Rowes, Long Wharf area; "Inner harbor" refers to other parts of the Boston, Charlestown, Revere, South and East Boston areas; "South shore" refers to points south of approximately Dorchester Bay.

3) "Private" means transportation provided by the sender's own organization. Costs are not detailed because of their wide variation due to freight volume variations and joint use of equipment and personnel.

4) See Table 2.1.

5) This service is often based upon verbal understandings betwen the sender, ferry operator and receiver. Typically, the sender transports the goods to the ferry terminal and the pick-up is made by the recipient.

Boston-Inner Harbor Area

The inner harbor area appears to have the potential for increased ferry shuttle and water taxi service. However, several points should be noted:

1. All-day passenger demand is not extensive at present and, accordingly, ferry schedules also reflect mostly peak-hour trips.
2. Use of the existing ferry services for transporting small items of freight during the day with only minimal passenger patronage is unlikely to cover the costs of operating most of the current ferry vessels.
3. The extent of future land use development and associated passenger and freight demand is difficult to estimate. However, with such development and the expansion of water taxi service, using smaller, less expensive vessels for shorter runs in the more congested Inner Harbor area, the implementation of all-day (or "on demand") service may well be financially feasible, and the passenger and supplemental freight services may be complementary.

For these reasons, it is suggested that potential options for Inner Harbor supplemental freight be kept open, but that detailed estimates and operations planning be deferred until more information is available.

Boston-South Shore

At present, when costs of overnight mail are considered, ferry transportation may result in reduced costs for the service, thereby making it competitive with current land routes. This situation is expected to obtain in future also, and so it is investigated in greater detail. Same day freight service is currently unfeasible on this route because service is offered only during peak periods. In future, if the proposed services are implemented, same day freight service could be a feasible operation because the proposed frequency of service would render it competitive with land-based routes. Accordingly, it is examined in greater detail.

Airport-South Shore

As is the case for the Boston-South route already discussed, there may be some potential for overnight mail using current peak-period ferry services, and this possibility is examined in greater detail (*10*). Currently, same day service is not possible because of the lack of off-peak passenger ferry service.

Future same day service appears to offer the greatest potential for future ferry service because of the planned frequency of all-day service, and this possibility is investigated in greater depth.

Airport-Inner Harbor Area

The same comments apply here as they do to the Boston-Inner Harbor area already described.

Inner Harbor-South Shore

This route is examined in the following paragraphs as a part of the Boston-South Shore route.

Analysis of Potential Supplemental Ferry Freight Scenarios

Each of the possible supplemental freight services selected for detailed study in this review of candidate services was examined for operating and cost feasibility compared with existing and future land-based transportation. As determined in the foregoing review, three groups of scenarios were identified, as follows:

South Shore-Boston Scenarios (Group 1)

1A1: Overnight mail with no collection from sender's premises
1A2: Overnight mail with pickup
1B: Same-day service with pickup

South Shore-Airport Scenarios (Group 2)

2A1: Overnight mail with no pickup from sender's premises
2A2: Overnight mail with pickup
2B: Same-day service with pickup

Boston-Airport Scenarios (Group 3)

As indicated earlier, the land routes for these terminal areas appear to be superior. However, one potential case in which supplemental freight on this route may be possible is where the delivery service contracted to the airlines currently charges $15 to customers for "rush" delivery between the airport and destinations in and beyond Boston. This price is $5 more than the regular fee and some reductions could be made if the ferry were used, with some portion of the savings being allocated to the ferry service. It appears that the success of these services would be dependent on a number of factors related to the detailed logistics of the operators. Because of several uncertainties associated with this scenario, it was not considered further at this stage.

Economic Evaluation

The objective of conducting an economic analysis was to determine the approximate cost savings likely to accrue from specific scenarios such as those outlined earlier in this paper. The results of this analysis, in turn, will help to indicate which scenarios are likely to be most beneficial from a financial feasibility analysis and would help in selecting possible demonstration projects.

In this investigation, because of the nature of the scenarios and the assumptions about package collection methods, a simplified, approximate estimate of cost savings was adopted.

It consisted essentially of estimating the savings in land transportation costs if ferry operation were implemented, as outlined in the scenarios already described. The major assumptions in conducting these estimates of cost savings were the following:

1. At the collection and delivery portions of the trip, as opposed to the line-haul portion, the resource costs of the totally land-based methods are approximately the same as those for the ferry-based services. This assumption appears generally valid because the route taken by collection/delivery vehicles, the provision of collection boxes, and the administration costs would not be significantly different.

2. The major savings in resource costs will accrue from the line-haul portion of the freight movements. For the current and future land routes between the South Shore and the airport, the costs are those for a van or other vehicle and the driver. For the ferry system, the resource costs for the line-haul portion of the costs are negligible because the freight would be supplemental to the ferry passengers, and this cost should therefore be significantly lower than current overnight mail operations. Also, no personnel are required in addition to those operating the regular passenger ferry service within the limits of package volumes investigated for these scenarios.

Because of the additional handling of the packages at the transfer point between land and ferries, the ferry route land costs may be somewhat higher than the all-land routes. This difference is expected to be small and is within the levels of approximation considered acceptable.

In order to present an illustrative level of demand believed to be realistic that would also be convenient for comparison purposes, a volume of 100 packages daily (50 each way) was assumed between the origin and destination points considered for each South Shore-Boston scenario, and 50 packages daily for each South Shore-airport scenario. The difference between the volumes reflects some relative difference between the total business activity in Boston versus the airport.

The results of this illustrative cost evaluation are summarized in Table 3. The assumptions concerning travel times, speeds, and costs are stated in the table. The results show that although some savings (approximately $12,000 per year) may accrue from Scenarios 1A1 and 1A2, and 2A1 and 2A2 (overnight services) the greatest savings would accrue for the

TABLE 3 ILLUSTRATIVE, ESTIMATED ANNUAL SAVINGS IN LAND-BASED LINE-HAUL PACKAGE FREIGHT TRANSPORTATION FOR SELECTED SCENARIOS(7) (9)

SCENARIO	ASSUMED NUMBER OF PACKAGES PER DAY (2-WAY)	ESTIMATED DAILY LAND TRANSPORTATION COST SAVINGS				
		Number of line-haul 2-way van trips	Round trip Distance (Miles)	Average 2-way trip time(Hr) (3)	Daily cost saving ($) (5)	Annual cost savings ($) (6)
South Shore - Boston						
1A1, 1A2 (Overnight, present, and future)	100	1(1)	20	1.5	28	7,280
1B (Same-day, Future only)	100	20(2)	20	1.5	560	145,600
South Shore - Airport						
2A1, 2A2 (Overnight, present, and future)	50	1(1)	26	2	19	4,810
2B (Same-day, Future only)	50	10(2)	26	2	370	92,600

Notes:

(1) For overnight service, assumes that all packages would be consolidated and carried in one van load.
(2) For same-day delivery, assumes 5 packages per 1-way van trip.
(3) For overnight mail, assumes 0.75 hour average 1-way trip time during evening hours (i.e. after approximately 7:00 pm); for same day service, assumes 1.0 hours average 1-way trip time during daytime, including some peak-hour traffic.
(4) $12.00 per hour, including benefits for driver, 50c per mile for van and operating costs.
(5) (Distance x 50c x No. trips) + (12.00 x Trip time x No. trips)
(6) Daily cost multiplied by 260 working days per year, exclusive of interest amounts.
(7) Highway costs are not included and would be insignificant due to the low vehicle volumes (max. 12 vehicles per day).

future same day services where the number of packages per vehicle would be expected to be relatively low, with a correspondingly higher cost saving per package. Consequently, scenarios 1B and 2B in the future are estimated to save about $240,000 per year. For other amounts of packages, these savings would vary accordingly.

CONCLUSIONS

From the results of the economic analysis, it appears that significant cost savings exist for the transportation of supplemental freight on certain of the existing and planned ferry routes in the Boston area. From this, it can be seen that each of the potential services may contribute to the overall effectiveness of ferry service, as long as the financial feasibility and profitability for ferry operators and associated service providers can be assured. Consideration of this latter requirement is beyond the scope of this paper and is the subject of ongoing investigations. Although detailed demand estimates and more accurate estimates of costs and revenues will have to be made in conjunction with operators of the service to determine financial feasibility, the investigations indicate that more detailed analysis leading to inauguration of supplemental freight services may prove beneficial to operators, passengers, and agencies that provide subsidies for passenger travel.

ACKNOWLEDGMENTS

The material described in this paper has resulted from research sponsored by the U.S. Department of Transportation, Urban Mass Transportation Administration, University Research and Training Program. The contents of the paper, however, reflect the views of the researchers. They are fully responsible for the facts, the accuracy of the data, and the conclusions expressed herein. The contents should not be interpreted as necessarily representing the official views or policy of the Department of Transportation or the United States government. The authors would like to express their appreciation to the many individuals and personnel of local, state, and federal agencies who provided comments and information used in conducting the work.

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Publication of this paper sponsored by Committee on Ports and Waterways.

Application of Ship-Handling Simulations in the Evaluation of Channels for Two-Way Traffic

Bent K. Jakobsen, Eugene R. Miller Jr., and Larry Daggett

The application of ship maneuvering simulations in the evaluation of restricted channels that are required to accommodate two-way traffic is described in this paper. The application is illustrated by results from actual studies of the Baltimore channels carried out to validate channel reductions from 800 to 700 ft and from 1,000 to 800 ft, respectively, and an increase of the water depth from 42 to 50 ft to allow ships with deeper draft and larger tonnage to call at Baltimore. Initial studies were conducted using two coupled ship-handling simulators, each conned by a separate pilot and crew in communication and visual contact with the other ship. This initial study covered meeting situations for two-way traffic in the Craighill Angle channels. The data from these simulations provided the meeting situation strategies used by the pilots. Based on these strategies, a traffic ship control system was developed for use in later phases of the program. In all meeting situations, both ships are described with full hydrodynamic models. The later phases of the program involved simulation studies of the Brewerton channels, Rappahannock Channel, and York Spit channels. These studies consisted of fast-time simulations in which both own ship and traffic ship were computer controlled, and real-time simulations in which the own ship was controlled by a pilot and the traffic ship was computer controlled. A rule-based traffic ship control system was developed to control both ships in fast-time simulations and the traffic ship in real-time simulations.

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INTRODUCTION

Restricted waterways and channels that are required to accommodate two-way traffic are a feature of many port and waterway development programs. The design and evaluation of these channels have a major impact on the safety and efficiency of navigation, and the capital and operating costs associated with port development. The designer must balance the conflicting demands placed on channel dimensions by the ship operators and economic constraints. Until recently, the designer was forced to rely on general published design criteria, the subjective judgment of pilots, and personnel experience. In general these approaches have worked but have limitations when unusual geographic and environmental conditions exist.

In the past 5 years, ship-handling simulation has been increasingly used as a tool to support the designer with quantitative evaluations of channel design alternatives. These simulator studies have been particularly effective when applied to channel design for one-way traffic (*1*). However, until recently simulator studies for channels with two-way traffic have been limited by the capabilities of available ship-handling simulators. These limitations have included

- Inability to model the complete hydrodynamic response of the traffic ship;
- Inability to introduce the interaction between the two pilots on the meeting ships or the inability to model the response of the pilot on the traffic ship; and
- Deficiencies in the modeling of ship-ship interactions particularly in shallow water and in the presence of channel banks.

These limitations have now been largely overcome by advances in the capabilities available in some ship-handling simulators.

Recently the Corps of Engineers had the requirement to evaluate the design of the new 50-ft depth channel system serving the Port of Baltimore. The new channel, which must allow two-way traffic over its entire length of more than 100 mi, follows the existing 42-ft channel. However, because of

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cost considerations, it appeared necessary to reduce the existing width of most of the deepened channel by between 100 and 200 ft. Simulator studies were used to evaluate the safety of the planned deepened channel. Tracor Hydronautics was assigned the task of conducting the simulator studies under the overall direction of the Corps of Engineers, Waterways Experiment Station (WES).

In the conduct of these simulation studies, Tracor Hydronautics and WES decided to use recent advances in simulation capabilities to overcome the limitations of previous simulator studies of two-way traffic situations. Described in this paper are the technical approach and some of the results that were developed for the evaluation of the deepened Baltimore channels.

TECHNICAL APPROACH

Ship-handling simulators have been improved with more realistic modeling, including ship-ship and ship-waterway interaction. This development also has been supported by significant advances in the quality and realism of computer- generated images of the out-of-window view from the ship's bridge. In 1988, a new ship-maneuvering simulation facility, owned and operated by MarineSafety International (MSI) and located at Newport, Rhode Island, became available for use in the Baltimore study. This facility is unique in that it contains four simulators that can be operated together in a completely interactive simulation. This facility was used to model two interacting ships using two coupled simulators, each conned by a separate pilot and crew in communication and visual contact with the other ship. The use of such a simulation facility allows testing and measurement of passing maneuvers at specific locations in proposed channel designs.

Based on the availability of ship-handling simulators with these improved capabilities, the following technical approach was applied:

- Identify critical simulator requirements for evaluation of two-way traffic channels,
- Conduct initial simulations using two coupled ship simulators to evaluate a critical section of the channel system,
- Use the results of the coupled two-ship simulations to determine the piloting strategies used in meeting situations in straight reaches and bends,
- Develop a traffic ship control system based on these piloting strategies for use in later phases of the study that were conducted on a single-ship simulator,
- Implement a traffic ship simulation with full hydrodynamic modeling and response,
- Conduct coupled fast-time simulations using the traffic ship control system for both ships to identify critical locations for real-time piloted simulations,
- Evaluate other channel sections using a single real-time piloted simulator interacting with a traffic ship conned by the traffic ship control system, and
- Evaluate the new channel design based on comparisons with simulations conducted in the existing channel.

In the Baltimore study, there are a large number of channels and bends. Each of these has unique dimensions, bank configuration, current, and wind conditions. For each channel and bend, there are a large number of meeting locations and traffic conditions (e.g., inbound containership meeting outbound bulkcarrier under ebb conditions) that need to be tested. It is prohibitively expensive and time consuming to evaluate all of these conditions with real-time simulations. Therefore, fast-time simulations using the traffic ship control system to control both ships is used to rapidly and efficiently determine the location and traffic condition that will be most critical in establishing channel dimensions. Real-time simulations are then conducted for the critical cases to evaluate the final channel dimensions. The real-time simulations are carried out using local licensed pilots. This approach has been used in the studies of the Brewerton channels, Rappahannock Channel, and York Spit channels. Data have been collected from simulations of 240 meeting situations using 18 different pilots familiar with the channels (*2–4*). All meeting situations were carried out in daylight clear weather conditions with maximum current and wind conditions (wind 20 knots from the northwest).

The performance of the pilots in the existing and planned channels was assessed quantitatively by calculating the following parameters:

- Clearance maintained between the ships;
- Clearance to the adjacent bank; and
- Ship controllability factors such as time histories of heading, rate of turn, rudder activity and propeller rpm.

The differences between piloting in the existing and planned channels were assessed qualitatively by interviewing the pilots and having them complete a questionnaire following the real-time simulations.

SIMULATION FACILITIES

MarineSafety International Shiphandling Simulator Facility

The MSI ship-handling simulator center is located at Newport, Rhode Island. This facility has four ship-handling simulators that are unique in that they are the only ones in the world that can be linked together so that each simulator conned by a separate pilot can be in communication with all the other ships. This study made use of two of the simulators linked together and operating in the same channel to produce representative meeting situations. This provided a realistic simulation of meeting situations in a channel that was not restricted by any artificial constraints on the motions on either ship. The two visual ship-handling trainers include the following major elements:

- Pilot house with typical bridge equipment
- Pelorus
- Four channel visual display system with 180-degree horizontal x 30-degree vertical field of view
- Raytheon RACAS V RADAR display with ARPA
- Simulated VHF communication system
- Video Situation Display (VSD) with touch-screen control
- Chart table with PMP and light

The VSD provides a birds-eye view of the ship tracks in the simulated channel. The simulator operator's area includes a terminal to control the simulator, monitors to display the visual scene and VSD, a printer, and a video hard copy device (Figure 1). The simulators are described in a paper presented at MARSIM 88 (*5*).

Tracor Hydronautics Ship-Handling Simulator Facility

The second simulator facility used in this study is located at Tracor Hydronautics Inc., Laurel, Maryland. This simulator has been used for numerous simulation studies over several years. The simulator system has been developed so that two ship simulations can be carried out with one ship conned by a pilot and the other ship controlled by a traffic ship control system. Both ships are modeled with complete hydrodynamic models. The simulation facility, as shown in Figure 2, includes the following major elements:

- Pilot house with mock-up of bridge equipment;
- One channel high resolution visual display system, 45-degree horizontal field of view that can be switched to view in different directions (e.g., rear view, and also to bridge wing view, port and starboard); and
- VSD (birds-eye view).

Two-Ship Simulation

The two-ship simulation programs are set up in such a way that the own ship and the traffic ship use exactly the same hydrodynamic calculations. Therefore, the full hydrodynamic model, including environmental effects, bank effects, and ship-ship interactions, is fully implemented for both ships. The own ship is controlled from the bridge mock-up, and the traffic ship is controlled from either the other simulator's bridge mock-up or from a rule-based system that controls an autopilot. The two simulation programs are controlled by a master program that lets the calculations alternate between the simulation programs for the own ship and the traffic ship. The master program also transfers the ship position and velocity to the other program.

DATA BASE AND INPUT DESCRIPTION

The input data include channel geometry, bottom topography, currents, tides, wind, waves, aids to navigation, the visual scene for the existing and planned channels, and ship parameters. These data are put into the following data bases for use during the simulations.

Current and Tides Data Base

The current data base is the simulator's source of information concerning current speed, current direction, and water depth. This information is assigned to a flexible grid that covers the simulated area. To obtain the current values, a finite element model of the channels has been developed by WES. Tidal and velocity measurements obtained from field measurements or a verified physical model are usually used to ensure that the model reproduces tidal velocity conditions in a reasonable manner. The current data was developed by WES and was provided for use in the simulation studies.

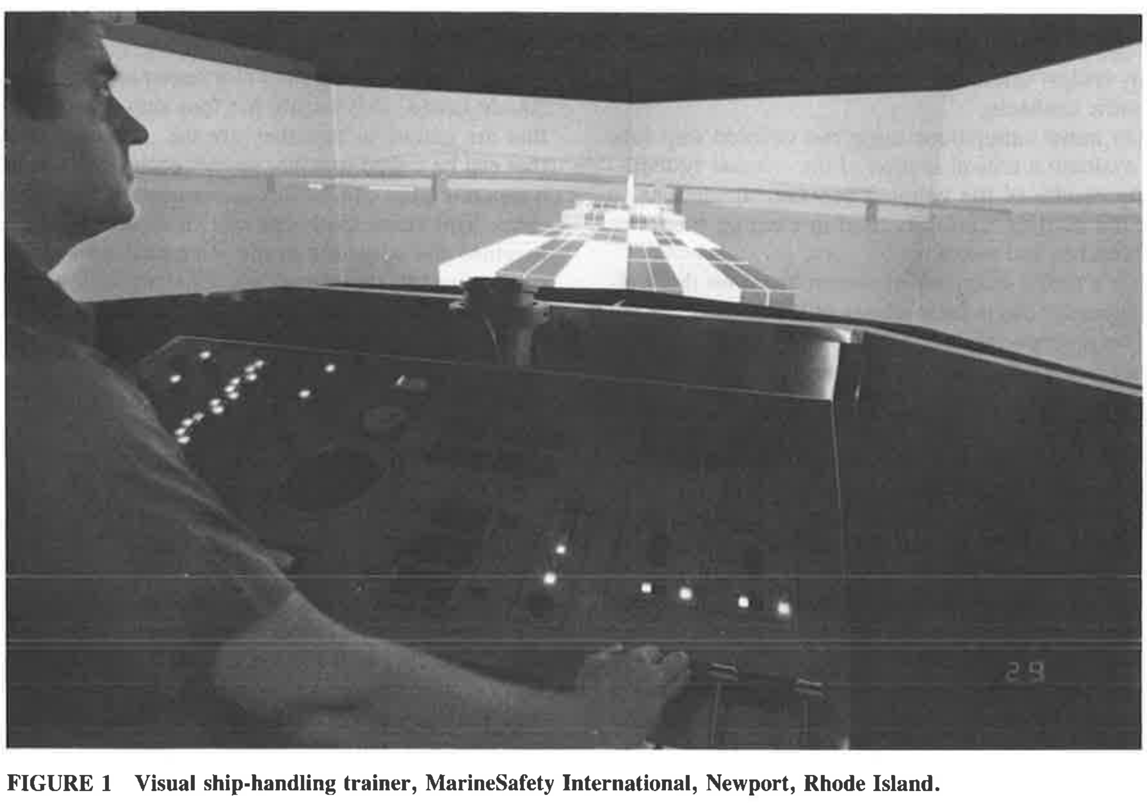

FIGURE 1 Visual ship-handling trainer, MarineSafety International, Newport, Rhode Island.

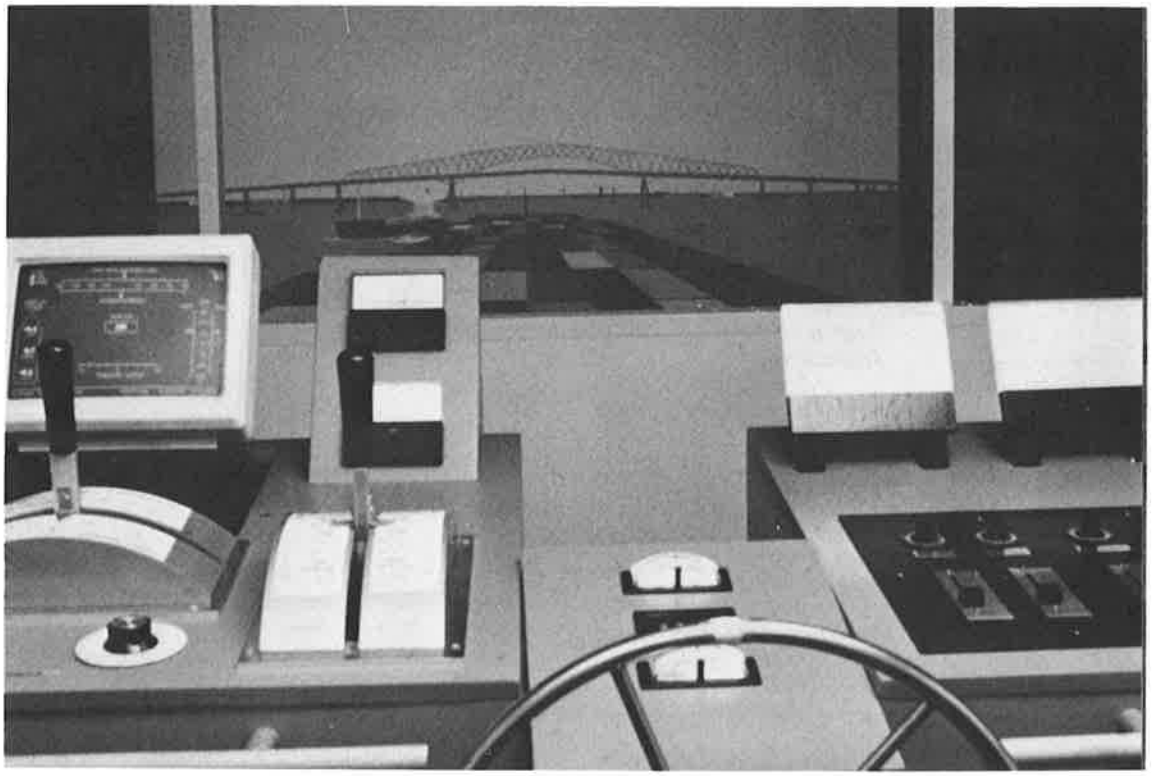

FIGURE 2 Tracor Hydronautics ship simulator.

Visual Scene Data Base

The visual scene data base contains a description of the significant objects in the visual scene, including aids to navigation such as buoys and ranges, land, and cultural contents. These scenes are generated by separate computer systems and high resolution projectors.

Radar Data Base

This data base contains the list of coordinates defining the border between land and water and the pertinent objects (e.g., traffic ships and aids to navigation). These data are generated by a radar signal generation computer and are displayed on an actual radar repeater for use by the pilots.

Hydrodynamic and Mathematical Ship Models

Valid ship models are one of the most critical items in harbor and restricted waterway studies. Significant efforts by WES and Tracor Hydronautics have been undertaken in recent years to ensure that the simulated ships perform realistically. This means that the simulated ship realistically responds to control and environmental forces and interacts with banks, channel bottom, and meeting or passing ships in a way similar to that in the real environment. The validity of ship models is directly tied to the availability of reliable information about ship performance.

Ship-ship interactions involve significant hydrodynamic forces and moments when two ships are moving in close proximity. These forces and moments are increased considerably when the meeting situation takes place in a channel that typically involves shallow water effects and bank effects. The interaction forces change with the square of the ship velocity, so ship speed is an important factor. Before the simulations, WES and Tracor Hydronautics devoted significant effort to the modeling and validation of the ship-ship interaction hydrodynamic forces. Some minor corrections were made based on the initial pilot evaluations (*6,7*).

SHIP CHARACTERISTICS

The two ships used in the Baltimore Channel simulations were a Panmax containership and a 150,000 DWT bulkcarrier. These ships were chosen to represent typical maximum size ships coming to Baltimore now and in the future. The ships have been used and validated in other simulation studies. The principal characteristics of the test ships are shown in Table 1.

TEST PROGRAM

Validation Tests

The ship-handling simulator provides realistic ship maneuvering performance of an actual ship in a given environment. Validation is the process used to evaluate whether the behav-

TABLE 1 PRINCIPAL CHARACTERISTICS OF TEST SHIPS

	Containership	Bulkcarrier
Length, overall, ft	949.79	950.00
Length, b.P., ft	915.00	915.00
Breadth, mld. ft	106.00	145.00
Propulsion system	direct diesel	direct diesel
Test conditions		
Existing channel		
Draft, ft	36.00	37.00
Displacement		
S.W. L. tons	79346	106554
Maximum speed (deep water)		
Knots	22.15	16.81
RPM	120	100
Test conditions		
Planned channel		
Draft, ft	36.00	45.00
Displacement		
S.W. L. tons	79346	129593
Maximum speed (deep water)		
Knots	22.15	15.99
RPM	120	100

ior of a simulation model agrees with that of the real system under study. Typically, validation methods cover both objective and subjective approaches. In the objective category, the ship responses are examined by fast-time computer predictions, which were compared with reliable data typically consisting of the generalization of the validated results from full-scale trials, model tests, and analytical predictions. Fast-time simulations are then carried out to validate the meeting situations to check all input data. Final validation tests (which are subjective) are carried out, using real-time computer simulations with experienced pilots, to determine the realism in the modeled ship dynamics, environment, instrumentation, and the visual scene, and to ensure maximum simulator performance validity.

Pilots and Quartermasters

All of the participating pilots were selected from the Association of Maryland Pilots and had extensive experience in piloting all types of ships through the Baltimore channels. All pilots were briefed on the purpose of the study, channel modifications, the ships and their characteristics, environment, bridge equipment, and data collection requirements (i.e., filling out of briefing and debriefing forms). Before the start of the simulation, each pilot was given the opportunity to become familiar with the ship models, channel configuration, bridge equipment, and the simulator in general.

The pilots were instructed to use normal piloting practice in positioning their own ship relative to the other ship in the meeting situation. The speeds for transit of the test ships were selected on the basis of normal piloting practice in each particular area of interest, so the meeting situation could take place at predetermined meeting locations based on these speeds. The pilots were, however, free to adjust propeller revolutions per minute (rpm), and thus the ship speed.

The ship simulations at MSI also included a quartermaster to make the simulations as realistic as possible. In the later phase, the simulation runs were carried out without a quartermaster. This has a tendency to affect the simulations to some degree, but it is not considered important for the conclusions of the study. The majority of pilots give rudder commands in multiples of 5 degrees. This form of maneuvering is similar to a "bang-bang" servo. When a pilot steers the ship himself, typically the rudder inputs are made in many smaller increments. The autopilot gives rudder commands even more smoothly, but the characteristics are similar to the pilot-controlled simulation. This may be seen in a comparison of rudder angles in Figures 3 and 4.

PILOTING STRATEGIES FOR MEETING

From the Craighill Angle simulation study with two coupled ship-handling simulators, each conned by a separate pilot, the following general observations were made:

1. The pilots started the meeting procedure when the ships were about 18 ship lengths apart. The pilot then steered in the direction the ship should be at the time of meeting. About two ship lengths before the meeting location, the ship was put on a course parallel to the channel. When the stern of each ship left the other, the ships were maneuvered back to the center of the channel. An example is shown in Figure 5.
2. The majority of pilots kept the propeller rpm constant during the entire meeting situation.
3. There was no clear pattern of which ship goes closest to the bank to give more room to the other ship (e.g., the containership would go closer to the bank than the bulkcarrier, which has the greater draft and displacement).
4. The rudder activity in the meeting situation is typically given as 10 or 15 degrees to starboard for a short period of

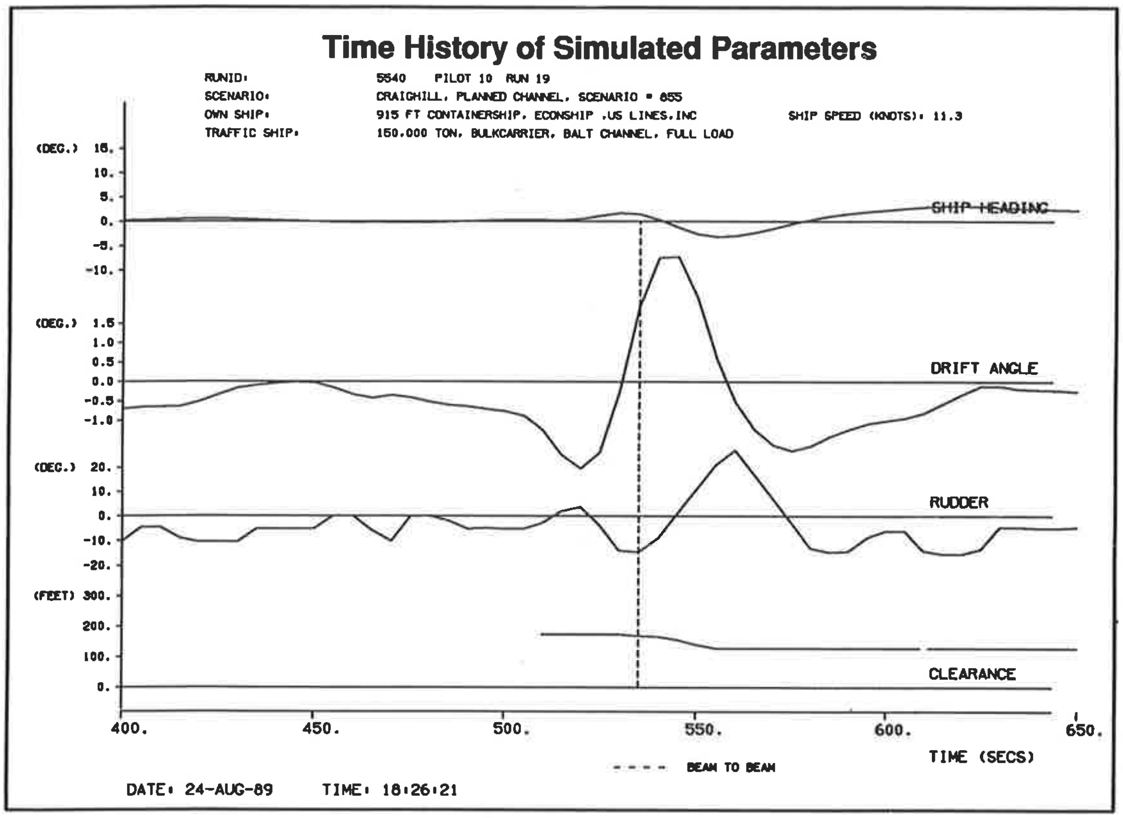

FIGURE 3 Time history of simulated parameters, pilot-conned ship.

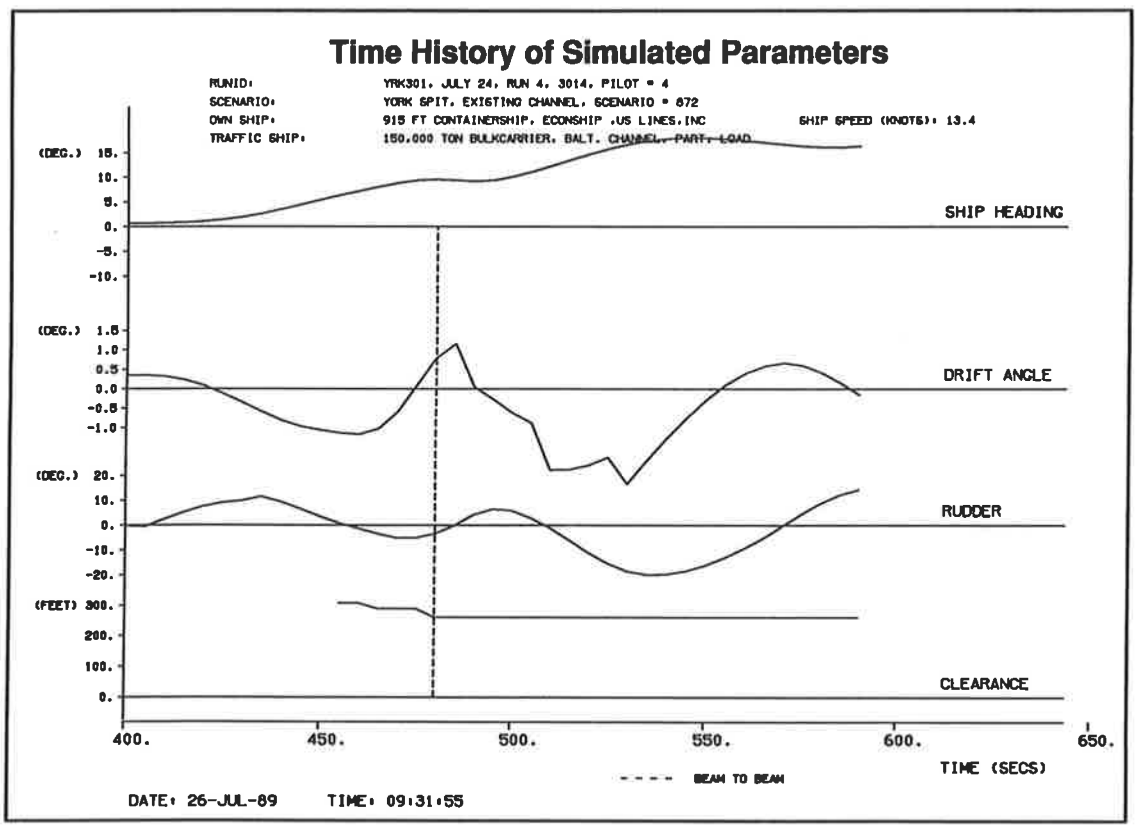

FIGURE 4 Time history of simulated parameters, autopilot controlled.

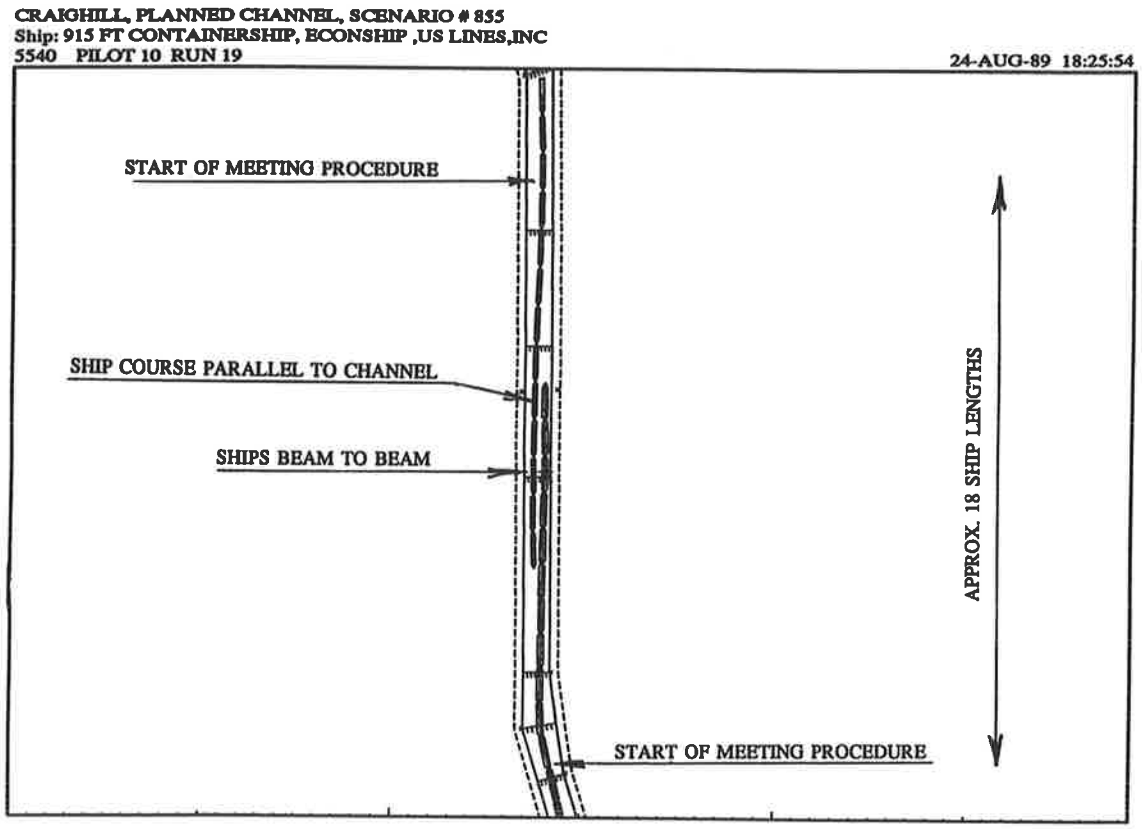

FIGURE 5 Track pilot of meeting situation.

time, where the pilot is watching the response of the bow. Then the rudder is activated again if the turning of the bow is not as expected.

DEVELOPMENT OF AUTOPILOT AND RULE-BASED SYSTEM

Based on 64 real-time simulation runs with eight pilots running coupled simulations of the Craighill Angle, a rule-based system was developed for the control of the traffic ship. The autopilot that was used in the simulations was a track-keeping autopilot controlled by six gain coefficients, which included control of the following:

1. Ship distance from predefined track,
2. Integrated distance from the predefined track,
3. Difference between current ship heading and command heading,
4. Turn rate of the ship,
5. Drift angle of the ship, and
6. Current rudder angle.

TRACKS

The basic track that a ship should follow when it transits the channel without meeting another ship is input to the simulation program. This track is defined by a location in the center of the channel and the heading the ship should follow to transit the channel. A plot of a track is shown in Figures 6 and 7. The tracks consist of a number of straight legs (lines) and circles that link the legs together into a track. The simulation program calculates a circle, defined by its radius, so that the two legs are tangents to the circle. The tangent points are indicated on the plots by crosses. The cross in the middle of the straight leg is the initial condition or start position.

Rule-Based System

A meeting situation is set up when two ships are heading toward each other and are 20 ship lengths apart. The track for the controlled traffic ship is then redefined to follow a path that will position the ship as desired in the channel when the ships are beam to beam. The autopilot is then commanded to follow the new track. This procedure is repeated every two ship lengths as the ships come closer to each other. The predicted position of the ship at meeting is also compared with the distance to the bank. Current and wind effects are also considered in the redefining of the track. When the two ship bows are one ship length apart, the command track for the autopiloted ship is made parallel to the channel centerline. When the two ships have passed each other, the track is again redefined so that the computer-controlled ship will be conned back to the original track in the center of the channel. The relative position of the ships at which the commands are made to return each ship to the centerline of the channel has been

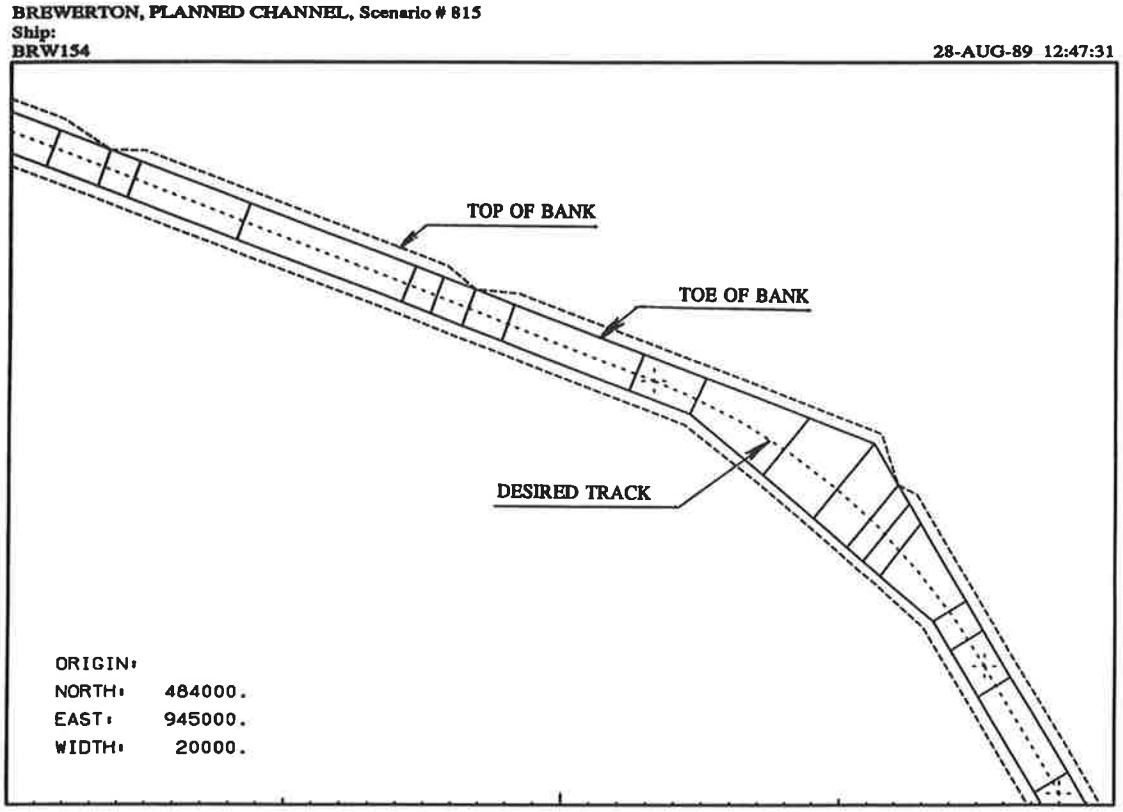

FIGURE 6 Track definition, Brewerton Channel.

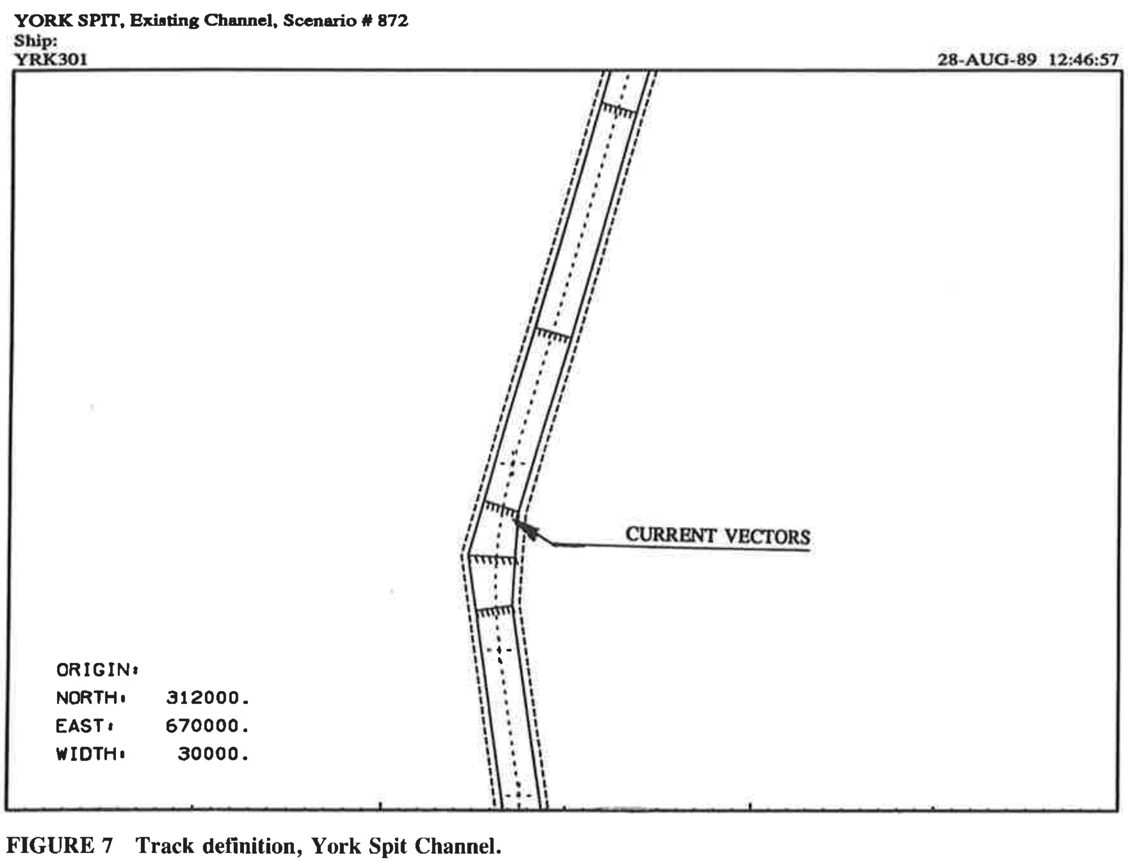

FIGURE 7 Track definition, York Spit Channel.

found to be important for the amount of rudder required to complete the maneuver.

When the meeting takes place in an "angle" where the ships also are making a turn, the meeting procedure becomes more complicated. Special logic in the program takes care of redefining the track circle to make room for the oncoming pilot-conned ship.

DATA EVALUATION

Track plots and parameter time histories were generated for all simulation runs. For each simulation run the following plots were generated:

1. Plots of the whole simulation run. A typical plot is shown in Figure 5.
2. Plots of a selected simulation period covering the close proximity of the ships to highlight the meeting situation. When the two ships were beam to beam, a cross was plotted on each ship to indicate where the meeting took place. Typical plots are shown in Figure 8.
3. Time history plots cover the same period as the enlarged plots mentioned above. The following parameters were plotted:

- Ship heading in degrees,
- Drift angle in degrees,
- Rudder activity, and
- Minimum ship clearance.

The meeting location, where the two ships are beam to beam, is indicated by a dotted line. Typical plots are shown in Figures 3 and 4.

Numerical Analysis

During each simulation run, approximately 30 physical parameters were automatically recorded every 5 sec. These data form the basis for all numerical analyses and plots. A number of other parameters such as ship clearance and bank clearance are derived from these data. Among these parameters, the following were selected for statistical analyses:

- Ship speed,
- Propeller rpm,
- Ship heading,
- Turning rate,
- Drift angle,
- Maneuvering factor,
- Clearance to traffic ship,
- Clearance to "west" bank,
- Clearance to "east" bank, and
- Rudder angle.

In addition to the parameters mentioned, statistics were calculated on minimum and maximum values for rudder activity, minimum ship-ship clearances, and minimum bank clearance.

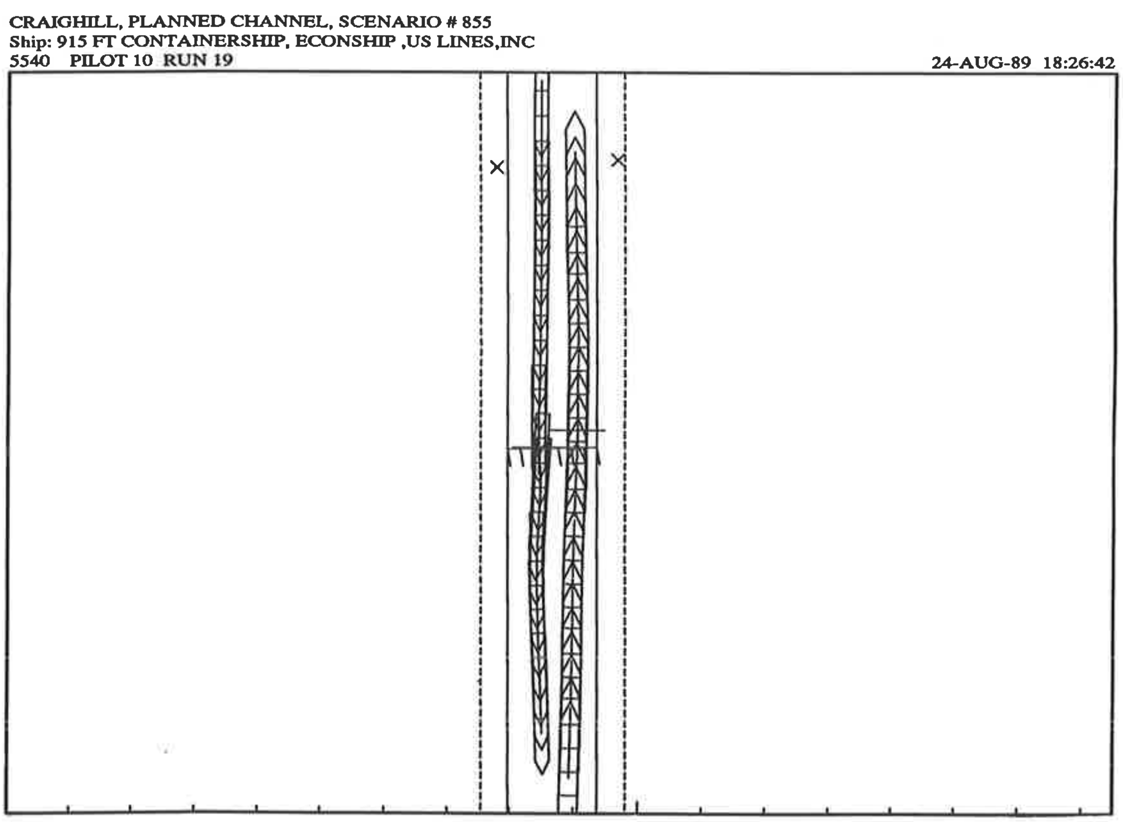

FIGURE 8 Close-up track plot of meeting situation.

Ship Controllability Measures

Results from the numerical analyses were tabulated as shown in Table 2. Further, these data are used to compare ship controllability measures from different channel sections to determine significant differences.

Ship Speed: The changes of speed for the traffic ship were all caused by hydrodynamic effects from shallow water, use of the rudder, bank effects, meeting situations, and so on. The pilots used changes in rpm now and then to keep up with a certain speed. A few pilots used a kick of rpm just before the meeting situation to increase the rudder effect.

Ship Heading: The ship heading data were included.

Turning Rate: The turning rate is a measure of the rotational speed about the ship's center of gravity. Because large masses are involved, the rate of turn should be carefully controlled to maintain good ship-handling. The simulation showed little difference between ship performance in the two channel designs.

Rudder Angle: The rudder activity (see Table 4) varies for different channel tests. High cross current generally requires more rudder activity. It is also found that the bulkcarrier needs more rudder activity than the containership. The largest rudder activity takes place when the ships are in close proximity. In meeting situations with ship clearances of about 100 ft beam to beam, full rudder deflection (35 degrees) is used to compensate for the heading change caused by ship-ship interaction, especially when the ship speeds are high. All the minimum and maximum rudder deflections found by statistical analyses of the individual pilots are collected, and then statistical analyses of these values are carried out.

Drift Angle: The drift angle, normally termed "set" by pilots, is the angular difference between the ship heading and the path of the center of gravity. These angles depend on the ship's heading relative to current, wind direction, bank effect, and ship-ship interaction effect. The drift angles are generally of the same magnitude for the pilot-conned ship and the autopiloted ship.

Maneuvering Factor: The maneuvering factor is defined as the absolute value of the product of rudder angle and rpm and is used as a comparative measure of the amount of maneu-

TABLE 2 ANALYSIS OF CONTROLLABILITY MEASURES, PILOT CONNED

	Containership Meeting Situation # 1		Bulkcarrier Meeting Situation # 2	
	Existing Ch.	Planned Ch.	Existing Ch.	Planned Ch.
SHIP SPEED [knots] over ground				
Minimum	11.11	10.69	10.05	8.22
Maximum	15.37	14.36	14.21	10.17
Average	13.64	12.73	11.11	9.22
Standard Dev.	1.04	1.16	1.28	0.43
SHIP HEADING [deg.]				
Minimum	124.50	129.95	314.14	312.95
Maximum	139.59	144.78	326.43	326.02
Average	136.02	138.05	320.29	320.35
Standard Dev.	3.09	3.36	2.90	3.16
TURN RATE [deg./sec]				
Minimum	-0.215	-0.364	-0.385	-0.286
Maximum	0.213	0.261	0.219	0.222
Average	-0.021	-0.013	-0.014	-0.016
Standard Dev.	0.054	0.091	0.080	0.077
RUDDER ANGLE [deg.]				
Minimum	-17.3	-29.2	-35.0	-29.5
Maximum	12.1	30.8	25.7	35.0
Average	-1.7	0.2	-1.9	-1.8
Standard Dev.	5.0	8.7	7.8	9.2
MANEUVERING FACTOR [rpm*rudder angle]				
Minimum	0	3	0	3
Maximum	1220	2734	3499	2631
Average	247	392	433	541
Standard Dev.	255	440	516	506
MINIMUM SHIP CLEARANCE [feet]				
Minimum	259.2	162.3	69.9	99.3
Maximum	385.4	294.4	206.1	186.6
Average	309.4	240.6	152.5	136.4
Standard Dev.	50.0	56.1	47.0	31.3
MINIMUM BANK CLEARANCE [feet]				
Minimum	-40.8	-11.4	107.6	59.8
Maximum	92.5	109.2	211.3	189.5
Average	33.2	22.3	144.6	141.9
Standard Dev.	58.1	58.1	36.0	44.6
Participating Pilots	6	4	6	6
Number of Samples	311	230	333	335

vering activity occurring in a specified maneuvering situation. Under these test conditions, low numbers are assumed to indicate fewer maneuvers than high numbers. Low numbers are an indication that a small percentage of the ship's maneuvering capability is used.

Minimum Ship Clearance and Bank Clearance: Statistical analyses of minimum ship clearance and bank distances were carried out for each meeting situation, as shown in Table 3. When the performance in channels with different widths was compared, these analyses revealed that the pilots preferred to go closer to the banks than to reduce the ship-ship clearance.

Composite Plots

Track plots for each run give useful information about ship clearances, bank distances, and the particular meeting situation. The general pilot performance in a meeting situation is well illustrated by making composite plots of all the individual track plots superimposed on each other, as shown in Figure 9. These plots give good information on where the meetings take place and how the pilots use the available space in the channel.

Pilot Evaluation Ratings

The pilot evaluation questionnaires were designed to evaluate the different meeting situations on clearance to the traffic ship and clearance to the bank. The pilots were also asked about their awareness of ship-ship interaction effects, bank effects, the amount of rudder activity, and if the traffic ship provided adequate sea room for the meeting situation. This is of particular interest if the traffic ship is computer controlled. Other questions addressed the experience level of the pilots and skill level required to carry out the meeting situation.

TABLE 3 ANALYSIS OF SHIP AND BANK CLEARANCE BASED ON MINIMUM VALUES FOR MEETING SITUATION NO. 4

Pilot	Containership Existing		Containership Planned		Bulkcarrier Existing			
	Bank Feet	Ship Feet	Bank Feet	Ship Feet	Bank Feet	Feet	Feet	Feet
	260.	144.	240.	83.	141.	39.	328.	-11.
	339.	57.	337.	9.	254.	70.	243.	44.
	207.	168.	292.	100.	338.	51.	334.	26.
	139.	216.	328.	73.	209.	95.	287.	21.
	134.	162.	196.	115.	107.	135.	128.	67.
	203.	156.	82.	185.	127.	170.	199.	44.
	273.	54.	135.	126.	195.	88.	88.	41.
	113.	215.	129.	169.	271.	124.	129.	82.
Minimum	113.	54.	82.	9.	107.	39.	88.	-11.
Maximum	339.	216.	332.	185.	338.	170.	334.	82.
Average	209.	146.	217.	108.	205.	97.	217.	39.
Std. dev.	79.	62.	96.	56.	80.	44.	96.	29.

TABLE 4 ANALYSIS OF RUDDER ACTIVITY BASED ON MINIMUM AND MAXIMUM VALUES FOR MEETING SITUATION NO. 4

Pilot	Containership Existing		Containership Planned		Bulkcarrier Existing		Bulkcarrier Planned	
	Min Deg.	Max Deg.	Min Deg.	Max Deg.	Min Deg.	Max Deg.	Min Deg.	Max Deg.
	-20.	20.	-15.	10.	-36.	19.	-23.	0.
	-20.	15.	-15.	15.	-18.	17.	-31.	28.
	-13.	9.	-15.	0.	17.	8.	-12.	0.
	-25.	20.	-10.	0.	-10.	2.	-22.	22.
	-11.	19.	-19.	19.	-19.	19.	-22.	11.
	-20.	20.	-20.	20.	-15.	16.	-22.	21.
	-20.	9.	-17.	19.	-22.	18.	-21.	9.
	-20.	18.	-15.	27.	-22.	20.	-22.	14.
Minimum	-25.	9.	-20.	0.	-36.	2.	-31.	0.
Maximum	-11.	20.	-10.	27.	-10.	20.	-12.	28.
Average	-19.	16.	-15.	14.	-20.	15.	-22.	13.
Std. dev.	4.	5.	3.	10.	8.	6.	5.	10.

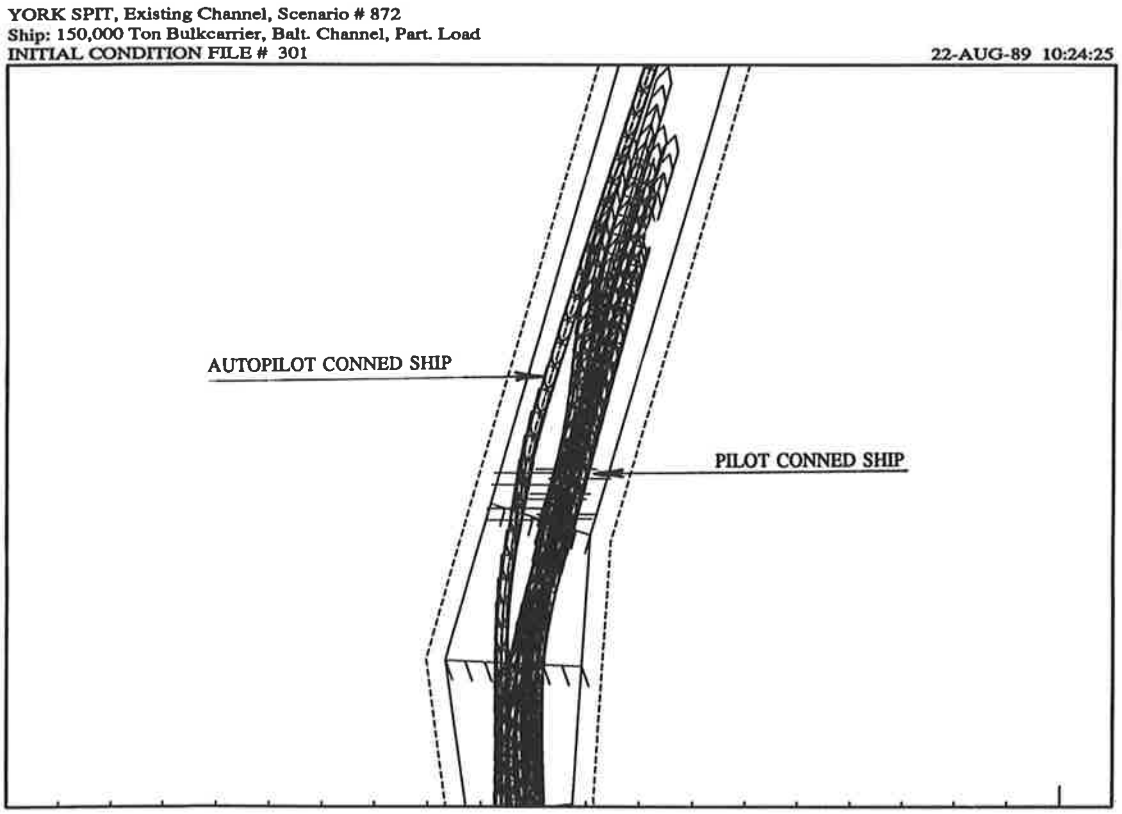

FIGURE 9 Composite plot, York Spit Channel.

CONCLUSIONS

In recent years, the process of harbor and waterway design and evaluation has increasingly made use of ship-handling simulations. These simulations have provided, in an organized way, both quantitative data and direct input of the valuable experience of pilots to the design and evaluation process. Advances in simulation technology, which are briefly described in this paper, have enhanced the applicability of ship-handling simulations to the design and evaluation of restricted channels for two-way traffic. The most significant of these advances include:

- The availability of coupled interactive simulators that allow the pilots on the meeting vessels to interact in an unconstrained and realistic way,
- The availability of interactive simulations that allow both ships to have complete hydrodynamic models that interact with each other,
- Improved models for ship-ship interaction forces and the influence of shallow water and channel banks on ship behavior, and
- The development of a traffic ship control system that makes use of data from piloted meeting situations to control ships in meeting situations for use in fast-time simulations and real-time simulations in single ship simulators.

The application of ship-handling simulations to the evaluation of a channel system with two-way traffic has been illustrated with results from studies carried out for the Baltimore 50-ft depth channel project. This study used coupled interactive simulators with full pilot interaction, as well as fast-time and real-time simulations with one or both ships conned by a traffic ship control system. In addition, improvements were made in the modeling of ship-ship and ship-waterway interactions for use in the simulation studies. In the case of the Baltimore channels, it was concluded that the planned deeper channel can be reduced in width and still allow safe piloting.

For future simulation studies of restricted channels with two-way traffic, it is recommended that

- Coupled interactive ship-handling simulators be used to properly include the effects of the pilots on navigation in unusual channel configurations,
- Simulations of two-way traffic situations use complete mathematical models for both ships and complete hydrodynamic interactions between the ships and the channel boundaries,
- Fast-time and single real-time simulations of two-way traffic meeting situations use a realistic traffic ship control system, and
- The development of traffic ship control systems that reproduce pilot behavior in meeting situations be continued and extended to more general cases.

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Publication of this paper sponsored by Committee on Ports and Waterways.

High-Speed Passenger Ferry Service: A Case Study

CARL BERKOWITZ

This case study evaluates the introduction of a high-speed passenger ferry to replace or compete with the existing Staten Island Ferry. The analysis compares three types of high-speed vessels, discusses the technology, general characteristics, operating conditions, and cost, fare structure, and passenger shifts. The analysis determines that 10 new 1,500-passenger, high-speed, surface-effect ship-type vessels operating at 35 mi/hr would be required to replace the existing ferry. This new system would attract 25 million passengers annually, which would be an increase of 20 percent over existing conditions. The results of this research are very encouraging, pointing to the exciting prospect of introducing high-speed ferry service.

To make high-performance passenger ferries competitive with land alternatives, engineers have sought to overcome the barriers that water imposes by reducing surface drag and improving ride quality by removing the vessel from the motions and actions of tides, waves, and currents. The solution to this problem has been use of the hovercraft, the hydrofoil, and the catamaran.

The hydrofoil rides on the hydrodynamic lift created between the upper and lower surfaces of its underwater foil as it moves through the water; whereas the hovercraft lifts itself from the water by either a dynamic or a static cushion of air and the catamaran uses a dual-hull design for minimum resistance to forward motion. These types of vessel are used in regular passenger service in 52 countries around the world. Since the 1964 New York World's Fair, there have been many high-speed demonstration projects which have resulted in only a few new services in the United States.

TECHNOLOGY

The hydrofoil operates above the surface of the water, supported by underwater foils connected to the vessel hull. At optimum speed, the foil generates the dynamic lift necessary to fully support the vessel's weight, placing the hull on top of the water. This permits the vessel to operate at higher speeds. Two basic types are the surface-piercing foils, which operate with only the area necessary to support the vessel at any given speed submerged, and the fully submerged foil, which operates entirely below the water surface.

The Jetfoil is a fully submerged foil type of vessel that has practically no wake, even while maneuvering. The vessel's speed ranges from 45 to 50 knots in seas of up to 16 ft. To date, the comfort characteristics of the vessel are better than any other and it has been described as the 747 of waterborne transportation.

The surface-piercing vessel is limited in its operation because of its wide fixed foil structure. It is capable of speeds of 30 to 40 knots, but in rough seas the ride quality is not quite equal to the Jetfoil.

The hydrofoil is uneconomical, operating below its design speed, because of high-vessel drag. The Jetfoil has the capability of retracting its foil; the surface-piercing foil does not, which presents operational problems in shallow water requiring deep berths and channels for hull-borne operation. The surface-piercing vessel does not serve as a boarding platform and cannot be brought alongside another structure or object without the risk of damage. The maneuverability of the surface-piercing foil is not quite as good as the fully submerged type because of the foil strut limitations. Whenever floating and subsurface debris is present, foil vulnerability can be a significant operating problem.

The hovercraft is supported above the surface of the water by a cushion of air and is classified into two basic categories: the air cushion vehicle (ACV) and the surface-effect ship (SES).

The ACV has a flexible skirt enclosing the air cushion, giving it the capability of operating over both land and water. These vessels are almost totally free of the water surface and propulsion is achieved by aircraft-type variable pitch propellers. ACVs have operated in calm waters at speeds of up to 75 mph. The ACV's principal disadvantages are (a) the speed declines with increases in sea state; (b) they are not as seaworthy as other high-performance vessels, being susceptible to wind drift; (c) significant spray in a stopped or slow-speed operation is created; and (d) the ride quality at high speed is not particularly comfortable.

The SES has rigid sidewalls that penetrate the water surface and extend the length of the vessel, joined fore and aft by flexible skirts that extend beneath the surface of the water to contain the air cushion. Unlike the ACV, the SES uses conventional marine propulsion and control technology. The design of the SES provides greater stability and a more effective air-cushion containment than that of the ACV. When operating on cushion, the sidewalls remain immersed and the hull bottom is elevated several feet. SESs are not amphibious; they are supported by an air cushion as well as by a hydrostatic and hydrodynamic lift on the sidewalls. The rigid sidewall gives the vessel directional stability, and the use of the conventional propulsion and control system increases the vessel's maneuvering capabilities. The SES is more efficient than the ACV at the same speed. Because of the hull design, the lift

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power requirements are reduced, allowing the efficient use of the propulsion system.

The catamaran's hull is C-shaped. Its most important features are the high degree of stability, excellent maneuverability, and capability of medium-to-high speed without sophisticated equipment. The ride quality is not equal to that of the hydrofoil. The catamaran is designed for least resistance to forward motion and is thus capable of speed with comfort.

Passenger Comfort

Ride comfort is a complex subject and depends to a great extent on the movement, acceleration, and frequency in the 6 degrees of freedom of movement (roll, pitch, heave, yaw, sway, and surge). The movement of the vessel and the levels of acceleration are dependent on sea state and the vessel's response, in addition to the its heading, speed, and the direction of the sea. Experts have tried to quantify ride comfort and establish evaluation criteria, but this effort has been less than satisfactory. They do agree, however, that a high level of comfort is essential to a successful operation.

Wake Characteristics

The wake created by high-performance vessels in normal operation is less than that of a conventional displacement vessel. The ACV generates a large stern wave while reaching optimum operating speed. At optimum speed, there are no significant wakes. Because a portion of the hull remains in the water, the SES does experience a slight bow and stern wave. The hydrofoil generates practically no wake because of the extremely low volume of water displaced while it is foilborne. The catamaran, because it displaces more water than other high-performance vessels, generates a wake less than that of conventional vessels.

A HIGH-SPEED FERRY FOR STATEN ISLAND

The ferry is the primary transportation link between Staten Island and the Manhattan central business district (CBD), with terminals located in St. George (Staten Island) and Whitehall (Manhattan). This service has existed since the early 17th century and today carries 21,000,000 passengers a year. It operates 7 days a week, 365 days a year, around the clock, with a seven-vessel fleet with capacities ranging from 1,200 (Austin Class), 3,500 (Kennedy Class), to 6,000 (Barberi Class) passengers. The total trip distance is 5 mi, trip time is 30 min, and round-trip fare is 25 cents. The vessels operate at an average speed of 15 mph. Scheduling allows for 15-min rush-hour headways, 20- to 30-min midday headways, and 1 hr in late evening. Time is allocated for fueling, cleaning, preventive maintenance, emergency downtime, and required dry docking and inspection.

TABLE 1 BASIC SYSTEM INFORMATION

	VESSEL TYPE					
ITEM	KENNEDY	BARBERI	SES(1)	SES(2)	JETFOIL	FORMULATION
INITIAL CPTL COST ($1M)	7.0	16.0	9.0	12.0	18.0	IC
ANNUAL COST ($1M)	1.1	2.5	1.4	1.9	2.9	AVCC=ICxCRF
SERVICE LIFE (YEARS)	25	25	20	20	20	SL
PASSENGER CAPACITY (000)	3.5	6.0	.65	1.5	.4	CAPi
CREW SIZE	13	15	5	7	5	CS
TRIP LENGTH (ROUND-TRIP)	10	10	10	10	10	L
OPERATING SPEED (MPH)	15	15	35	35	45	OSi
NUMBER OF TERMINALS	2	2	2	2	2	NT
TERMINAL TIME (HR)	.16	.16	.13	.15	.13	TEi
TRAVEL TIME RT (HR)	1.0	1.0	.55	.60	.50	Ti(*)
ROUND-TRIPS (HR)	1.0	1.0	1.82	1.66	2.00	Ni=1/Ti
# PK-HR PASS/VESSEL (000)	3.5	6.0	1.18	2.49	.80	Pi=NixCAPi
TOTAL TRIP TIME (HR)	.50	.50	.27	.30	.25	Ti/2
FUEL CONSUMPTION (GAL/HR)	200	220	300	450	540	Fi
FUEL(GALS/PASS-MILE)	.001	.002	.013	.009	.013	FGPM
VARIABLE COST (PER HOUR OF OPERATION)						
FUEL COST ($)	200	220	300	450	540	FC
MAINTENANCE COST ($)	75	75	75	125	220	MC
CREW COST ($)	320	370	100	135	100	$CC = \sum_{i=1}^{n} N_i W_i$
TOTAL VARIABLE COST ($)	595	665	475	710	760	TVC

RT - round-trip
PK-HR - peak-hour
CRF - capital recovery factor for the service life at 15% interest
Ni - number of crew members in work category i
n - number of labor classifications included in the crew
Wi - hourly wages plus benefits for work category i

FUEL (GAL/PASS-MILE) = Fi/ CAPi x OSi
* Ti = L/OSi + NT(TEi)

ANALYSIS

This analysis is limited to vessel operating costs (cost of terminal facilities is assumed to be constant) including vessel construction costs amortized over the vessel's service life (15 percent interest rate based on the financial risk of the proposal) and variable costs (crewing, fuel, and maintenance). The basic system information for the existing ferry, Bell-Halter SES and Boeing Jetfoil is presented in Table 1.

From earlier research conducted by the author on waterborne transportation user characteristics, it was determined that reducing the Staten Island Ferry travel time, by increasing operating speed, resulted in significant increases in ferry ridership. By reducing ferry travel time, the impact of introducing a high-speed ferry was evaluated. It was found that by reducing the model's ferry travel time by 50 percent, 35 percent more users were attracted from the competing modes. (*1*).

Docking for the SES and Jetfoil requires stopping, turning around, and backing in. Loading and unloading is at the ground level, whereas the conventional ferry has a double-ended configuration, with loading and unloading at two levels.

Total Cost

On a cost-per-vessel-hour basis, the SES(1) vessel has the lowest variable operating cost. It can be seen from Table 1 that, except for the SES(1), high-performance vessels will cost more than conventional types and their economic viability will depend on other mitigating factors necessary to offset this higher cost, such as the number of vessels used, hours of operation, and level and quality of service.

Vessel Requirements

The number of vessels required to replace the Staten Island Ferry depends on the service provided and the round-trip travel time during the peak hour. In Table 1, the round-trip travel time, the total number of round trips per hour and the number of passengers that can be processed during an operating hour are shown.

As previously discussed, if high-speed vessels are assigned to replace the conventional ferries with no fare increase, the projected increase in users is 35 percent (*1*). The Staten Island Ferry System transports approximately 13,500 passengers during the peak hour. The number of vessels that would be required for a new high-speed service are presented in Table 2.

Vessel Hours of Operation

The three Kennedy Class (3,500 passenger) vessels operate approximately 10,060 hr/yr, and the two Barberi Class (6,000 passenger) vessels operate for 6,250 hr/yr. During the peak hours, for the purpose of this analysis, high-speed vessels are considered to be 80 percent loaded. The number of round trips operating during the off-peak period will be 50 percent of the rush-hour total. The number of annual vessel hours of operation is found by using Equation 1, and the results are presented in Table 3.

$$\begin{aligned} AVHi = {} & (NVi \times TPHi) + [(NMDVi \times (16 - TPHi)] \times 255 \\ & + (NMDVi \times 16) \times 110 + (NFVi \times 8) \times 365 \\ & - [(NVi - 1) \times TSi] \times 255 \text{ (no. of operating weekdays)} \\ & - (NMDVi \times TSi) \times 110 \text{ (no. of weekend days and holidays)} \\ & - (NFVi \times TSi) \times 365 \text{ (days/yr)} \end{aligned} \tag{1}$$

where

i = vessel type,
$AVHi$ = annual vessel hours of operation,
NVi = number of vessels in weekday peak-hour daytime service,
$NMDVi$ = number of vessels in weekday, nonpeak-hour daytime service,
$TPHi$ = number of peak hours' operating time,
$NFVi$ = number of vessels in late night operation, and
TSi = vessel preparation time.

Total Annual Operating Cost

The total annual cost of operating the service with the conventional and high-speed vessel is computed using Formula 2. The results are presented in Table 3.

TABLE 2 OPERATING INFORMATION

ITEM	KENNEDY	BARBERI	SES(1)	SES(2)	JETFOIL	FORMULATION
			VESSEL TYPE			
PK-HR PASS DEMAND (OOO)	13.5	13.5				DPi
ADD'L USERS HIGH-SPEED			1.35	1.35	1.39	HSFi
LOAD ADJUSTMENT FACTOR			1.20	1.20	1.20	LAFi
NO. VESSELS TYPE i	2	2	17	9	28	NVi(*)
TOTAL ADJUSTED PK-HR PASS LOAD (OOO)			21.87	21.87	22.52	TPCi
NO. ROUND-TRIPS PK-HR			37	18	56	NTPi=TPCi/Pi/2

* NVi = DPi x HSFi x LAFi/Pi

TABLE 3 ANNUAL VESSEL-HOUR OF OPERATION AND COST

<table>
<tr><th>ITEM</th><th>KENNEDY</th><th>BARBERI</th><th>VESSEL
SES(1)</th><th>SES(2)</th><th>JETFOIL</th></tr>
<tr><td>NVi</td><td>2</td><td>2</td><td>19</td><td>9</td><td>28</td></tr>
<tr><td>NMDVi</td><td colspan="2">2</td><td>2</td><td>1</td><td>3</td></tr>
<tr><td>TPHi</td><td colspan="2">6</td><td>6</td><td>6</td><td>6</td></tr>
<tr><td>NFVi</td><td colspan="2">1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>TSi</td><td colspan="2">1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>AVHi</td><td>10,060</td><td>6,250</td><td>36,455</td><td>23,705</td><td>54,940</td></tr>
<tr><td>NVi+1</td><td>3</td><td>2</td><td>20</td><td>10</td><td>29</td></tr>
<tr><td>ACi</td><td>1.08</td><td>2.48</td><td>1.44</td><td>1.92</td><td>2.88</td></tr>
<tr><td>CVHi</td><td>595</td><td>665</td><td>475</td><td>710</td><td>760</td></tr>
<tr><td>AOCi($1M)</td><td>9.63</td><td>9.49</td><td>47.78</td><td>35.91</td><td>132.69</td></tr>
<tr><td>SYSTEM COST, NO AMORTIZATION($000)</td><td colspan="2">29.27</td><td>50.87</td><td>39.42</td><td>131.78</td></tr>
<tr><td>AMORTIZATION($000)</td><td colspan="2">8.20</td><td>28.80</td><td>19.20</td><td>83.52</td></tr>
<tr><td>TOTAL SYSTEM COST + AMORTIZATION($000)</td><td colspan="2">37.47</td><td>79.67</td><td>58.62</td><td>215.30</td></tr>
</table>

$$AOCi = (NVi + 1) \times ACi + (AVHi \times CVHi) \qquad (2)$$

where

$AOCi$ = total annual operating cost for vessel, Type i,
$NVi + 1$ = number of vessels required, (includes one backup),
ACi = annual cost of amortizing vessel (millions of $),
$AVHi$ = annual vessel hours of operation, and
$CVHi$ = cost/vessel hour.

System Cost

The total annual operating cost does not include support personnel, administrative staff, materials and supplies, miscellaneous expenses, terminal costs, indirect expenses, and non-operational fuel expenses. To adjust the total annual operating cost to reflect system cost, the system expense ratio (SER) is applied. The SER is obtained by dividing system cost by its annual operating cost. This cost does not include amortization of vessel capital investment. The Staten Island Ferry's total system cost is $29,270,000 and the total annual operating cost is $10,920,000, resulting in a 2.68 SER.

FINAL COMPARISON

By analyzing the total system operating cost and the total ferry users, the SES (1,500 passenger) is the most cost-effective vessel. Based on this result and the author's research on revenue and expenses versus users, an analysis was conducted to determine the break-even fare and its impact on ferry users (Table 4).

The break-even, one-way fare for the high-speed ferry is $2.37. This is based on a total system operating cost of $58,600,000 and a ridership of 25,300,000. The impact of varying both the travel time and the trip cost reflects the trade-off between reduced time and increased cost, indicating the importance of time in terms of the fares. This high fare would result in a 12 percent decline in potential ferry users at the existing fare (*1*). However, a $2.25 fare increase is not considered politically viable on Staten Island. Currently, ferry riders are charged only 12.5 cents for a one-way ferry trip. Local leaders, who continually advocate low ferry fares, might find a 19-fold increase hard to accept. The 20 percent increase in ferry users from the high-speed ferry, however, can have a significant impact on CBD traffic congestion and air quality.

A second analysis was conducted excluding the vessel capital cost from the calculations. The lowest system cost is $39.42 million for operating the SES(2), as indicated in Table 3. By instituting a break-even fare for the system, the total number of high-speed ferry users will equal 26.5 million passengers, requiring a one-way, break-even fare of approximately $1.50. This fare is competitive with the $4.00 express bus and automobile alternative but not with the fare being charged conventional ferry users. Using a $29.27 million total system operating expense (excluding the vessel capital cost), the

TABLE 4 EFFECTS OF SPEED AND COST ON FERRY RIDERSHIP (*2*)

FERRY FARE ONE-WAY (CENTS)	CHANGE IN FERRY RIDERSHIP CONVENTIONAL REVENUE	USERS	THIRTY-FIVE MPH REVENUE	USERS
12.5	2.6	21.0	3.6	28.4
50	10.0	20.5	14.0	27.9
100	20.0	19.5	27.4	27.4
160	30.0	18.5	42.3	26.5
230	40.0	17.5	58.9	25.6

SOURCE: Berkowitz, C.M., "Modeling Waterborne Passenger Transportation User Characteristics," Polytechnic Institute of New York, January, 1985 conventional ferry fare would have to be increased to approximately $1.40 one-way break-even. This fare level will result in the loss of approximately 2,000,000 users and a cost that is 10 cents lower than the cost of the proposed high-speed replacement service.

CONCLUSION

The results of this research are very encouraging, pointing to the exciting prospect of introducing a competitive high-speed ferry service between Staten Island and the Manhattan CBD.

REFERENCES

1. C. M. Berkowitz. Ferries and Waterfront Development. In *Proc., Second Annual Conference of Boston Harbor Ferries: A New Transportation Network*, Boston, Mass., May 1985.
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Publication of this paper sponsored by Committee on Ports and Waterways.

Modeling Waterborne Passenger Transportation User Characteristics

CARL BERKOWITZ

This research was conducted on Staten Island, New York, and provides an analytical tool to evaluate the viability of implementing new waterborne passenger transportation systems. The analysis of passenger travel characteristics and ridership potential is conducted using a logit-based demand model. The model and data collection techniques are discussed, including the essential elements of time, cost, comfort, convenience, special enjoyment, and validation. Special emphasis is given to the analysis of passenger travel characteristics and mode potential using demand modeling. The model is used to estimate the effects of policy decisions on travel behavior. The effects of these changes are represented in terms of overall patronage estimates by varying the values of one or two variables. This study area is served by passenger ferry, express bus, and automobile operating in direct competition with each other. This relationship makes the model suitable for transfer to other locations with similar geographical configurations.

Staten Island, New York, was selected as the study area because it is the home base for the Staten Island Ferry. As an island suburb of New York City it is linked to the central business district (CBD) via ferry, express bus, and automobile operating in direct competition with each other.

To obtain data for the model, three representative census tracts were selected using the following criteria: they must be (a) served by at least two competing modes, (b) have travelers destined for the Manhattan CBD, (c) have household income distributed from low to high, (d) have at least 700 households, (e) have different housing types and be representative of old and new communities (Table 1).

SURVEY

A mail-back survey was chosen for data collection based on the author's experience with this method. (A 1975 Staten Island mail-back survey conducted by the author had a 29 percent return.) The survey was designed for the work trip with four separate information sections: user travel data, comfort and convenience evaluation, demographic data, and modal comparison.

The form was designed to be completed in less than 30 min. A 100 percent sampling was conducted of the 5,118 residential households in the selected area. A survey return of 22 percent (1,123) was obtained; of these, 76 percent were traveling to the Manhattan CBD and 89 percent of the responses were considered usable.

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To overcome the potential problem of respondents overestimating travel time, the survey used a graphic form designed to improve travel time information accuracy. Travelers were asked to specify the travel time components that form the total work trip (access times, wait times, mode times, destination times, and so on). This information did not always agree with the response to a control question that requested: Usual time it takes to go from your home to your place of work (min). Field travel time studies were conducted to verify the accuracy of the graphic form travel time. The field reported travel time was found to be within 10 percent of the reported travel time.

Information questions on comfort, convenience, and special enjoyment were asked. Responses provided insight into factors that might influence the mode choice decision (Table 2). Respondents were asked to select four areas that were most important in the comfort, convenience, and special enjoyment categories, and to rank them, from most important to least important, in terms of personal travel needs. This was accomplished by having the respondent circle the four characteristics considered most important and check the appropriate box to indicate order of importance. These questions quantified the relative importance of these characteristics in terms of the respondents' mode choice and assisted in determining the characteristics that affect the traveler's decision-making process.

To obtain a respondent profile, a series of demographic questions were asked (Table 3). Several conclusions were drawn from this analysis. Female respondents had a strong preference for the express bus. Express-bus and ferry passengers have similar income distributions; automobile drivers and passengers have a greater number with incomes in the $50,000 plus range. The ferry has the highest percentage of low-income passengers. Commuters live in private homes and own at least one automobile.

The survey also collected information on travel characteristics. Travelers were asked to evaluate the ferry, the express bus, and the automobile for the work trip. This evaluation was important because it was based on the concept that an individual will choose a mode on personal perceptions—correct or incorrect—and the mode selection is based on a series of behavioral characteristics. The respondent was asked to give an opinion on how satisfied or dissatisfied they were with the ferry, the express bus, and the automobile. The respondent was then asked to make a mode comparison, even if the particular form of transportation had never been used, by indicating how satisfied or dissatisfied they might be. Satisfaction was divided into five categories from very dissatisfied to very satisfied (Table 4).

CALIBRATION

A general model was then developed from these survey data. First, the total data set was randomly divided into a two-third and a one-third sample. The two-third sample was used for calibration, reserving the one-third sample for later validation. The UTPS/U-Model program was used to develop the required calibration files for input into the UTPS/U-Logit computer model package.

Fifty-five different variables were evaluated by the program and screened for their ability to predict mode choice. More than 100 models were formulated, tested, and evaluated using different variable combinations (Table 5). Variables that had poor statistical tests, or that did not affect the model split, or did not represent the present transportation conditions, were eliminated from consideration.

MODEL

The resulting U-LOGIT model had the following form:

$$p(i) = \frac{e^{-du(i)}}{\sum_{i=1}^{3} e^{-du(i)}}$$

where

Mode 1 = ferry
$du(1) = C11(\text{PRTRF}) + C12(\text{ATIME}F) + C13(\text{COST1}F) + C14(\text{COMCO}F)$
Mode 2 = express bus
$du(2) = C21(\text{COST1}B) + C22(\text{COMCO}B)$
Mode 3 = automobile
$du(3) = C31(\text{TIME}A) + C32(\text{COST1}A) + C33(\text{COMCO}A)$

and

Cij = coefficient of calibration for Mode i and Variable j

PRTRF = principal mode travel time (ferry)
ATIMEF = access time (ferry)
COST1F = cost of trip/income index (ferry)
COMCOF = comfort and convenience factor (ferry)
COST1B = cost of trip/income index (express bus)
COMCOB = comfort and convenience factor (express bus)
TIMEA = total travel time (automobile)
COST1A = cost of trip/income index (automobile)
COMCOA = comfort and convenience factor (automobile)

Access Time Versus Principal Mode Travel Time

To better understand the factors that affect mode choice, an evaluation of access time and principal model travel time was undertaken (Table 6).

The average travel time for ferry and express bus users was 90 min; this time is 30 min greater than the automobile travel time. The ferry access time is equal to the express bus in-vehicle time and the ferry in-vehicle time is equal to the express bus access time.

TABLE 1 CENSUS TRACT STATISTICS

CENSUS TRACT	INCOME RATING	MEDIAN AGE	MEDIAN NO. PERSONS/ HOUSEHOLD	HOUSEHOLDS
1	D	44	3.2	727
	C	48	3.1	794
2	E	46	3.3	165
	E	49	3.7	871
3	B	39	3.7	2734
	A	42	3.7	964

NOTE: A - Highest, E - Lowest

Source: Cole Directory, Staten Island, 1980.

TABLE 2 KEY TRAVEL CHARACTERISTICS

TRAVEL CHARACTERISTIC	DESCRIPTION	FIRST CHOICE RANKING FERRY	EXBUS	AUTO
COMFORT	Safety from crime	1	3	1
	Availability of seating	2	6	6
	Cleanliness of vehicle	3	5	5
	Safety from injury	4	4	4
	Heat/air conditioning	5	2	2
	Comfortable seating	6	1	3
CONVENIENCE	Reliability of schedule	1	1	2
	Cost of trip	2	2	4
	Travel time	3	3	1
	Reliability of vehicle	4	4	3
	Waiting time	5	5	5
SPECIAL ENJOYMENT	Quality of ride	1	1	1
	Relaxing	2	2	2
	Enjoyment of ride	3	3	3
	Freedom of movement	4	5	4
	Attractiveness of vehicle	5	4	5

TABLE 3 KEY USER DEMOGRAPHICS (percent)

CHARACTERISTIC	FERRY	EXPRESS BUS	AUTO
GENDER			
Male	72.6	58.8	86.9
Female	27.4	41.2	13.6
AGE			
18-24	10.1	7.7	-
25-34	30.0	33.5	45.9
35-44	26.0	34.8	29.5
45-54	20.5	15.8	14.8
55-64	11.7	7.2	9.8
65+	1.7	0.9	-
PRIVATE HOMES	87.7	95.0	95.0
OCCUPATION			
Clerical	25.8	22.5	-
Craftsman/foreman	6.9	10.6	11.5
Civil servant	10.7	5.0	31.1
Sales	2.5	4.1	8.2
Manager	21.0	27.1	21.3
Student	2.5	0.9	-
Professional	15.5	20.6	19.7
Other	15.1	9.2	8.2
DRIVERS LICENSE	89.7	91.9	96.7
AUTOS IN HOUSEHOLD			
One	52.0	61.3	30.0
Two or more	44.6	36.4	70.0
AUTO AVAILABILITY			
Always	52.2	47.1	83.3
Sometimes	22.3	23.1	11.7
FAMILY INCOME			
Under $14,999	9.7	4.0	1.7
15,000-19,999	8.9	7.5	-
20,000-24,999	15.1	15.0	15.5
25,000-29,999	20.2	20.5	17.2
30,000-39,000	26.2	29.5	31.0
40,000-49,000	12.2	12.5	12.1
over 50,000	7.6	11.0	22.4

TABLE 4 EVALUATION OF TRAVEL CHARACTERISTICS

CHARACTERISTIC	MODE	MODE USER														
		FERRY USER (PERCENT)					EXBUS USER (PERCENT)					AUTO USER (PERCENT)				
		VD	SD	NN	SS	VS	VD	SD	NN	SS	VS	VD	SD	NN	SS	VS
TRAVEL TIME	FERRY	9	19	14	38	20	13	15	50	17	5	15	21	33	23	8
	EXBUS	32	23	33	11	1	36	30	10	21	3	40	25	20	12	3
	AUTO	19	21	41	12	7	16	11	47	16	10	12	28	9	20	31
AVAILABLE SEAT	FERRY	10	18	15	31	26	6	10	53	18	13	16	25	21	28	10
	EXBUS	33	20	34	8	5	36	26	8	17	13	33	30	16	16	5
	AUTO	2	1	47	3	47	1	1	46	4	48	2	3	13	3	79
COMFORT (RIDE QUALITY)	FERRY	3	8	16	32	41	5	8	54	20	13	3	13	32	26	26
	EXBUS	25	22	38	12	3	31	31	12	25	1	28	34	20	15	3
	AUTO	2	6	47	13	32	2	2	46	6	44	7	3	14	15	61
COST OF TRIP	FERRY	6	2	12	19	61	4	4	48	15	29	5	5	26	16	48
	EXBUS	47	20	31	1	1	54	23	18	4	1	31	36	23	8	2
	AUTO	42	11	41	3	3	32	16	44	4	4	36	15	13	15	21
SAFE FROM CRIME	FERRY	6	18	21	36	19	15	17	47	15	6	15	26	23	21	15
	EXBUS	2	5	40	26	27	2	4	15	30	49	3	7	26	30	34
	AUTO	1	2	42	7	48	1	0	41	5	53	3	3	10	5	79

VD - VERY DISSATISFIED; SD - SOMEWHAT DISSATISFIED; NN - NEITHER SATISFIED NOR DISSATISFIED; SS - SOMEWHAT SATISFIED; VS - VERY SATISFIED

TABLE 5 VARIABLES TESTED

CATEGORY	DESCRIPTION	
TIME	1. USUAL TRAVEL TIME DOOR TO DOOR	
	2. WALK TIME TO ACCESS MODE	
	3. TIME WAITING FOR ACCESS MODE	
	4. TRAVEL TIME ON ACCESS MODE	
	5. TIME ON PRINCIPAL MODE	
	6. TIME WAITING FOR PRINCIPAL MODE	
	7. MODE LINKING PRINCIPAL MODE TO DESTINATION	
	8. TIME TO PARK AUTO USED AS PRINCIPAL MODE	
	9. TIME TO WALK TO DESTINATION	
	10. FINAL WALK TIME TO FINISH TRIP	
	11. TOTAL TRAVEL TIME FOR ENTIRE TRIP	
COST	1. ONE WAY COST	2. TOLLS
	3. TRANSIT FARES	4. PARKING COST
	5. CARPOOL COST (OW)	6. AUTO TRIP LENGTH (OW)
COMFORT	1. SAFETY FROM CRIME	2. CLEANLINESS OF VEHICLE
	3. SAFETY FROM INJURY	4. FREEDOM FROM ANNOYANCE
	5. WEATHER PROTECTION	6. COMFORTABLE SEATING
	7. HEAT AND AIR CONDITIONING COMFORT	
CONVENIENCE	1. COST OF TRIP	2. RELIABLITY OF SCHEDULE
	3. TRAVEL TIME	4. RELIABILITY OF VEHICLE
	5. WAITING TIME	6. EASE OF TRANSFER
	7. CONTINUOUS RIDE	8. AVAILABILITY OF INFO
	9. PROXIMITY OF SERVICE TO ORIGIN AND DESTINATION	
SPECIAL ENJOYMENT	1. ENJOYMENT OF RIDE	2. ATTRACTIVENESS OF RIDE
	3. QUALITY OF RIDE	4. SCENIC RIDE
	5. NOSTALGIA	6. RELAXING QUALITIES
	7. FREEDOM OF MOVEMENT	8. OPPORTUNITY TO BUY FOOD
	9. SOCIAL ENVIRONMENT	10. OTHER
DEMOGRAPHIC	1. MALE OR FEMALE	2. MARRIED OR SINGLE
	3. AGE GROUPINGS	4. HOUSING TYPE
	5. DRIVERS LICENSE	6. # OF AUTOS IN HOUSEHOLD
	7. AUTO AVAILABILITY	8. INCOME GROUPINGS
	9. LICENSED DRIVERS IN HOUSEHOLD	

TABLE 6 COMPARISON OF AVERAGE ACCESS TIME AND PRINCIPAL MODE TRAVEL TIME (minutes)

MODE	ACCESS TIME	PRINCIPAL MODE TIME	TRAVEL TIME
FERRY	64.91	25.00	89.91
EXPRESS BUS	23.15	66.49	89.64
AUTOMOBILE	13.75	46.13	59.88

This time relationship partially explains the results obtained from the survey question, "I do not use the Staten Island Ferry to commute to work because. . . " answered by express bus users. Sixty-six percent of the survey respondents selected inconvenience, whereas 23 percent selected slower travel time as their answer. Although the travel times for ferry and express bus users are comparable, the need to use at least two modes to complete a ferry trip gives the potential user an incorrect perception.

Final Variable Selection

On evaluation of the different variables, it was determined that most of the variables did not contribute to the model's ability to predict. The final analysis identified principal mode in-vehicle travel time; total access time; total travel time; and total trip cost, comfort, and convenience as the most important variables.

Variable Selection for Express Bus Model

In the process of selecting the variables for inclusion in the express bus part of the model, total travel time, access time, waiting time, and principal mode time were tested. When the travel time variables were included and the model was calibrated, the resulting variable coefficients assumed negative or zero values. The resultant statistical test was below acceptable standards established in the literature.

This result was not expected and an investigation was conducted to determine the possible reasons. A series of conditions were developed to help explain the lack of impact exhibited by the express bus travel time variable.

Express bus service on Staten Island was established in 1966. In the first year of operation, the system transported 18,000 passengers. In 1981, the system reached its peak, transporting 7,400,000 passengers. At the time of this research, the annual ridership was approximately 6,500,000. In-house studies conducted by the New York City Department of Transportation and other agencies indicate that the express bus system may have reached its capacity on Staten Island.

The first express bus users were diverted from the Staten Island Ferry. This modal shift was attributed to the express buses' improved travel time, levels of comfort and convenience, and pricing structure. Based on the system's initial success, the service was expanded with additional equipment and routes. The expanded system attracted ferry users and new residents. In recent years a new trend has emerged in which passengers who might have used the express bus have instead selected the ferry. This trend can be attributed to the express bus losing its competitive edge in travel time, trip cost, comfort, and convenience. The cost for an express bus trip at the time of the study was $3.00; today it is $3.50, and in January 1990 it increased to $4.00.

Annual ferry ridership declined from 18,000,000 in 1975 to 14,000,000 in 1979, increased to 21,000,000 in 1983, and remained constant through 1989. The increase in ferry users is attributed to the population explosion on Staten Island, increases in express bus fares, express bus system capacity restraints, and reductions in the general quality of express bus service. This service decline has spawned van pooling, minibuses, and community charter buses. This latter development has resulted in the leveling off of ferry ridership growth. Improvements to the express bus system, including special bus lanes and traffic control modifications, have not significantly improved the system's operating characteristics.

Attempts to mitigate the negative attributes have been unsuccessful. One possibility that has not been investigated is a combined ferry-express bus system. This system would combine the positive attributes of both services. This service offers an opportunity to reduce ferry access time. One scenario being investigated is a guided bus system used in conjunction with an abandoned railroad right-of-way that conveniently accesses the Staten Island Ferry Terminal.

FINDINGS

Survey respondents were asked to comment on their perceptions of satisfaction or dissatisfaction about trip cost and travel time. The majority of express bus users indicated their dissatisfaction with trip cost and travel time. When asked to evaluate the ferry, they were neither satisfied or dissatisfied with trip time and indicated their satisfaction with ferry trip cost (Table 7).

Total Trip Cost/Income

Dividing cost by income allows for the testing of the concept that travelers with different incomes value travel costs differently.

One-Way Automobile Operating Cost

To obtain the one-way automobile operating cost, the total cost of parking and tolls was divided by two and added to the total operating cost. The total operating cost, including maintenance, fuel, depreciation, insurance, and other direct costs was established at 35 cents/mile.

Comfort and Convenience Index

To establish comfort and convenience indexes, scaling techniques were used to weigh the relative importance of each characteristic for each mode as determined by the respondents (Table 8). The comfort and convenience index formulations are made up of five characteristics: travel time, trip cost, comfortable seat, available seat, and safety from crime. The weighing factors were based on the relative importance given by the respondents to each factor. Respondents were asked to evaluate a series of comfort and convenience characteristics and give their perceptions even if the mode was never used.

TABLE 7 PERCEPTIONS COMPARED FOR TRAVEL TIME (TT) AND TRIP COST (TC)

PRINCIPAL MODE	MODE	SATISFIED (PERCENT)		DISSATISFIED (PERCENT)	
		TT	TC	TT	TC
FERRY	FERRY	58	80	28	8
	EXBUS	12	2	55	67
	AUTO	19	6	40	53
EXPRESS BUS	FERRY	22	44	28	8
	EXBUS	24	5	66	77
	AUTO	26	8	27	48
AUTOMOBILE	FERRY	31	64	36	10
	EXBUS	15	10	65	67
	AUTO	51	36	40	51

TABLE 8 COMFORT AND CONVENIENCE INDEX VARIABLES

		MODE CHOICE					
		FERRY		EXPRESS BUS		AUTOMOBILE	
GROUP	VARIABLE	RESPONDENT FIRST CHOICE GROUP (PERCENT)		RESPONDENT FIRST CHOICE GROUP (PERCENT)		RESPONDENT FIRST CHOICE GROUP (PERCENT)	
COMFORT	AVAILABILITY OF SEATING	15.75	(40)	19.40	(46)	14.63	(35)
	COMFORTABLE SEATING	6.01	(15)	10.13	(24)	9.35	(23)
	SAFETY FROM CRIME	17.56	(45)	13.00	(30)	17.47	(42)
CONVEN-IENCE	TRAVEL TIME	14.80	(46)	16.53	(58)	18.56	(63)
	COST OF TRIP	17.30	(54)	11.73	(42)	10.98	(37)

This evaluation was then correlated with the ranking of the characteristics in the order of subjective importance.

Statistical Summary

The UTPS/U-LOGIT statistics package is designed to help determine whether the model is acceptable. This, however, is not the only criterion. The most important consideration is whether the model is consistent with subjective experience of the travel behavior being investigated. In developing the model, care was taken not to include highly correlated variables in the same utility expression. The statistical summary of the selected independent variables is presented in Table 9.

Table 10 indicates the correlation matrix of independent variables used to determine whether or not the selected variables show any degree of independence. Explanatory variables do not have high levels of correlation one to another. Because it is impossible to obtain a set of variables that do not correlate at all, the matrix helps select appropriate variables. Independent variables highly correlated with other independent variables were not included in the same utility expression. The variables selected have intercorrelation values ranging from 0.0002 to 0.3117. This is considerably below the unacceptable range of 0.6 to 1.0, as indicated in the literature.

Final Model Coefficient Values

The final coefficient values and the results of the model calibration are presented in Table 11. The values are the reverse

TABLE 9 STATISTICAL SUMMARY OF INDEPENDENT VARIABLES

VARIABLE	MEAN	STANDARD DEVIATION	LARGEST VALUE	SMALLEST VALUE	UNITS
PRTRF	25.00	0.00	25.00	25.00	MIN.
ATIMEF	64.91	18.99	155.00	9.00	MIN.
COSTIF	4.87	5.14	56.00	1.20	----
COMCOF	30.09	8.10	44.50	8.90	----
COST1B	7.92	5.61	81.80	1.50	----
COMCOB	16.99	4.72	34.60	6.60	----
TIMEA	59.88	11.16	110.00	32.00	MIN.
COSTIA	28.20	24.60	163.70	2.00	----
COMCOA	24.01	4.66	35.00	10.60	----

TABLE 10 CORRELATION MATRIX OF INDEPENDENT VARIABLES

	1	2	3	4	5	6	7	8
2	0.0002							
3	-0.0046	0.1667						
4	-0.0105	-0.0945	-0.0730					
5	-0.0196	0.0163	0.2283	-0.0274				
6	-0.0115	0.0046	0.0594	0.1444	0.0179			
7	0.0003	0.2762	0.0568	-0.0321	-0.1208	0.0019		
8	-0.0142	-0.0415	0.2266	0.0404	0.3117	0.1112	0.1367	
9	-0.0099	0.0233	-0.0341	0.0345	-0.1165	0.0633	-0.0642	-0.1600

TABLE 11 FINAL COEFFICIENT VALUES

COEFFICIENT	FINAL VALUE	STANDARD ERROR	T RATIO
C11	0.2917	0.0480	6.07
C12	0.0219	0.0089	2.45
C13	0.1557	0.0340	4.58
C14	-0.5108	0.0477	-10.70
C21	0.3890	0.0637	6.10
C22	-0.3681	0.0443	-8.30
C31	0.0881	0.0193	4.55
C32	0.6840	0.1033	6.62
C33	-0.5205	0.0591	-8.81

of how they are actually applied in the logit form. In the actual logit form, the disutility has a negative sign; thus the signs are reversed. Therefore a negative sign means that a disutility has become a utility.

The signs of all the coefficients were checked for consistency with expected behavioral attitudes and whether they displayed reasonable trends. It was found that when travel time and cost increased, ridership declined; when comfort and convenience offered greater satisfaction, ridership increased.

The final model equations are

Ferry Mode:

$$du(1) = 0.2917\text{PRTR}F + 0.0219\text{ATIME}F + 0.1557\text{COST1}F - 0.5108\text{COMCO}F$$

Express bus mode:

$$du(2) = 0.3890\text{COST1}B - 0.3681\text{COMCO}B$$

Automobile mode:

$$du(3) = 0.0881\text{ATIME}A + 0.6840\text{COST1}A - 0.5205\text{COMCO}A$$

Statistical Tests

The UTPS/U-LOGIT program produced a series of statistical tests that aid in the evaluation of the quality of the model: standard error, T-ratio, equal and alternate dependent probability hypothesis, and pseudo R-square (Table 12).

Observed Versus Correctly Predicted Modal Split

This analysis tests the goodness of fit, measured as a percentage of correctly predicted trips. This percentage refers to the proportion of observations in which the mode of highest probability is also the mode of choice. This statistic provides a direct mode-by-mode indication of the ability of the model to simulate the individual choice process. The model correctly predicted 93 percent of the ferry passengers, 84 percent of the bus passengers, and 77 percent of the automobile users. These results for a small sample are excellent.

McFadden Success Predictions (MSP)

To further validate the model, the McFadden Success Predictions Method was used to calculate the probability of successful prediction for each of the three modes, using the 1/3 data set reserved for validation.

TABLE 12 STATISTICAL TESTS

TEST	ACCEPTABLE	ACTUAL	EXPLANATION
T-TEST	> 1.96	> 2.45	Final coefficient values are significantly different from zero
EQUAL PROBABILITY HYPOTHESIS	>16.92	950.2	Calibrated model is better than an equal share model (Chi-square)
ALTERNATE DEPENDENT PROBABILITY HYPOTHESIS	>16.92	704	Calibrated model is better than a model chosen in proportion to the number of passengers observed selecting the mode (Chi-square)
PSEUDO R-SQUARE LIKELIHOOD RATIO INDEX	.12 -.63	.75	How well the model fits the data

The MSP examines the proportion of successful predictions on an overall basis or by alternatives and gives a success index, which is obtained by normalizing the predicted success proportion by the samples' observed share. A success index of 1.0 indicates that the model predictions are no better than chance; values greater than one indicate greater predictive success. The indexes ranged from 1.76 for the ferry, 2.44 for the express bus, to 6.43 for the automobile (Table 13).

Conclusion

Based on the final results of the statistical test, it can be concluded that the model does an excellent job in predicting modal split for CBD-bound ferry, express bus, and automobile users. All tests exceeded minimum levels of acceptance, as established in the literature available.

DECISION ANALYSIS

The developed model estimated the effects of policy decisions on travel behavior of overall patronage caused by changes in time, cost, comfort, and convenience. This analysis consisted of estimating the modal split by changing the values of one or two independent variables. The results were estimates of the number of trips for the incremental change in the variable.

Ferry Time Variables

By varying travel time, the impact of introducing a faster ferry was considered. Speed was increased by reducing travel time by 20 percent; the higher speed attracted 16 percent more users, with 80 percent of the new users diverted from the express bus. A 50 percent reduction in travel time resulted in attracting 35 percent more users with a 78 percent diversion from the express bus.

Ferry access time was found to have a small impact on ridership. For example: a 75 percent reduction in ferry access time resulted in a 12 percent increase in ferry users, with 82 percent of the passengers diverted from the express bus. A 75 percent reduction in ferry travel time resulted in a 46 percent increase in ferry users, with 75 percent of the passengers diverted from the express bus. It should also be noted that a 75 percent reduction in the average ferry access time of 69 min was reduced by 49 min to 16 min, whereas for a 75 percent reduction in ferry travel time, the average in-vehicle time was reduced by 19 min to 6 min. It can be concluded that in-vehicle travel time was more important than access time. This was a big plus for high-speed ferry service.

Total Ferry User Trip Cost Indexed By Income

To evaluate the impact of increased total trip cost, the indexed cost of the ferry trip was varied. A 50 percent increase in total trip cost resulted in a 4 percent decline in the number of ferry users, with 87 percent of the users diverted to the express bus and 13 percent to the automobile. Every 55 percent increase in total trip cost resulted in an aproximate 4 percent decline in ferry ridership.

Ferry Comfort and Convenience Index

Improvements in the comfort and convenience index showed the greatest impact on ferry users. A 20 percent improvement in this index resulted in a 26 percent increase in the number of passengers attracted; conversely, a 20 percent decline in the index resulted in a 36 percent decline in the number of passengers using the mode. When the improvement in the index was 50 percent, a 44 percent increase in the number of passengers using the ferry mode resulted; conversely, a 50 percent decline in the index resulted in a 91 percent reduction in ferry users. It is noted that the express bus received the largest share of the passenger diversion.

The components that made up the comfort and convenience index include the subjective psychological characteristics of travel time, trip cost, safety from crime, seat comfort, and availability. The subjective characteristic that offers the greatest opportunity for improvement is travel time. Most passengers have an available seat, although in the peak rush hours a proportion of passengers are required to stand. The seats

TABLE 13 McFADDEN SUCCESS PREDICTION TABLE

	FERRY	EXPRESS BUS	AUTOMOBILE	OBSERVED COUNT	OBSERVED SHARE
FERRY	86	4	0	90	0.489
EXPRESS BUS	10	56	2	68	0.370
AUTOMOBILE	4	2	20	26	0.141
PREDICTED COUNT	100	62	22	184	1.000
PREDICTED SHARE	0.54	0.34	0.12	1.00	
PROPORTION SUCCESSFULLY PREDICTED	0.86	0.90	0.91	0.88	
SUCCESS INDEX	1.76	2.44	6.43	--	

in the ferry are either hardwood or formed plastic. In general, there is little or no crime except for violations such as smoking and loud radio playing. The cost of the ferry ride is minimal.

The index could be affected by an increase in the perceived travel cost, travel time, and in the crime rate. These would result in an index decline, which in turn would produce user losses.

Ferry Travel Time and Ferry User Total Trip Cost

The impact of varying both the principal mode time and the total trip cost indexed by income was evaluated. Ferry travel time was reduced by 5 min to determine its effect on ridership when total travel cost was increased. It was found that when ferry travel time was reduced by 5 min, total travel cost could be increased by 200 percent without a significant change in ridership. When the ferry travel time was reduced by 50 percent and a 300 percent increase in total cost was instituted, there was still a gain in ridership. This also reflects the tradeoff between reduced travel time and increased trip cost, indicating the value of time in terms of the fare charged.

The joint effect of travel time and total trip cost on users indicates that ferry riders are not as sensitive to cost increases as other mode travelers. This can be attributed to the fact that a significant percentage of ferry users are captive riders, a lesser percent having the opportunity to divert to competitive modes. This is definitely not the case with express bus and automobile users, who are more sensitive to changes in cost. The express bus user was found to have minimum sensitivity to time.

PRACTICAL APPLICATION

The policy analysis results were used to determine a required fare level required to break even on the Staten Island Ferry operating expenses. The ferry currently has a 25 cent two-way fare. This fare generates $2,625,000 in revenue from 21,000,000 annual passengers. The operating budget for this analysis is approximately $29,000,000. The Staten Island Ferry earned approximately $3,000,000 from concessions and other nonfare sources; this left $26,000,000 to be recovered from the fare box. To meet the total operating cost based on this analysis, it was necessary to charge a one-way fare of $1.37. This fare takes into consideration the loss of users resulting from the fare increase.

The analysis indicates that ferry passengers are affected less by increases in the fare structure than they are by ferry travel time. A 50 percent increase in ferry travel time reduces ridership by 38 percent, whereas a 50 percent increase in the fare charged results in only a 4 percent decrease in ridership.

SUMMARY AND CONCLUSION

The model can be used to estimate the effects of policy decisions on travel behavior. The effects of these changes can be represented by changes in ridership. Because the study area is served by ferry, express bus, and automobile operating in direct competition with each other, the model is suitable for transfer to other locations with similar geographical configurations.

Publication of this paper sponsored by Committee on Ports and Waterways.

Liquid Cargo Movements and Incidents on the Minnesota Portion of the Upper Mississippi River

W. WILLIAM NEWSTRAND

The major spill from an onshore oil tank in Pennsylvania, which caused major pollution on the Ohio River system, generated considerable concern about a similar happening in Minnesota. This study was made in response to that concern. Records of liquid cargo movements on Minnesota's portion of the Upper Mississippi and of spills into the water were reviewed to determine historic patterns and the effectiveness of the commercial navigation system in handling liquid cargoes. Results of the study show that barges carry nearly a billion gallons of liquid cargo each year in Minnesota. Spills from navigation functions, that is, vessels and terminals, account for 0.00003 percent of the volume carried. The study also showed that the majority of spills into the river system came from nonnavigation activities. Over a 4-year period, 106,287 gal of contaminating liquids were spilled into the navigable portion of the Mississippi system in the state. Of that total, navigation activity contributed only 4,099 gal. Also reviewed in the study was the makeup of the tanker barger fleet that plies the upper river. Nearly 87 percent of the fleet is made up of double-hulled barges. Double-hulled barges are rapidly replacing the remaining 13 percent of the fleet.

Many individuals and organizations along the Upper Mississippi River have expressed concern about the possibility of a spill from tank barges. Their concern has prompted the preparation of this paper, which focuses on the navigable portion of the Mississippi River system within the St. Paul District of the Corps of Engineers. Concern about spills of waterborne liquid cargoes has prompted a number of studies on ways to reduce their numbers and impacts. Those same concerns have generated significant advances in the technology of containment and cleanup as well as dedicated response from both public and private organizations to such spills. Much of the activity has been directed toward the intercoastal and tidewater systems rather than the rivers because of the greater volumes of liquid cargo moved in the saltwater areas. However, a recent major spill from an on-land tank into the Ohio River has sparked new levels of concern in the interior.

BACKGROUND

Liquid cargoes make up as much as 10 percent of the nongrain freight volume handled each year by Minnesota's river transportation industry. Because many of the commodities included in the liquid cargo category are classified as hazardous material, there is serious concern about the potential for spills. Hazardous material spills in the water are more difficult to contain and clean up than similar on-land spills, and their environmental impacts are generally greater in both the amount of damage and areal coverage.

The most recent studies of river liquid cargo vessels and riverine spills were done by the Maritime Transportation Research Board (MTRB) and by the Corps of Engineers (COE). Both of these analyses covered areas significantly larger than the St. Paul District of the COE, which is the geographic extent of this analysis.

The MTRB study *Reducing Tankbarge Pollution* (*1*) resulted from controversy over a U.S. Coast Guard proposal that would have required double-hulled tank vessels for all waterborne oil transport. Study recommendations ranged from suggestions that the Coast Guard modify its proposal to force use of only double-hulled barges and find other ways to reduce spills, to such things as changing tankerman licensing requirements. The study addressed the national picture with divisions of analysis composed of entire rivers or major segments of rivers, such as the upper Mississippi. A major part of the study involved offshore and coastal waterway operations.

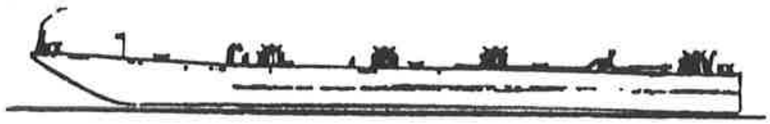
The COE's analysis for the supplement to the Environmental Impact Statement (EIS) for the second lock at Alton has a closer spatial relationship to this study in that it covers the Upper Mississippi on a pool-by-pool basis. The main difference is that it looked only at volumes of both cargo and spills and did not discuss vessel or facility types. The COE's effort also did not survey nonriver-related spills that entered the water.

VESSELS

There are several types and sizes of tank barges operating on the nation's shallow draft navigation system; most of them also operate in Minnesota. The basic design and range of sizes is shown in Figure 1. Differences in design and deck equipment respond to special cargo types. In Minnesota, all tank barges are fairly well standardized. The basic difference in tank barges that operate on this part of the river is in internal construction design; that is, there are single-hulled, single-sided barges, single-hulled, double-sided, and double-hulled barges. Figures 2, 3, and 4 are representations of barge construction plan drawings that show the three types of tank barges.

Regionally, there is considerable concern about the possibility of leaks from tanker barges, especially the single-hulled

Minnesota Department of Transportation, Transportation Building, St. Paul, Minnesota 55155.



Typical Sizes

Length (feet)	Width (feet)	Capacity (gallons)
175	25	302,000
195	35	454,000
290	50	907,000

FIGURE 1 Liquid cargo barges.

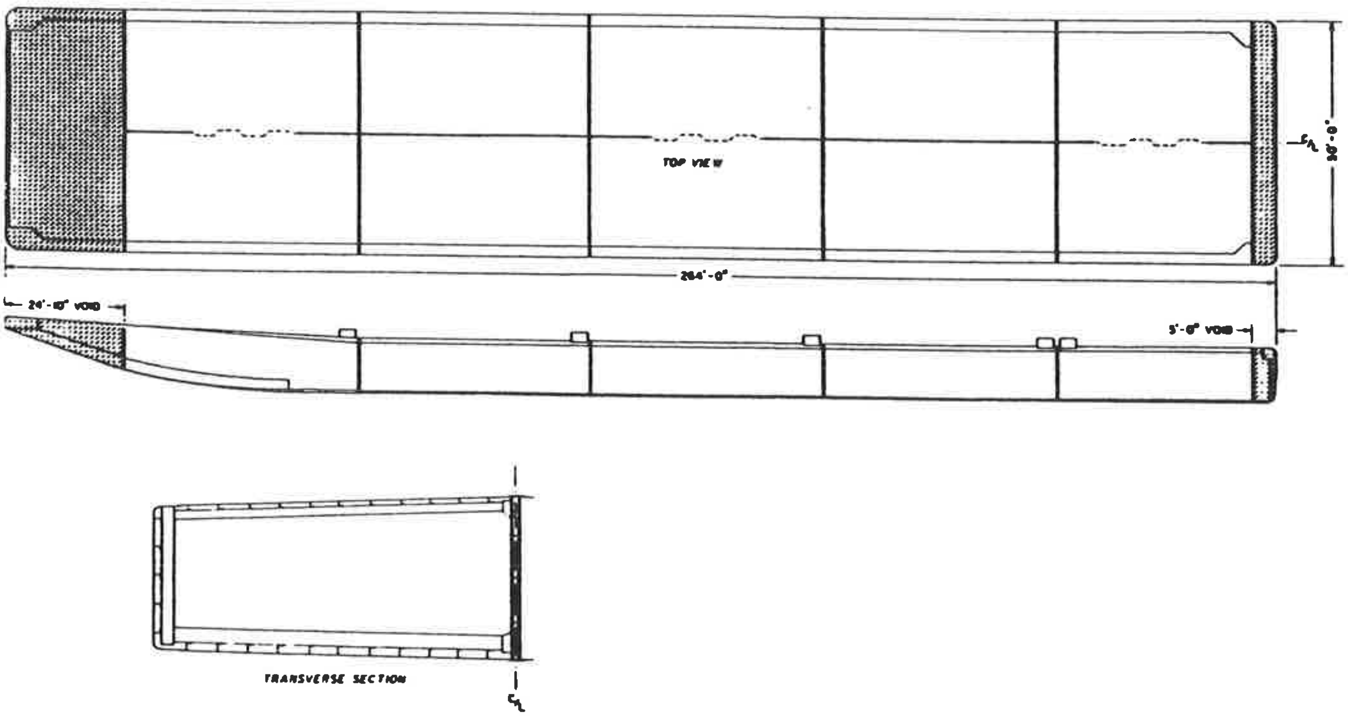


FIGURE 2 Liquid cargo: single-skin barge.

vessels that do not have side and bottom void compartments. As shown in Figures 2, 3, and 4, all tank rake barges, whether single or double hulled, have void compartments, collision bulkheads, and strengthened bracing in their bows and sterns to prevent cargo compartment damage in case of a collision. Rake barges, those with scow-type bows, are normally placed in the fronts of tows because their bow designs move more smoothly through the water and they have collision-protection void compartments of 25 ft or more. Box tank barges have smaller void compartments but they are usually placed in the center or rear of the tows and gain added protection from the other barges in the tow.

The total U.S. tanker barge fleet, according to towing industry records, consists of 3,563 vessels, 870 of which are single hulled, 1,306 are double sided, single hulled, and 1,387 are double hulled. The Minnesota Department of Transportation (Mn/DOT) surveyed all tank barge owners and operators listed in *Inland River Guide* (2) to determine the numbers of each kind of tank barge used on the Upper Mississippi and the total capacities of each type. Thirty-five of the 147 tanker barge owners who work on the inland river system operated on the Upper Mississippi and 30 of them in Minnesota waters at the time of the survey. That number was confirmed through industry contacts. Table 1 represents a summary of the data collected in the 35 responses to the Mn/DOT survey. Only 8.4 percent of the tank barges used in the COE's St. Paul District are single skinned, only 4.7 percent are double sided, and nearly 87 percent are double hulled. Of the total fleet capacity operating in Minnesota, single-hulled barges account for 10 percent, double-sided barges for less than 5 percent, and double-hulled barges for 85 percent.

Although there is not federal law requiring double-hulled construction on new tank barges, all that are currently being built for the inland system are double hulled. This has been true since the 1970s.

U.S. Coast Guard regulations have helped cause this change to double-hulled construction. Their inspection requirements for double-hulled vessels cost considerably less than do those

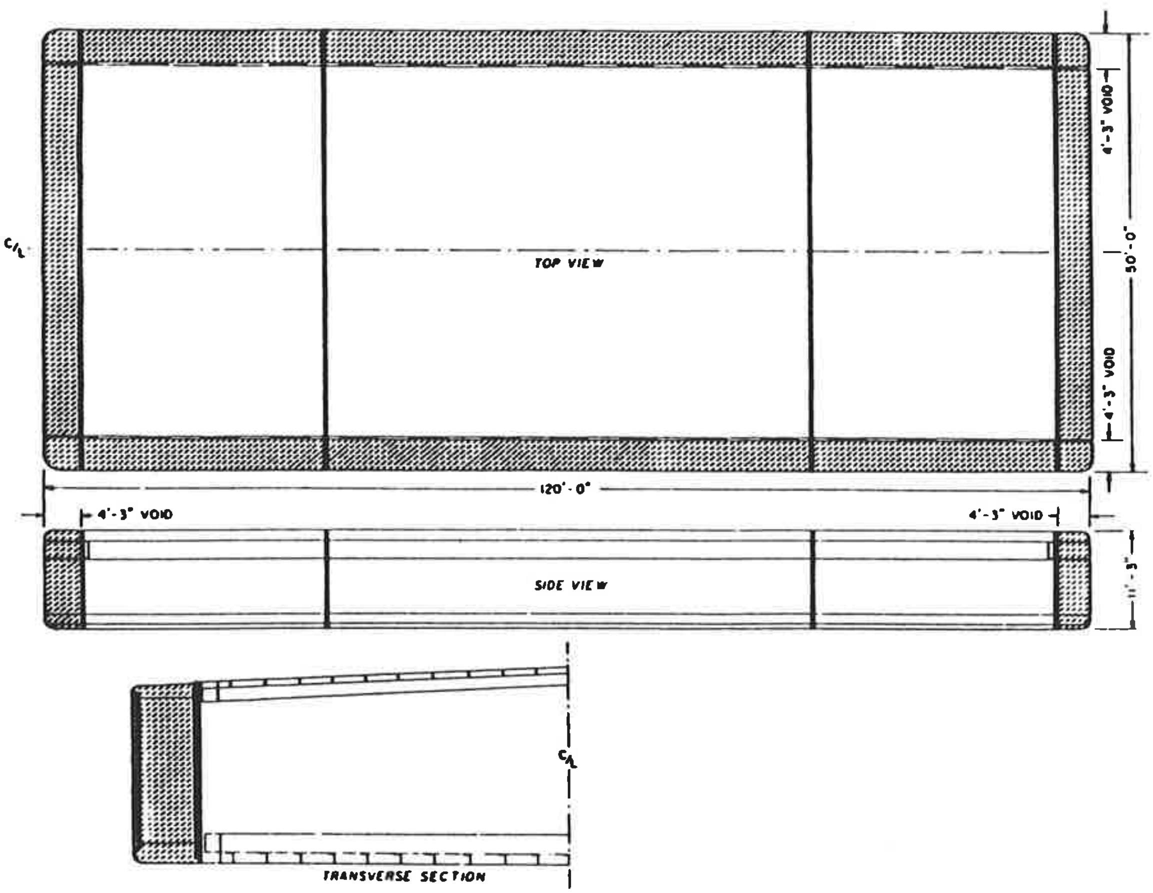


FIGURE 3 Liquid cargo: single-skin barge with double sides.

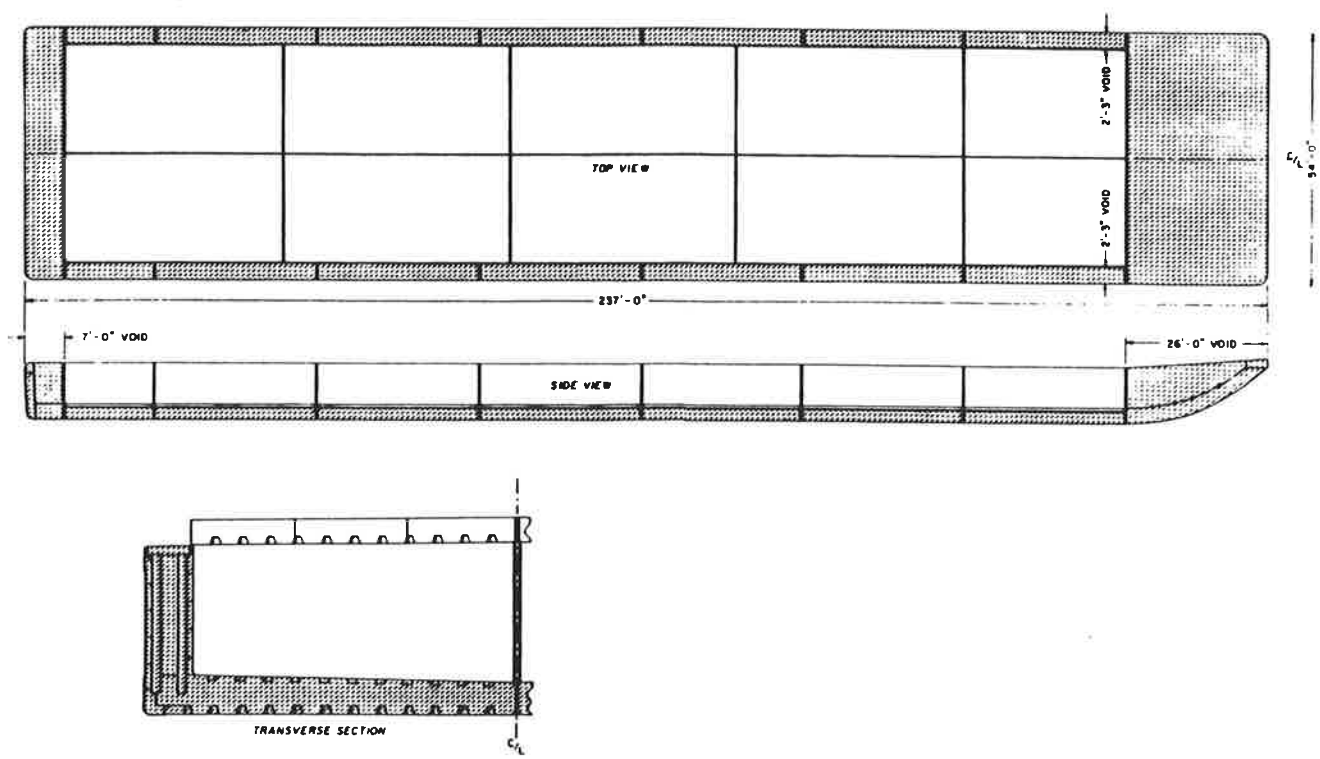


FIGURE 4 Liquid cargo: double-skin barge with double sides.

TABLE 1 MINNESOTA PORTION, UPPER MISSISSIPPI TANKER BARGE FLEET, FALL 1987

	Number of Companies	Number of Barges	Capacity Range 1,000 gallons	Total Capacity 1,000 gallons
Single Hull	5	45	343.2-1,041.0	31,495.4
Double Sided	5	25	328.9-1,001.0	14,700.4
Double Hull	23	463	328.9-1,086.8	262,197.7

for single-skin barges. The savings in inspection costs justify the added construction costs for double hulls over the long term.

All 30 companies who operate on the Upper Mississippi reported that as their single hulled barges are scrapped they will be replaced by double-hulled vessels.

LIQUID CARGO MOVEMENTS

Liquids carried by barges in Minnesota include a wide variety of commodities. Major movements include such commodities as crude oil, refined petroleum products, fertilizers, and industrial molasses, along with lesser quantities of vegetable oils, caustic soda, paints, fish emulsions, asphalt, and assorted chemicals.

There are 22 active river terminals that handle liquid cargoes in Minnesota. Three other, currently inactive, terminals have capacities for handling and storing a variety of liquid cargoes, mostly petroleum products.

The history of liquid cargo movements in the St. Paul COE District for the period 1978 through 1987 is shown in Table 2. Total liquid cargo movement for the period was 32 million tons, or approximately 9.2 billion gallons. Average annual quantities are 3.2 million tons (with a range of 2.6 million tons to 3.8 million tons) or 923 million gal (with a range of 783 million to 1.1 billion gal). All data are recorded by the Corps and the towing/terminal industry by tons; conversion to gallons was based on 7 lb/gal, or 286 gal/ton for all liquids except asphalt, which was computed at 235 gal/ton.

SPILLS

There are two basic categories of spills that have an impact on the river: those that involve activity on the water or on the shore and those that occur on dry land but drain to the water. In the first category, the spills are caused by commercial vessel, terminal, small boat, and marina accidents. Land spills include a wide variety of operations including railroads, trucks, pipelines, and off-river terminal or factory operations.

The St. Paul Office of the Coast Guard and the Minnesota Pollution Control Agency (PCA) have records of all such spills in the Minnesota portion of the study area for the period 1984 through 1987. Although PCA spill records predate 1984, that year's change in record keeping made it possible to determine spills that were definitely river related. Their records show

TABLE 2 BULK LIQUID CARGO MOVEMENT, ST. PAUL DISTRICT CORPS OF ENGINEERS (thousands of gallons)

YEAR	POOL 2 INTERPOOL	POOL 2 INTRAPOOL	NON-METRO COE DISTRICT	TOTAL
1978	816,077	183,004	81,338	1,008,419
1979	703,351	177,648	92,928	973,927
1980	697,610	183,250	154,555	1,035,415
1981	774,645	179,000	104,448	1,058,093
1982	556,885	182,750	90,262	829,897
1983	585,437	185,475	114,657	885,569
1984	539,771	177,250	186,329	903,350
1985	520,239	180,785	82,482	783,506
1986	522,451	185,650	128,013	836,114
1987	536,393	182,347	129,730	848,470
TOTAL	6,252,859	1,817,159	1,164,742	9,162,760

TABLE 3 LIQUID CARGO SPILLS 1984–1987, MINNESOTA PORTION OF MISSISSIPPI RIVER

Source	Occurrences	Volume (Gallons)
Commercial Navigation	32	4,399
Recreational Boating	3	260
Railroads	12	40,810
Other Transportation	15	7,900
Non River Industry	34	52,918
Totals	96	106,287

the location of each spill, the source, the commodity, and the amount of liquid involved.

Data from the U.S. Coast Guard and PCA reports are summarized in Table 3. PCA data is limited to those spills that occurred in Minnesota. These data were supplemented by Coast Guard information on vessel cargo losses on the Wisconsin portions of the river. Records of non-vessel spills from the Wisconsin side were unavailable. There is no liquid cargo generation in the Iowa portion of the COE St. Paul District.

Data in Table 3 show that in the 1984 to 1987 period a total of 96 river-contaminating spills occurred in the Minnesota/Wisconsin portion of the Corps' St. Paul District. The volume of liquid lost was unknown for 17 of those spills. Of the 79 incidents with measured cargo losses, the total volume was 106,287 gal. Of the total 96 incidents, 21 with 4,038 gallons can be charged to commercial river vessels and 9 with 361 gallons are the responsibility of river terminal facilities. The remaining 66 spills of 101,888 gal occurred in non-commercial navigation-related operations. Data on recreational boating cover only reported incidents at marinas involving equipment failures.

Individual PCA spill records generally indicate the success of cleanup efforts, that is, the amount of spilled liquid that was recovered. Because water spills were often recorded as "sheens," or the amount of spill was unknown, this analysis did not attempt to determine the percent of recovery.

Petroleum distillates account for the majority of spills into the river, with gasoline being the commodity with the highest volume of spills. Some detail on such spills and commercial navigation's (vessels and facilities) share of the total is given in Table 4.

SPILL PREVENTION, CONTAINMENT, AND CLEANUP

This study did not attempt to determine levels of recovery of spilled material. Records on many in-water spills are sketchy because of the rapid dispersal of liquids in the river. An accurate count of the percentage of spills recovered is difficult.

All tank barge operations require at least one licensed tankerman as part of the crew. When an under-way vessel starts to leak, the tankerman will stop the leak before major cargo loss occurs. Only on the rare occasion of a major collision or a sinking is the tankerman unable to stop cargo loss quickly. Tankermen are also on duty during vessel-to-shore facility transfer operations. Federal law requires each liquid handling river terminal to have ready access to a spill-containment system such as floating booms, which are placed around the

TABLE 4 PETROLEUM SPILL STATISTICS 1984–1987, MINNESOTA PORTION OF MISSISSIPPI RIVER

	Total Occurrences		Commercial Navigation Share			
Commodity	Number	Volume (gallons)	Number	Pct of Total Occurrences	Volume	Pct of Total Volume
Gasoline	10	8,505	5	50.0	68	0.8
Heating Oil	15	7,529	11	73.3	3,977	52.8
Diesel Oil	8	4,525	2	25.0	100	2.2
Other Oils	32	542	16	50.0	89	16.5

vessel in the water. If there is a spill, the booms keep the floating material from dispersing into the river, making it easier to clean up. Many of the terminals that handle liquid cargoes only have their own containment and cleanup systems. Others, which only occasionally handle liquids, rely on contract spill recovery teams or enter into cooperative agreements for the purchase and use of the costly systems.

The individual terminals are responsible for cleanup of any spill caused by their operations. If they fail to respond, the Coast Guard, the EPA, or the Minnesota PCA will contract for the cleanup with one of the private contractors and then charge the cost to the responsible party. In addition to the cost of cleanup, an operator of a boat or terminal facility can be fined according to procedures in the Clean Water Act.

CONCLUSIONS

This review of cargo and spill data, vessel and fleet characteristics, and spill response techniques indicates that water transportation of liquid cargoes poses little threat to the riverine environment in Minnesota. During the 1984 to 1987 period, the waterborne freight industry lost only about 4,399 gal of liquid cargo out of the nearly 3.4 billion gal it carried in Minnesota.

There are 288 mi of commercially navigable river in this report's study area. Assigning an average yearly liquid cargo loss of 1,100 gal to those miles, there was about 3.8 gallons/mi of liquid cargo spilled in the river by the towing and terminal industry each year. That would probably generate a less significant sheen than the one produced by the thousands of outboard motors that ply the same portions of the river.

There is no intention here to minimize the potential impact on the environment from a spill into the river. The intent is to stress the excellent safety record owned by the towing and river terminal industry. In fact, the record of all of the liquid cargo handlers in the river valley is impressive. For example, Mn/DOT freight records for 1985 show that the railroads moved 57,600 cars with 1.3 billion gal of liquid cargo in the river valley. With liquid cargo levels of that magnitude, the recorded 12,000 or so gal that are spilled each year into the river is a very small portion representing a five decimal percentage of the total. The nonriver facilities included in the data also have exemplary spill safety records when the volumes of liquids handled are considered.

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Publication of this paper sponsored by Committee on Inland Water Transportation.

Impact of Technological Change on Foreign Trade: Comparative Analysis of the St. Lawrence Seaway and the Panama Canal

HOWARD E. OLSON AND DAVID V. GRIER

Two modern canals that have been especially important to waterborne commerce of the United States are the Panama Canal and the St. Lawrence Seaway. The Panama Canal, opened in 1914, connects the Pacific and Atlantic Oceans via the narrow isthmus of Panama, saving thousands of miles of travel around South America. The St. Lawrence Seaway, opened in 1959, connects the inland Great Lakes of the United States and Canada with the Atlantic Ocean via the St. Lawrence River. Both of these waterways are considered vital arteries of commerce for U.S. foreign trade. But today, evolving shipping technologies on both land and sea and changes in world trade patterns raise questions about the long-term role of both waterways. The Panama Canal consists of six double-chambered locks with dimensions of 110 by 1,000 ft and a controlling depth of 41.5 ft. The St. Lawrence Seaway consists of seven locks 80 by 860 ft and a controlling depth of 27 ft. The lock dimensions, in turn, affect the maximum vessel sizes able to transit each waterway. These limiting dimensions are becoming an increasingly important factor in the role each waterway plays in world trade. Although a trend toward larger vessel sizes has been common throughout the history of world trade, the rapid increase in the size of vessels in the post-war period has been especially dramatic. Traffic trends are revealing: Panama Canal traffic peaked in 1982 and then declined precipitously with the recession, a decline in grain traffic, and the opening of a trans-isthmus pipeline. Traffic recovered slowly through 1988, but declined again in 1989. The advent of rail "minibridge"—the movement of Far East imports in double-stack container trains from the U.S. West Coast to markets in the Midwest and East—has siphoned off high-value traffic that would otherwise have moved via the Panama Canal. The introduction in the Pacific trade of "post-Panamax" containerships that are too wide to transit the canal further entrenches the minibridge alternative. As the double-stack network in the United States matures, greater westbound movements off the Atlantic seaboard seem inevitable. In the bulk trades, particularly coal, deepening at U.S. ports favors the use of larger ships that are also unable to transit the canal. Similarly, traffic on the St. Lawrence Seaway peaked in 1979 and has been largely flat or in decline in the years since. Grain exports are being shipped more economically via the Mississippi River and Gulf ports or via West Coast ports, and container traffic is virtually nonexistent. As the average vessel size in the world fleet continues to grow, the percentage of the fleet able to transit each waterway continues to decline. Enlarging either system to handle larger ships would be a very expensive undertaking and would also raise a host of environmental issues, so ultimately both waterways seem likely to play a diminished role in world trade.

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Throughout history waterways have been used to facilitate trade and reduce the cost of transporting cargo from here to there. Rivers were deepened and widened to allow safe passage of boats for passengers and cargo. Canals were dug around rapids or to connect other bodies of water. Two modern canals that have been especially important to waterborne commerce of the United States are the Panama Canal and the St. Lawrence Seaway. The Panama Canal connects the Pacific Ocean with the Caribbean Sea and the Atlantic Ocean across the narrow isthmus of Panama, saving thousands of miles of travel around South America. The St. Lawrence Seaway connects the inland Great Lakes of the United States and Canada with the Atlantic Ocean via the St. Lawrence River. Major characteristics of both of these contemporary waterways will be examined in this paper, including their origins, traffic patterns, physical dimensions, and the implications of evolving vessel technologies on the role of each waterway in future world trade.

Topics	*Panama Canal*	*St. Lawrence Seaway*
5 Ws	✓	✓
Traffic	✓	✓
Revenue	✓	✓
Lock size	✓	✓
Ship size	✓	✓
Technology impacts	✓	✓
Outlook	✓	✓

HISTORY AND CHARACTERISTICS

Both of these canal systems were envisioned for hundreds of years, but actual construction and operation did not take place until this century as follows:

		Panama Canal	*St. Lawrence Seaway*
When:	Authorization	1902	1954
	Construction	1904–1914	1955–1958
	Open	1914	1959

The Panama Canal took over 10 years to build, and opened for shipping in August 1914 (*1*). The St. Lawrence Seaway was built in joint cooperation between the United States and Canada over a four-year period and opened to deep draft traffic in 1959 (*2*).

The United States, under treaty with Panama, undertook the construction of the Panama Canal for a number of reasons, including military and strategic, trade between the east and west coasts of the United States, and the facilitation of world trade, as follows:

	Panama Canal	*St. Lawrence Seaway*
Why:	U.S. Navy U.S.-U.S. trade World trade	Labrador iron ore to United States Grain exports World trade
Who:	United States and treaty with Panama	Canada (72%) and United States (28%)

The St. Lawrence, on the other hand, was built jointly by Canada and the United States, with the former sharing the much larger ownership stake (72 percent versus 28 percent for the United States). Connecting the Great Lakes and the Gulf of St. Lawrence with a waterway that could handle oceangoing ships facilitated both the movement of Labrador iron ore to Great Lakes steel mills and the export of Canadian and U.S. grain, and it opened up the midcontinent market to world seagoing trade.

The Panama Canal has six double-chamber locks with dimensions of 110 by 1,000 ft and a controlling depth of 41.5 feet. The St. Lawrence Seaway consists of seven locks 80 by 860 feet and a controlling depth of 27 ft. The Seaway lock size was designed to be consistent with the eight Welland Canal locks built by Canada during the 1930s to connect Lake Ontario and Lake Erie. The lock dimensions, in turn, affect the maximum vessel sizes able to transit each waterway. On the Panama Canal, the maximum vessel size is 106 by 950 ft, and a loaded draft of about 40 ft. On the St. Lawrence, vessels may be no longer than 76 by 730 ft and draw 26 ft of water.

These limiting vessel dimensions are becoming an increasingly important factor in the role each waterway plays in world trade. Although a trend toward larger vessel sizes has been common throughout the history of world trade, the rapid increase in the size of vessels in the post-war period has been especially dramatic. Between 1947 and 1968, the number of ships in the world fleet increased by about 50 percent. However, the cargo capacity of the world fleet increased by about 200 percent during this period, suggesting a remarkable increase in average vessel size (*3*). This growth in average ship size is based on the economics of transport. As the draft (and overall size) of a dry bulk vessel or tanker increases, more cargo can be loaded per vessel and the cost per ton-mile falls. Of course, a similar relationship holds for containerships and other commercial vessels. As the vessel capacity in Twenty-foot Equivalent Unit containers (TEUs) increases, the relative cost of per container space diminishes (Figure 1).

PANAMA CANAL TRAFFIC

Looking at fluctuations in Panama Canal traffic over time will help put some of these changes in vessel technology into perspective. The canal stretches for more than 50 mi between the Pacific and the Caribbean (Figure 2). Vessels "step up" via the locks to freshwater Gatun Lake, 85 ft above sea level, which provides water to operate the system. Channel widths through the canal vary from 500 to 1,000 ft. The average transit time is 8 to 10 hr.

Total traffic through the canal peaked in 1982 at over 185 million long tons (Figure 3). Tanker and dry bulk vessels dominated. Tonnage declined precipitously in 1983 with the opening of the trans-Panama oil pipeline and the recession in world shipping (*4*). Tanker volume fell by half, and dry bulk volume had moderate declines through 1986. Total traffic showed no real rebound until 1987, when dry bulk volumes recovered to 1983 levels. Container traffic has generally posted small increases in tonnage each year. In looking at volume of traffic by direction, impact of the 1983 pipeline opening on tankers is even more dramatic (Figure 4). Pacific to Atlantic tanker traffic fell by nearly two-thirds in that year. It was squeezed even more in 1987 by changing patterns associated with the fall in oil prices. For Atlantic to Pacific traffic, the recession had more impact, especially on the bulk trades (Figure 5). Recovery began in 1987, when sharply higher bulk tonnage pushed total traffic to over 87 million tons.

A look at traffic by commodity also shows the dominance of the liquid and dry bulk trades. For total traffic, petroleum and products dominated until the opening of the pipeline, but

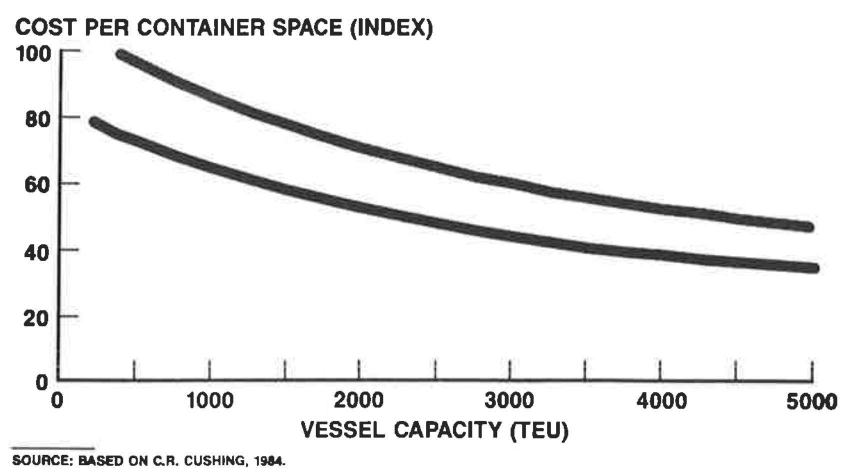


FIGURE 1 Relationship of container-carrying capacity to cost-container.

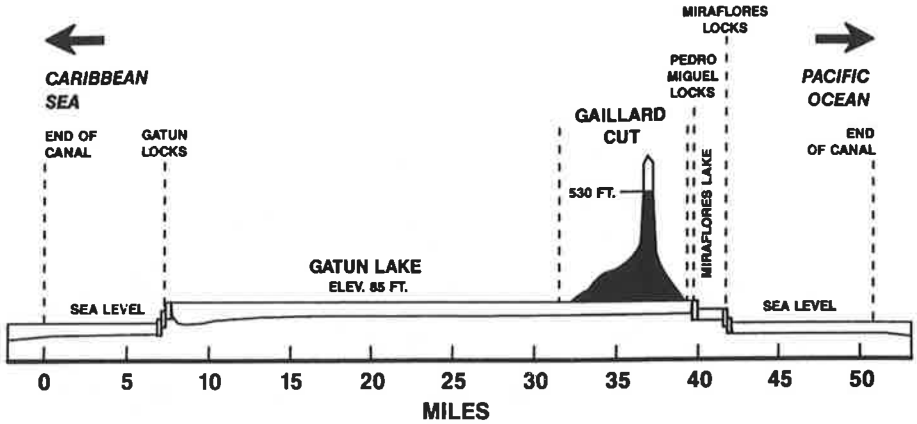
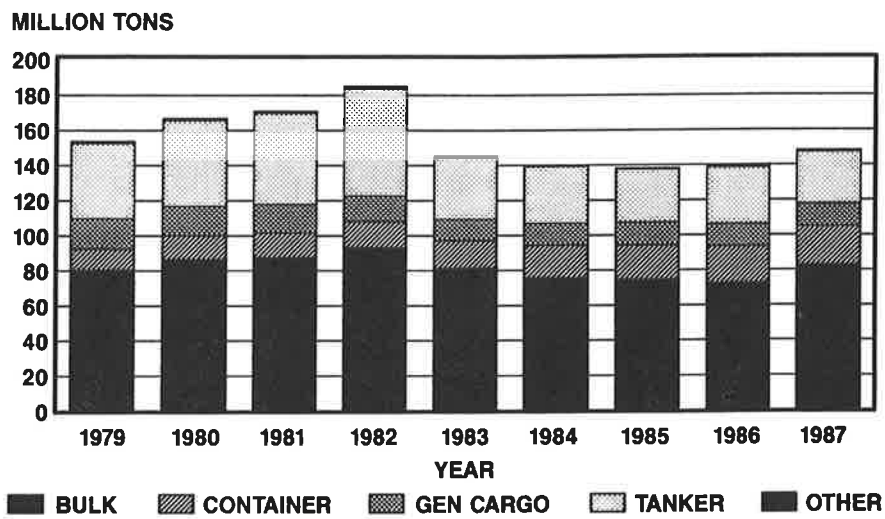


FIGURE 2 Longitudinal profile of Panama Canal (vertical exaggeration 80 times).



Source: Panama Canal Commission, Annual Report.

FIGURE 3 Panama Canal traffic by vessel type: total for both directions.

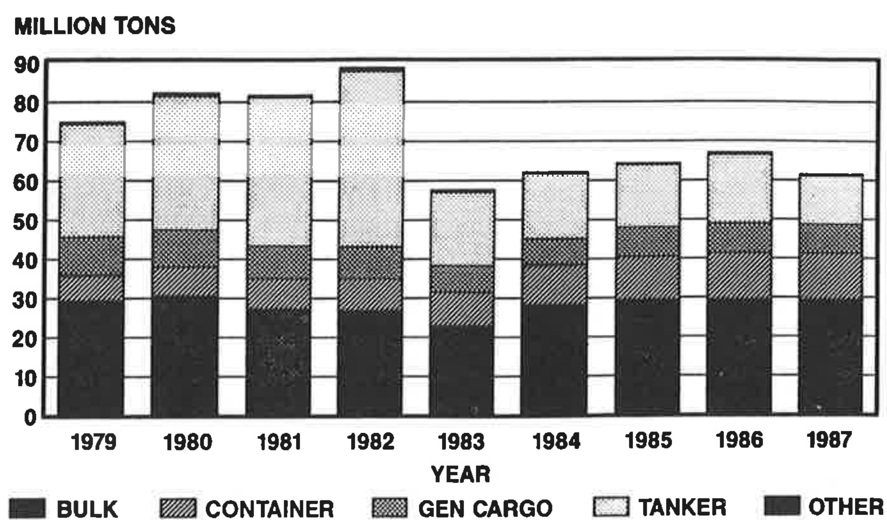
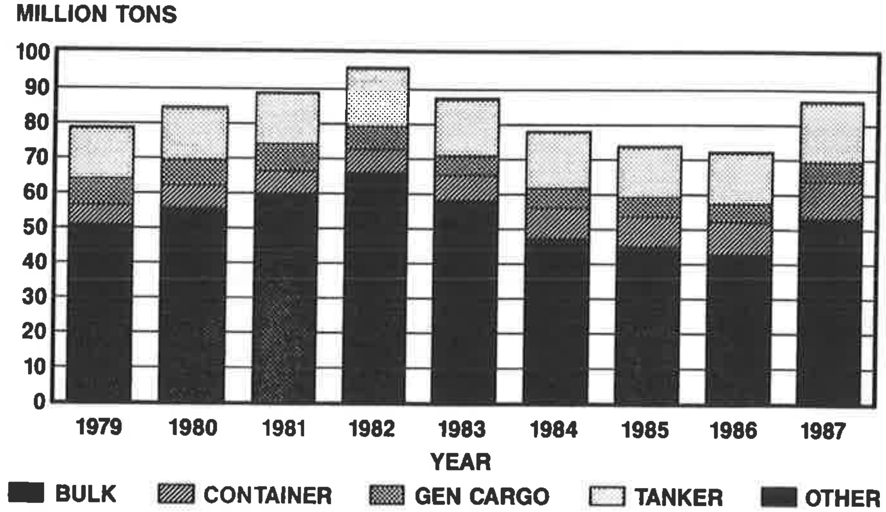


FIGURE 4 Panama Canal traffic by vessel type: Pacific to Atlantic.



Source: Panama Canal Commission, Annual Report.

FIGURE 5 Panama Canal traffic by vessel type: Atlantic to Pacific.

farm products were an important second and coal was growing steadily (Figure 6). With the recession and the oil pipeline opening, coal and petroleum fell markedly. Farm products traffic began declining in 1984. Recovery in 1987 was due to growth in farm products, forest products, and fertilizers and other minerals. Coal and petroleum continue to be weak. By direction, Pacific to Atlantic traffic in petroleum of course plunged in 1983, but there was also weakness in other commodities (metallic ores, farm products) that has persisted to the present time (Figure 7). Growth has been notable only for forest products and fertilizer and other minerals. For Atlantic to Pacific traffic, the fall in coal after 1982 and farm products after 1983 is most prominent (Figure 8). Farm products traffic recovered notably in 1987, and fertilizer and other minerals also showed growth.

Container Trade

Unlike the bulk trades, container traffic through the Panama Canal has generally continued to grow each year, led by rapidly increasing demand for containerized imports to the United States. For example, the growth in containerized imports from Pacific Rim nations to the U.S. more than doubled from 1.3 million TEUs in 1982 to nearly 2.8 million TEUs by the end of 1987 (*5*).

Like the bulk trades, however, containerships have been characterized by continued growth in vessel dimensions. This has culminated in the development of the "post Panamax" container vessel (Figure 9) (Speech by Brig. Gen. Patrick J. Kelly, USACE, on "West Coast Ports and Future Trends" at meeting of Panama Canal Commission, January 1988).

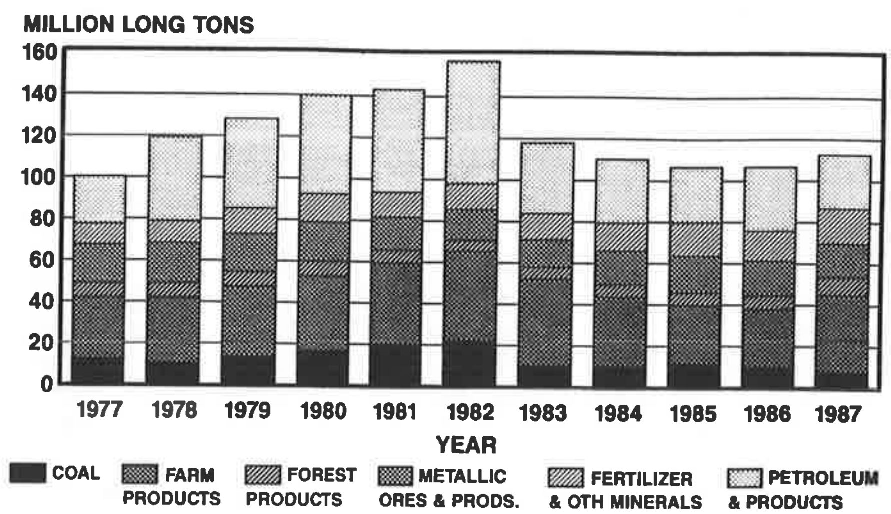
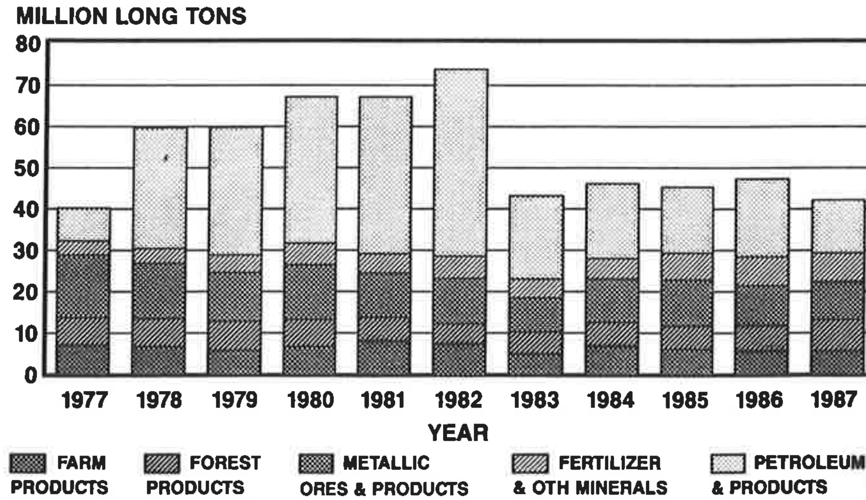
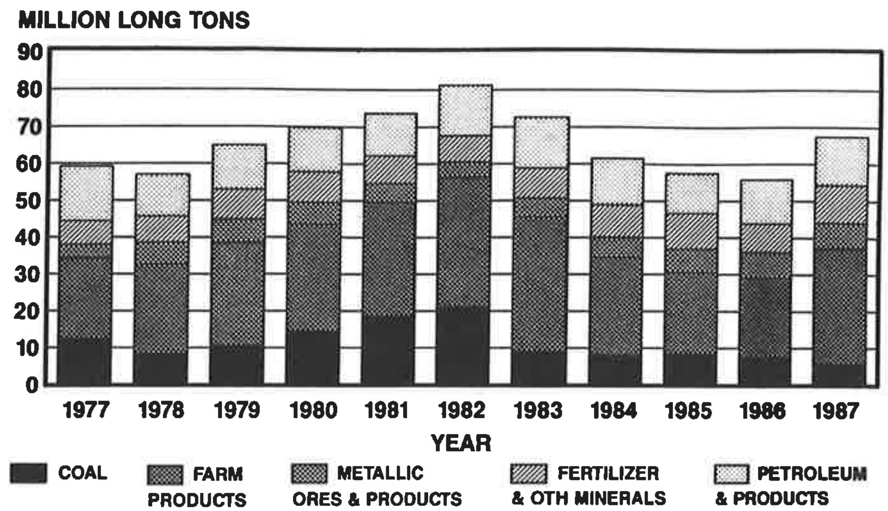


FIGURE 6 Panama Canal traffic: major commodities, both directions.



Source: Panama Canal Commission, Annual Report.

FIGURE 7 Panama Canal traffic: major commodities, Pacific to Atlantic.



Source: Panama Canal Commission, Annual Report.

FIGURE 8 Panama Canal traffic: major commodities, Atlantic to Pacific.

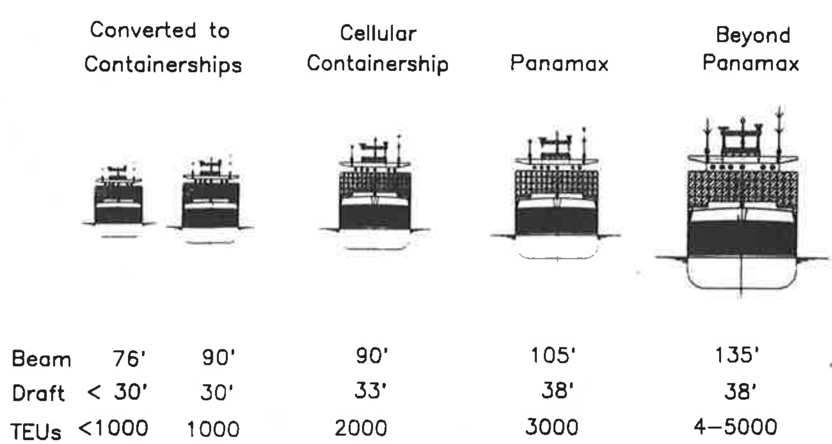


FIGURE 9 Containership evolution: beam size and draft.

Early containerships were modified general cargo ships with a beam of about 76–90 ft. Subsequently, fully cellular containerships were built with about double the TEU capacity of earlier ships. Panamax-sized vessels followed with a beam of about 105 ft and about a third more TEU capacity than the earlier cellular containerships. This was the largest practical vessel beam that would still permit transit of the Canal. In 1988, American President Line (APL) took delivery of five new "C10" ships with a beam of 129 ft, making them the first containerships too wide to transit the Panama Canal (*6*). APL has committed to a strategy of relying on rail minibridge to move Far East imports from West Coast ports to markets in the eastern United States, bypassing the canal. That this APL strategy is paying off is shown by the carrier's dominance of containerized imports entering the Eastern seaboard from Asia (*7*).

The challenge to the Panama Canal from such minibridge movements can be seen graphically in Figures 10 and 11. Containerized imports from the Far East destined for markets in the eastern United States can move via the Panama Canal

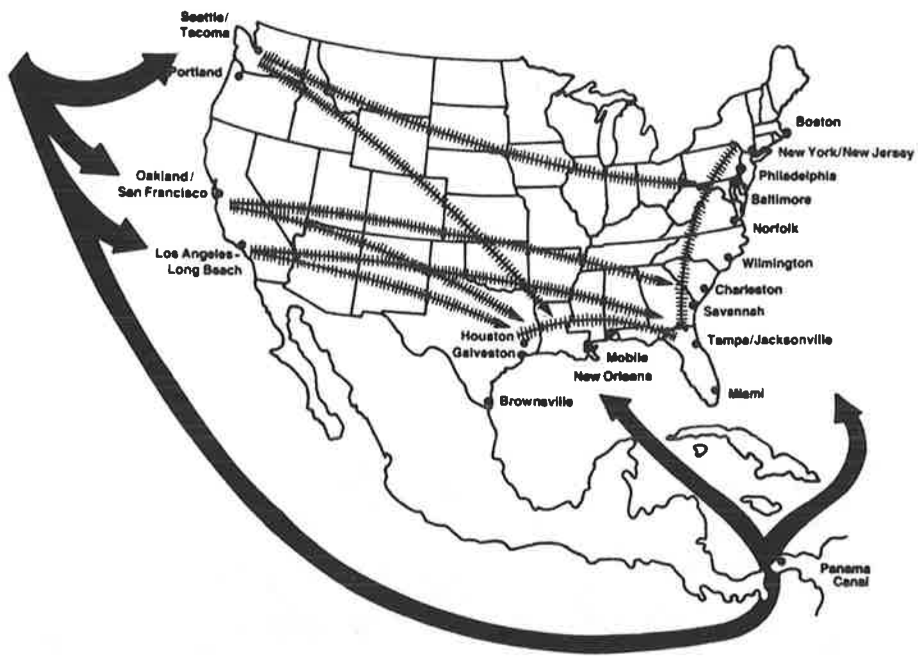


FIGURE 10 East and Gulf Coast via West Coast from Asia.

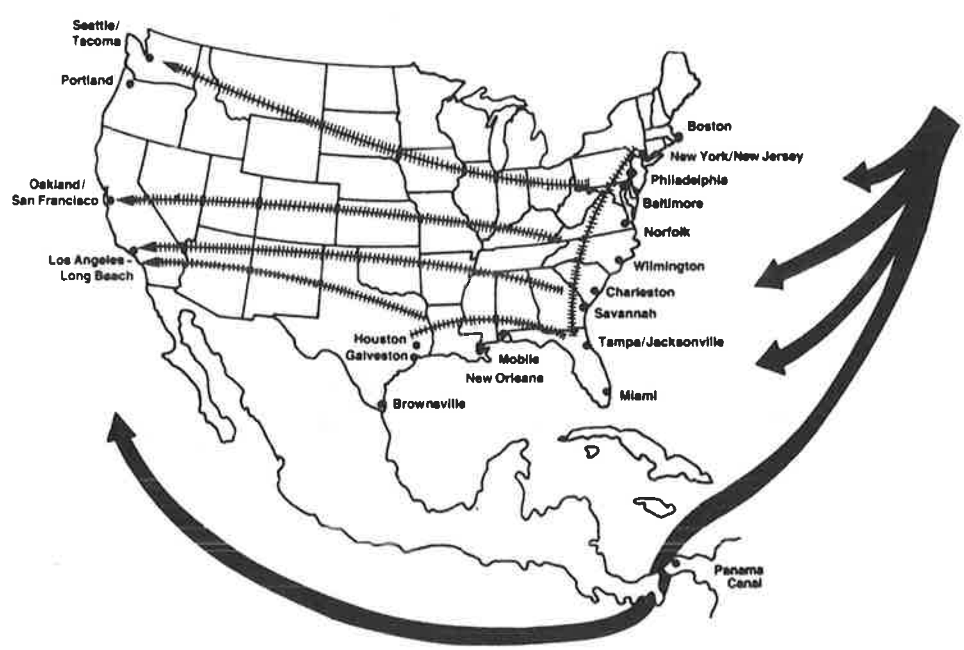


FIGURE 11 Europe to West Coast via East and Gulf Coast.

to ports on the U.S. Gulf and East coasts, as they have done traditionally, or they can be unloaded at a West Coast port and move by rail across the country to their final destination. Likewise, imports from Europe to the markets in the western United States can transit the canal or move by rail from an East Coast port.

As noted earlier, container traffic through the Panama Canal has continued to increase, and, with declining bulk traffic after 1982, containership percent of total volume has grown even faster from about 8 percent in the 1976–82 time period to about 15 percent in the 1986–87 time period (Figure 12) (*8*). Toll receipts from containerships have increased steadily during the 1980s and have accounted for more than 20 percent of Canal revenues since 1983 (Figure 13). However, the containership percent of total receipts has fallen slightly since 1985 as bulk traffic rebounded. Container movements to or from the United States dominate container tonnage through the canal, accounting for more than 70 percent (Figure 14). So emerging technologies such as rail minibridge, which could herald a shift in shipping patterns in the U.S. container trade, have important implications for the canal.

Growth of Minibridge Traffic

Further evidence of the growing importance of minibrige is the rapid increase in containerized imports at U.S. West Coast ports (Figure 15). U.S. Pacific ports increased their share of the nation's container trade from 31 to 46 percent between 1981 and 1987, and handled a little less than 75 percent of the Far East liner trade (*9*). Los Angeles and Long Beach dominate West Coast container traffic, having grown at an annual rate of nearly 20 percent from slightly more than 1 million TEUs in 1981 to more than 3 million TEUs in 1987 (or nearly 23 percent of the U.S. total). Seattle and Tacoma have experienced significant growth since 1984, with volume nearly doubling by 1987 to more than 1.7 million TEUs. The rapid growth in container throughput at the Puget Sound ports

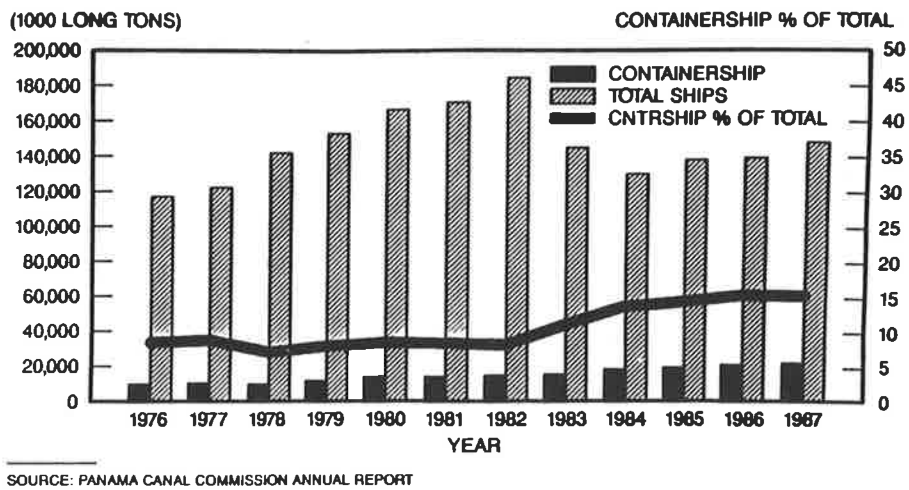


FIGURE 12 Panama Canal traffic, 1976–1987, total transits (in 1,000 long tons)

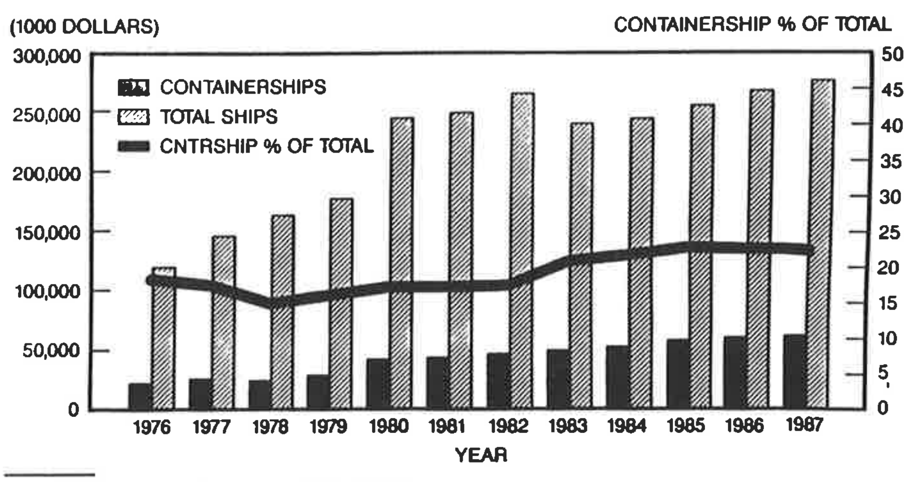


FIGURE 13 Panama Canal toll collection, 1976–1987 total transits (in $1,000).

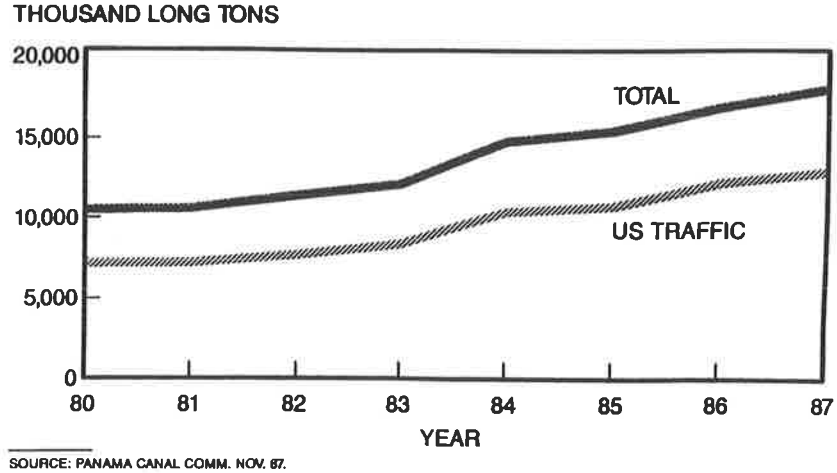


FIGURE 14 Container movements via Panama Canal: total and U.S. traffic.

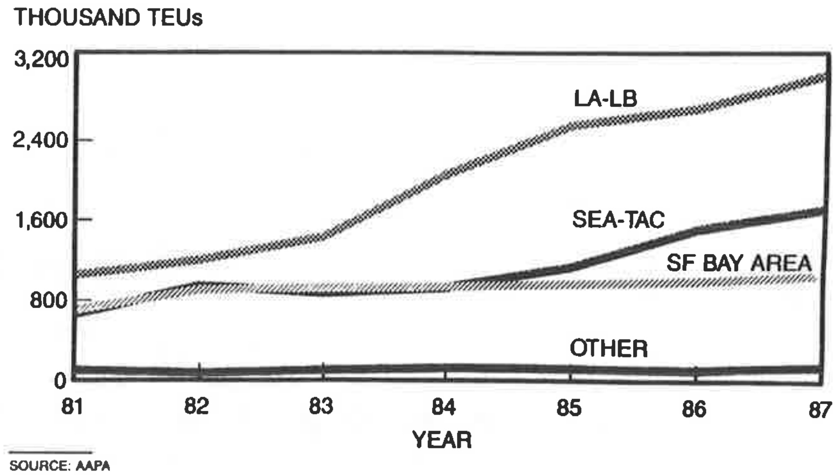


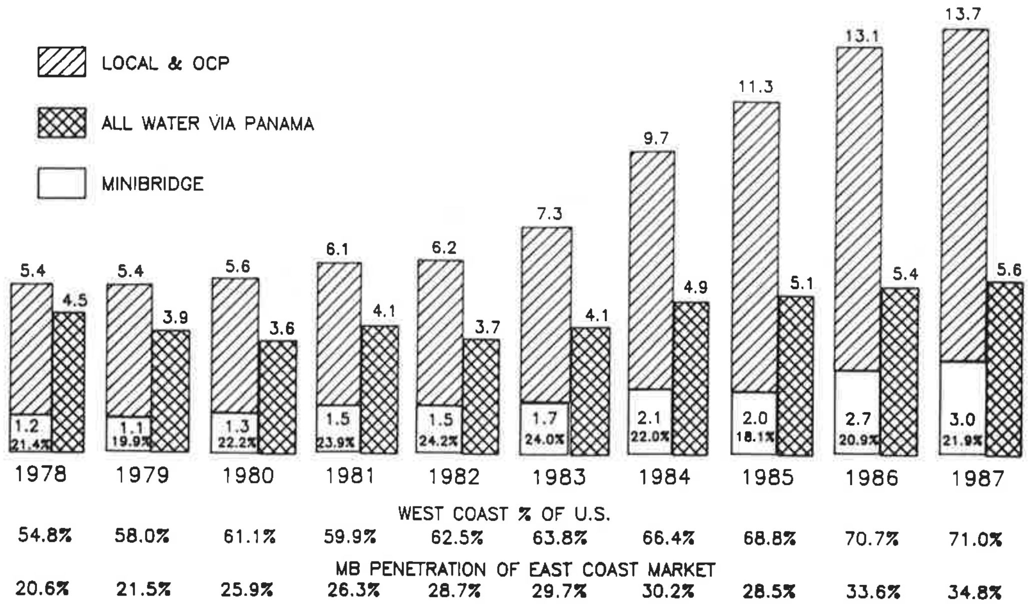
FIGURE 15 Growth in West Coast port container traffic, 1981–1987.

coincides with the introduction of dedicated double-stack rail service from this region to Chicago and the construction of added terminal facilities for this traffic.

An analysis of Census Bureau foreign trade data by the Port of Oakland estimated containerized imports to the U.S. East Coast based on liner traffic statistics (more than 90 percent are generally containerized) (*10*). The study found that minibridge rail traffic in Far East containerized imports bound for the U.S. East and Gulf Coast areas has been growing nearly every year since 1978 (Figure 16). Minibridge volume is estimated to have grown from less than 1.1 million tons in 1978 to 1.7 million tons by 1983 (an annual rate of 9 percent). The rate of growth then increased to more than 15 percent annually, and volume of traffic reached 3.0 million tons in 1987. Meanwhile, liner imports via the Panama Canal increased from 4.1 to 5.6 million tons between 1983 and 1987. The data indicate that minibridge captured a slowly increasing share of the East Coast market, growing from 29.7 percent in 1983 to 34.8 percent in 1987 (for an annual growth rate of about 4 percent).

The economics driving this increase in minibridge rail traffic are based on the savings associated with the use of double-stack container unit trains in dedicated scheduled service between West Coast ports and points in the Midwest and East. A double-stack container train can carry more than twice the cargo volume of a conventional piggyback service and do so with only a marginal increase in locomotive power and virtually no increase in labor (*11*). The potential efficiencies of double-stacks for both railroads and ocean carriers has led to a rapid increase in the number and routes of double-stack unit or mixed trains departing West Coast ports every week for interior and East Coast destinations. The number and destinations of stack trains has proliferated dramatically over the last several years, increasing from 22 per week in February 1986 to at least 76 by January 1988 (*12*, *13*). By August 1988, the number of departures was reportedly over 100 (*14*).

A principal factor driving the increase in rail minibridge traffic is the potential savings in time versus the all-water route (Figure 17). This savings in time can amount to 10 days or more from various Far East ports to New York (*15*). This can



SOURCE: PORT OF OAKLAND, 1988.

FIGURE 16 Far East and SEA liner imports to West and East Coast, 1978–1987 million short tons.

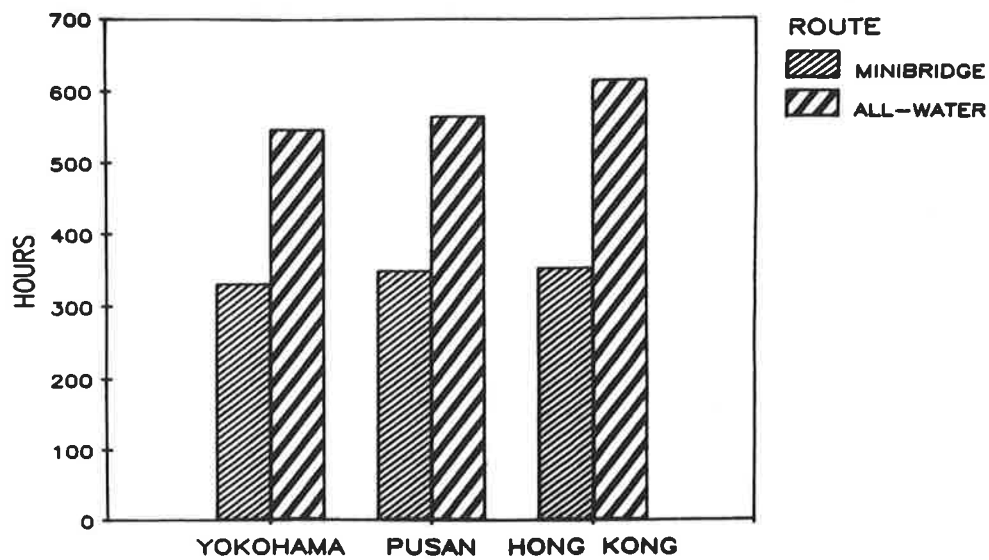


FIGURE 17 Average hours for container movement, selected Asian ports to New York: alternate routes via West Coast minibridge and via all-water through Panama Canal.

be especially desirable for high-value commodities. However, the minibridge cargo movement has to balance the higher cost per mile of the shorter rail movement across the United States with the lower cost per mile of the longer all-water route through the Panama Canal (*16*).

For certain destinations and time-sensitive commodities, the savings associated with double-stack unit trains can make the necessary difference to shift cargo from the all-water route (Figure 18). An analysis by Booz-Allen & Hamilton compared shipping costs from the Far East to U.S. East and Gulf Coast destinations by all-water, by single-stack container-on-flat-car (COFC) unit train from the West Coast, and by double-stack unit train from the West Coast (*17*). The analysis shows a range of costs depending on the Far East origin and makes some favorable assumptions about rail use. In general, however, the study found all-water to be cheaper to Savannah/Charleston and, depending on the origin port, to Baltimore, but only marginally so. Double-stack rail minibridge was cheaper to New York, Houston, and Chicago, and in all cases was cheaper than COFC unit trains. The high all-water costs

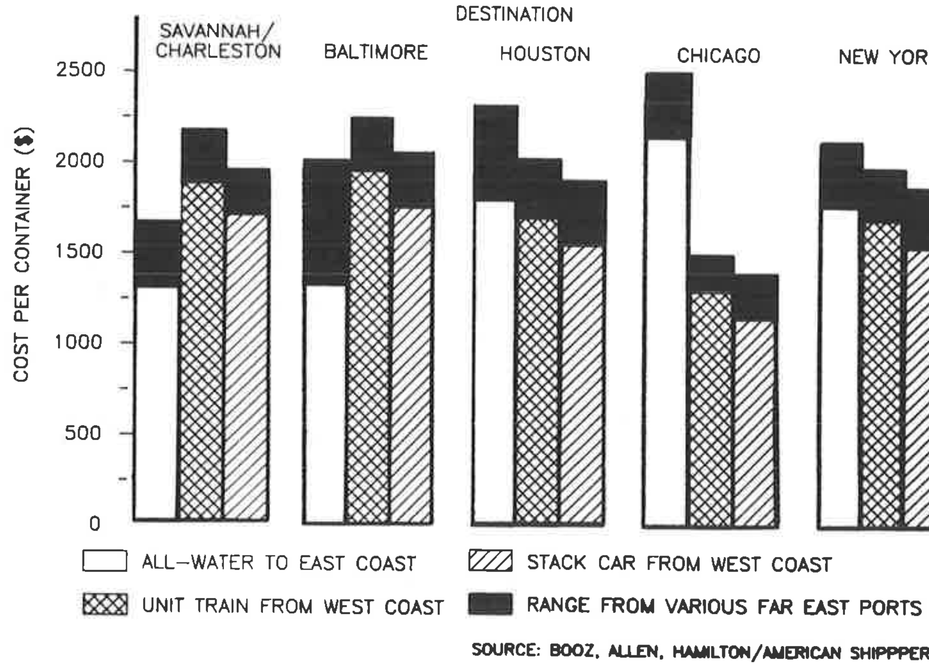


FIGURE 18 All-water versus bridge and stack car operating costs from Asia to selected destinations.

to Chicago are particularly striking and indicate the uncompetitive position of Great Lakes/Seaway ports in trading with the Far East.

For the bulk trades, minibridge rail is not a factor, but changing vessel sizes are. As noted earlier, coal traffic through the Panama Canal showed sizable increases up to 1982 and then dropped off dramatically. The early 1980s was a peak period for U.S. coal exports, totaling more than 112 million tons in 1981 (*18*). Importing nations in Europe and the Far East deepened their ports to handle increasingly larger coal colliers and urged exporting nations to do the same to take advantage of the much lower costs/ton for shipping. Australia and South Africa moved quickly to develop export terminals that could handle very large coal colliers. Canada also has deep draft coal export facilities in British Columbia. The United States, however, was unable to proceed with port-deepening plans until funding mechanisms were reconciled by passage of the Water Resources Development Act of 1986. Now the United States has been surpassed by Australia as the world's leading coal exporter and most forecasts do not project again achieving the level of coal exports of 1981 during the remainder of the century.

The following section presents a similar analysis of the development and traffic patterns of the St. Lawrence Seaway, and the forces of technological change that may be affecting its future and that of the Panama Canal.

ST. LAWRENCE SEAWAY

Earlier in this paper the what, when, where, why, and who of the Panama Canal and the St. Lawrence Seaway were discussed. In this section of the paper, the situation of the St. Lawrence Seaway and information on the world fleet that can transit the restrictive dimensions of the Panama Canal and the St. Lawrence Seaway are reviewed in more detail.

Purpose of the Seaway

The St. Lawrence Seaway was constructed mainly to serve inbound iron ore and outbound grain. The iron ore movement is from Labrador in Canada to steel mills along the U.S. shoreline of the Great Lakes. Iron ore movements are from Sept-Iles on the lower St. Lawrence (as shown in Figure 19) through the St. Lawrence, Lake Ontario, and the Welland Canal to steel centers such as Buffalo, Cleveland, Toledo, Detroit, and Chicago. The iron ore is also transshipped to the Pittsburgh area from locations such as Conneaut and Ashtabula on the shore of Lake Erie. The dominant outbound movement is grain exports from both the United States and Canada. The main grain export from Canada is wheat, whereas the U.S. exports are corn, soybeans, wheat, barley, rye, and other small grains. This movement of the grain downbound in lakers with a return haul upbound of iron ore is a very efficient move. The U.S. grain is unloaded for storage and transferred to ocean vessels at Montreal, Quebec, Baie Comeau, and other ports on the lower St. Lawrence. In addition to the iron ore-grain movement, grain is exported directly from the ports on the Great Lakes to overseas destinations via the Welland Canal and the St. Lawrence Seaway. Potential overseas general cargo is generated by the industrialized and highly populated Midwest of the United States, plus major Canadian cities. Overseas general cargo in the area of the United States that could be served by Great Lakes ports has been estimated at 15 to 25 percent of total U.S. overseas general cargo. However, only a small fraction of that trade moves directly overseas via the Great Lakes/St. Lawrence Seaway, partly because of the 9-month navigation season.

Profile of Great Lakes-St. Lawrence

Why the canals? The extreme topography that must be overcome in arriving at the most inland of the Great Lakes is

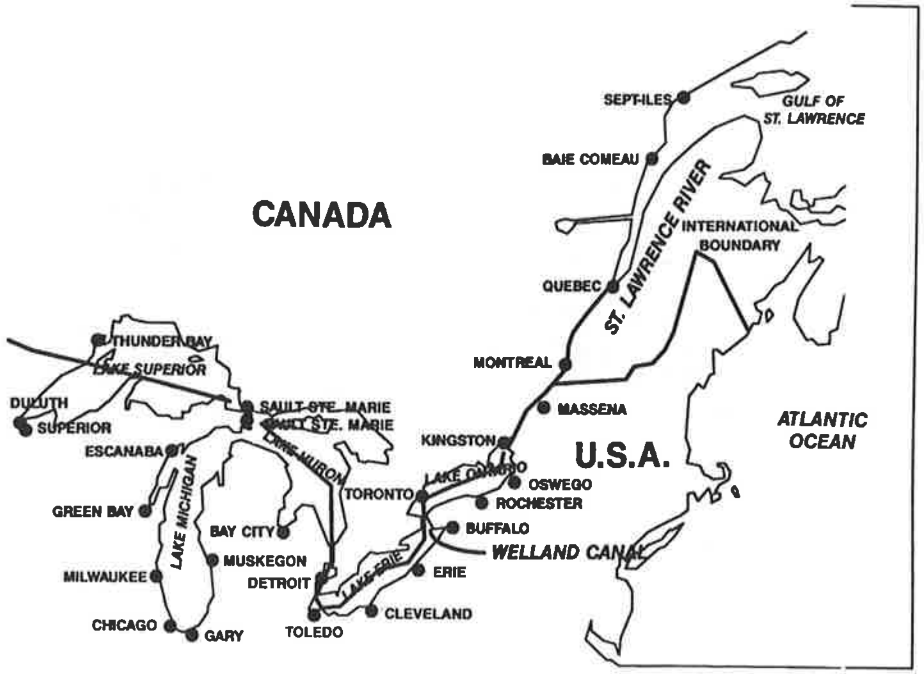


FIGURE 19 St. Lawrence Seaway system.

illustrated in Figure 20. The rise is about 20 ft from the Atlantic Ocean to Montreal at tidewater, which is about 1,000 miles from the sea. From Montreal, the St. Lawrence River has rapids and rises to 248 ft above sea level in Lake Ontario. The next climb, a very steep one in the vicinity of Niagara Falls, lifts the ships via the Welland Canal from 248 to 572 ft above sea level in Lake Erie. The navigation from Lake Erie to Lake Huron and Lake Michigan requires no canals. However, the next jump up to Lake Superior is about a 27-ft rise over the St. Mary's River Rapids, at Sault Ste. Marie, Michigan, and Ontario. This gives a total distance from the Atlantic Ocean to Duluth, Minnesota, at the head of the lakes, as 2,342 miles.

Traffic

The traffic on the St. Lawrence Seaway responded very rapidly from a low tonnage in 1958 with only a 14-ft channel to about 20 million tons in 1959 with the opening of the St. Lawrence Seaway with a 27-ft controlling depth. The traffic continued to increase until 1974, then fell during a recession but rebounded rapidly until it peaked in 1979 at about 74 million tons (Figure 21). The traffic has declined since that time, with peaks and valleys to the current traffic of about 50 million tons in 1987 (*19*). Preliminary estimates for 1988 are an increase of one to two percent (conversation with Robert J. Lewis, Seaway Development Corporation, Washington,

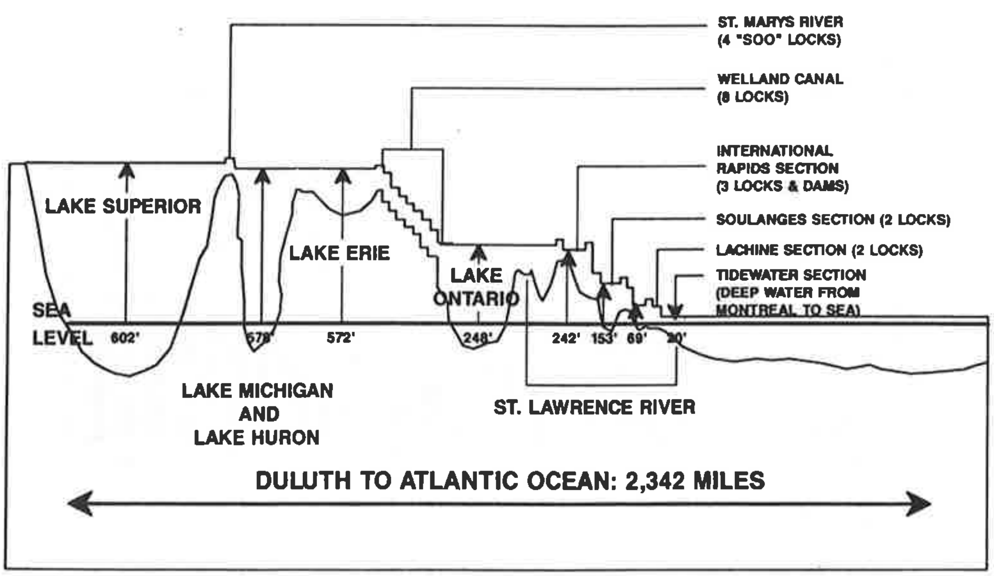


FIGURE 20 St. Lawrence Seaway system profile.

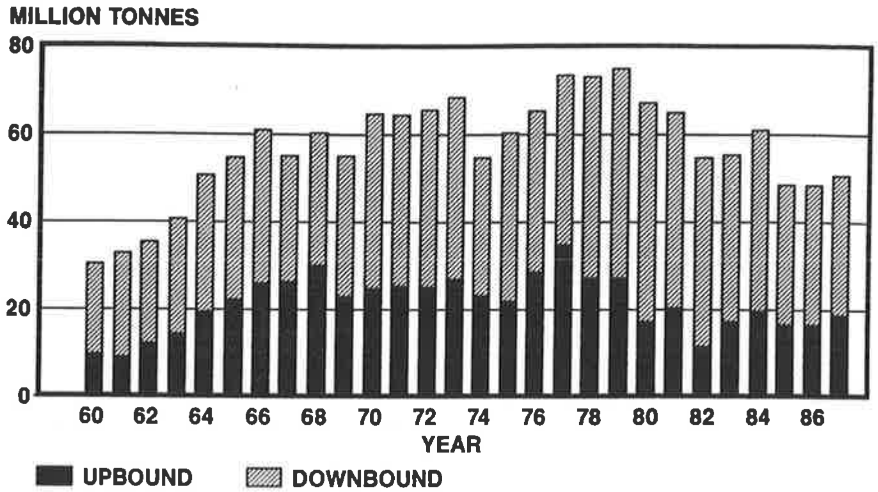


FIGURE 21 St. Lawrence Seaway traffic cargo tonnes (million).

D.C.) The pattern of upbound and downbound traffic shows the upbound traffic peaking in 1977 because of the iron ore movement. It has been on a decline since that time, with some reversal in 1987. The downbound movement has been greater than the upbound movement in most periods, such as 1987 when about 32 million tons moved downbound, whereas only 18 million tons moved upbound.

The revenue received from tolls for 1959 to 1987 is shown in Figure 22 (*20*). This shows a pattern similar to traffic with increases until 1974. Tolls then drop off, followed by a substantial rise in the late 1970s. Presently, tolls are near the 1984 peak, when toll revenue reached $71 million.

Major Commodities and Industrial Types

The composition of the traffic on the St. Lawrence Seaway, on the Montreal to Lake Ontario section is as follows (*20*). The major commodities are Canadian grains at 32 percent, iron ore at 25 percent, U.S. grains at 13 percent, iron and steel at 10 percent, miscellaneous minerals at 10 percent, miscellaneous manufactures at 5 percent, and chemicals and petroleum products at 5 percent. Adding the two grains together, indicates that about 45 percent of the traffic is composed of grains and that is dominantly for export overseas. It is clear that grains combined with iron ore make up about 70 percent of total seaway commerce. The iron and steel is dominantly imported steel; however, there have been some exported iron and steel. The miscellaneous manufactures and the iron and steel that are included among oceangoing general cargo commodities account for only 15 percent of seaway traffic.

Vessels carrying the cargo in 1987 included the laker, which is dominant in the movement of iron ore upbound and grain downbound to the lower St. Lawrence ports. It accounted for 64 percent of the cargo moved and carried 25 million tons (*20*). Ocean ships carried 15 million tons and accounted for 36 percent of the cargo (grain exports as well as general cargo).

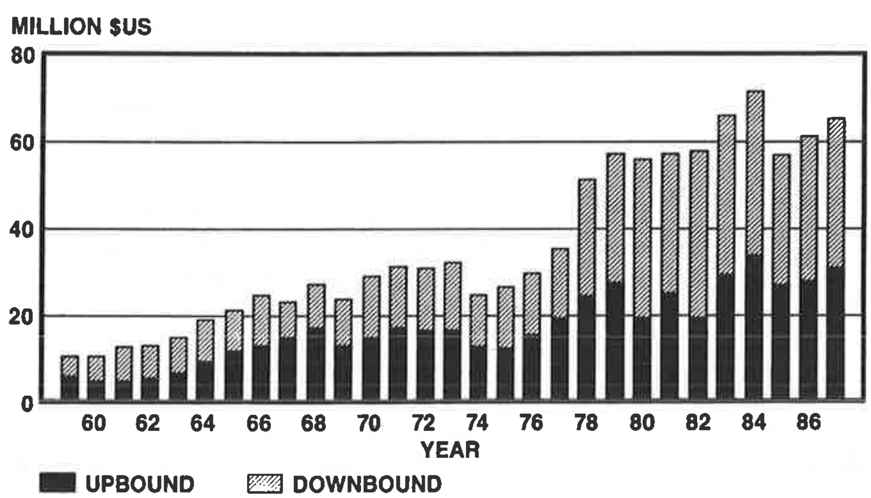


FIGURE 22 St. Lawrence Seaway traffic revenues ($ U.S. million): 1959–1987.

U.S. Areas Served by the St. Lawrence Seaway

Before the opening of the 27-ft St. Lawrence Seaway in 1959, most U.S. Great Lakes ports sought deepening to serve the vessels that would transit the St. Lawrence Seaway. The Corps of Engineers of the North Central Division undertook extensive studies of general cargo (*20*) and grain (*21*) to estimate the future traffic for the Great Lakes ports that were seeking improvement—largely deepening—with federal funds. Most of the Great Lakes ports were in the range of 18- to 23-ft-deep channels. The ocean ports, that is the Atlantic, the Gulf, and the Pacific ports, were all concerned about the competition that would be offered to them by the St. Lawrence Seaway. It is well known that the Midwest was a great generator and consumer of manufactured goods and producer of agricultural commodities. To obtain data necessary for the transportation analyses, an origin and destination study was conducted under agreement with the U.S. Bureau of the Census (*22*). A transportation cost analysis, based on land and ocean carrier costs and least-cost routing models, produced the areas tributary to the Great Lakes ports shown in Figure 23 for overseas general cargo traffic (*20*). As expected, the most extensive tributary area was for Europe, especially northern Europe, which is a great circle route from the Gulf of St. Lawrence. The least extensive tributary area was for the Far East with a routing via the Panama Canal. A parallel study was conducted for grain exports. The result of that transportation cost analysis is shown in Figure 24 (*21*), which depicts the tributary area for wheat exports to Rotterdam. That tributary area is shown extending as far as Montana on the north and into Nebraska and parts of Missouri and central Illinois, central Indiana, and central Ohio to the south. The major differences compared with the general cargo tributary area is that the Minneapolis/St. Paul area is shown being on

FIGURE 23 Areas tributary to the Great Lakes-St. Lawrence Seaway.

Wheat to Rotterdam, Netherlands, Post Seaway — Phase I

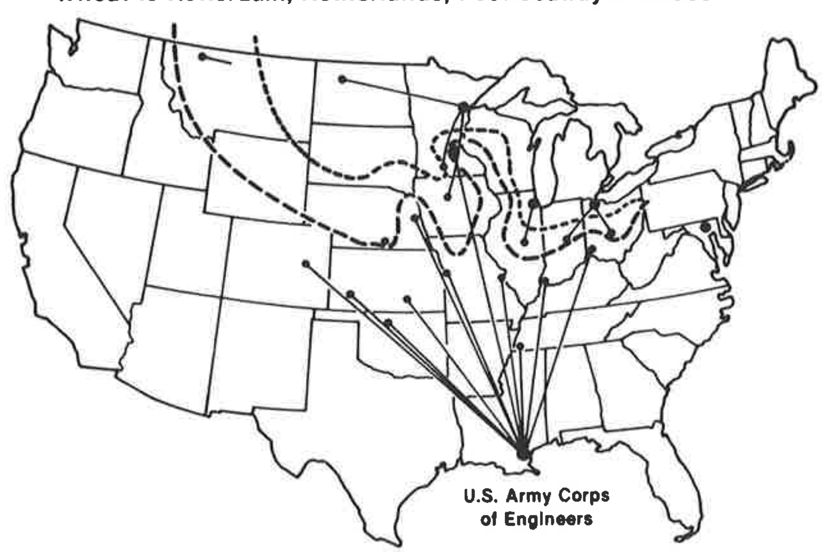


FIGURE 24 Contours of transportation cost advantage for exports via Great Lakes-St. Lawrence Seaway.

the border of the tributary area for grain. This is based on the low-cost barge movements down the Mississippi River from Minneapolis/St. Paul to export in the Gulf. This feature shows that grain traffic from Minneapolis/St. Paul could move either by the Great Lakes or New Orleans for about the same transportation cost. These cost relationships to depict the tributary areas are shown in Figures 23 and 24 and labeled "Phase I," which represented an equilibrium for 1959 continuing to the early or mid 1970s.

Projected and Historical Traffic

The studies conducted produced the projections of imports and exports of general cargo and exports of grain as shown in Figure 25 (*23*). When the studies were made before the St. Lawrence Seaway was built, the existing traffic was 0.6 million tons. In the first year of the seaway, the traffic was about 5 million tons. It continued to increase, as shown by the solid line, to about 12 million tons in 1970, and then, amid peaks and valleys, hit almost 20 million tons in the late 1970s. Traffic then declined to about 8 million tons in the early 1980s and currently is around 10 to 12 million tons. The projected traffic is shown by the dashed line and is very similar to the actual traffic up to the period of the early 1970s, when actual traffic began to experience wide fluctuations. This disparity between the historical traffic and the projected traffic is largely the result of technological changes, which will be discussed in the following sections.

Impact of Technological Changes

The largest volume of traffic on the St. Lawrence Seaway is grain, both Canadian and U.S., which accounts for about 45 percent of the traffic. In the late 1970s and the early 1980s, the United States dominated that grain movement with up to two-thirds of the world's total. Presently, that number is more like 50 percent. Why? The green revolution in many countries resulted in a great increase in production in countries competing with the United States. This green revolution witnessed technological developments in seed, fertilizer, and agricultural practices. Advances in barge efficiency have produced a heavy flow down the Mississippi River for export from New Orleans and other Gulf ports. The development of the 100-ton hopper rail car and the unit train has also provided substantial competition to the Seaway. These efficient movements by rail for grain movements to east and west coast ports have brought further competition for the Seaway. The grain movement on the Mississippi starts at Minneapolis/St. Paul, which is right in the backyard of the Great Lakes. Grain movement to Great Lakes and Seaway ports is dominantly carried out by shorthaul overland movement by truck (*24*). The development of larger ocean vessels that call at ocean ports that have been or are being deepened provides further stiff competition to the Seaway, with its fixed dimensions. The shift by western Europe from major importer to exporter of grain has changed U.S. export markets to areas less favorable to the St. Lawrence Seaway route. The U.S. Great Lakes ports' percentage of the nation's grain exports has declined over the years from a high of about 15 to 20 percent in the early years of the Seaway to around 10 percent of the U.S. waterborne grain exports currently moved by the Seaway.

For general cargo, the technological advances in transportation have been in the field of containerization, which has brought very stiff competition to the Great Lakes. All time-sensitive shipments, which may be of high value, are candidates for the ports that can provide highly frequent service and are able to accommodate large containerships that cannot transit the Great Lakes/St. Lawrence Seaway. Development of the double-stack container car and train has brought even more efficiency to the inland movements serving ocean ports. Chicago has become the major center for a transfer of double-stack trains from east and west coast origins and destinations. Containers are distributed from Chicago by either train or truck. The port of Milwaukee recently announced double-stack train service resulting from rail movement of double-stack cars from Montreal as the deep-water port.

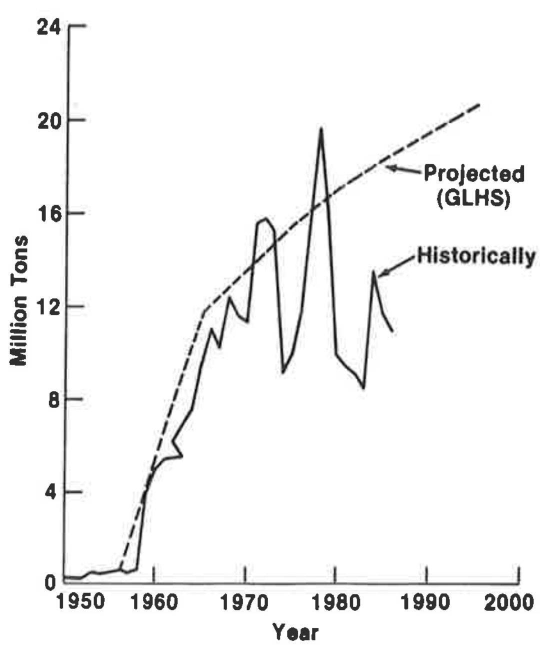


FIGURE 25 U.S. Great Lakes-overseas: direct waterborne commerce.

Technological Changes and Transportation Costs

Technological changes in transportation have resulted in lower costs to the shipper, as noted in Figure 26 (*25*). The 4,200-TEU containership has a cost of about 0.3 cent/ton-mile compared with 1 cent/ton-mile for the 1,800-TEU containership. This compares with the conventional freighter of about 4 cents/ton-mile. This difference has a decided impact on movement of traffic through the Panama Canal, which cannot accommodate the 4,200-ton ship, or through the St. Lawrence Seaway, which largely accommodates the conventional freighter. For rail movement, the double-stack express train is shown as about 3 cents/ton-mile, compared with the conventional rail which ranges from about 4 to about 15 cents/ton-mile or an average of about 8 cents/ton-mile. For further cost comparisons, the relative shipper cost index for a variety of over-

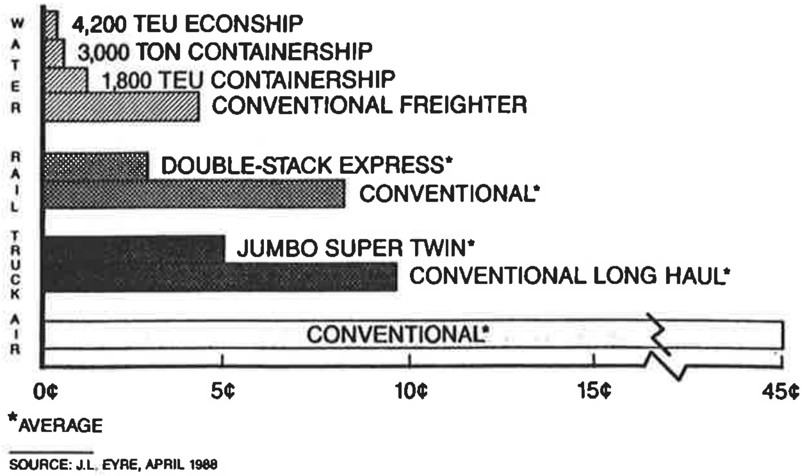


FIGURE 26 Cost per ton mile.

land movements is shown in Figure 27. Using truck as an index of 100, the twin trucks are shown at 65, the box car at 80, the trailer and flat car at 75, and the container on a flat car at 65. The double stack, however, is 40. This 40 index represents about a 38 percent saving over the conventional COFC or the truck twin 45s.

Another factor in the movement of foreign trade is that of port costs. The cost for New York is $36/ton for handling containers, whereas for Boston and Baltimore it is $31. For U.S. west coast ports it is $25. This cost differential helps the economy of the minibridge movements from the U.S. west coast ports. The port of New York has recently announced a substantial rebate for container traffic that originates or terminates in a 250-mi radius.

Another aspect of transportation costs is that of the balance of movement. The imports of merchandise from Asia have been the dominant move in recent years, although there has been some recent improvement in the export picture. The U.S. merchandise trade balance for March 1988 is shown in Figure 28. This indicates that on the plus side, the first bar is the agricultural commodities, which are to the right, or a favorable plus balance of trade. The long bar indicates manufactured goods, the dominant move in containers. Other major commodities not containerized are petroleum and products, and bituminous coal, which is a plus but is a bulk commodity without backhaul potential. To rectify the situation, the major U.S. and foreign lines have developed a pattern in which they handle containerized domestic cargo as a backhaul that moves from eastern and Midwest points to U.S. west coast ports. This gives a balance of movement and hence reduces the overall cost.

World Fleet Able to Transit the Panama Canal and the St. Lawrence Seaway

To attempt to determine the world fleet able to transit the Panama Canal and the St. Lawrence Seaway, computer runs of Mardata were made based on (a) the length and beam limitations discussed earlier in this paper and (b) length, beam, and draft limitations, assuming that the ship was loaded to capacity. Data were developed for major types of vessels: containerships, general cargo, roll-on, roll-off, (RO-RO) vessels, dry bulk carriers and tankers, and these are shown in Table 1. The results for the Panama Canal are shown in Figure 29. Based on the number of ships in the world fleet and the limitation of length and beam, approximately 80 percent of the world's fleet could transit the Panama Canal. But if the

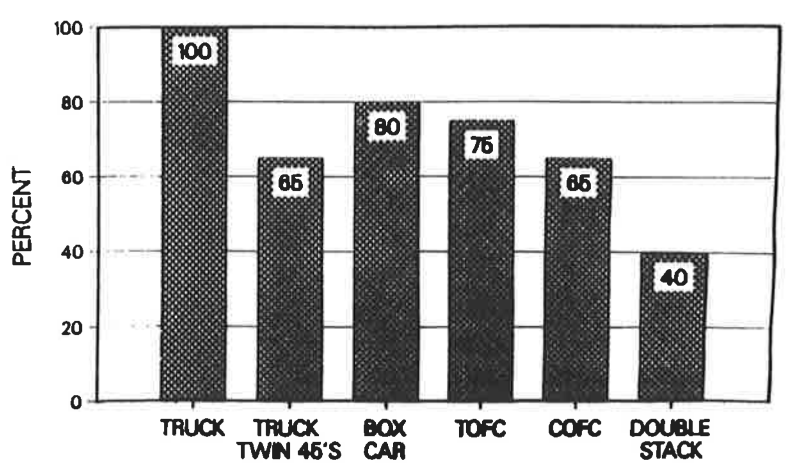


FIGURE 27 Relative shipper cost index.

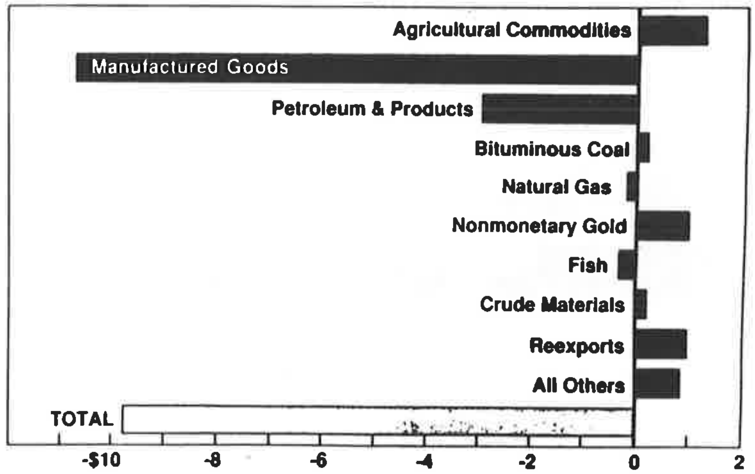


FIGURE 28 U.S. merchandise trade balance by category for March 1988 (in $ billion)

TABLE 1 PERCENT OF WORLD FLEET ABLE TO TRANSIT PANAMA CANAL AND ST. LAWRENCE SEAWAY

	Existing Vessels		Vessels On-Order	
Panama Canal				
	Vessel Maximum Dimensions (Feet)			
Length	950	950	950	950
Beam	106	106	106	106
Draft, 15 ft to	no limit	40	no limit	40
	Percent of World Fleet Based on Number of Ships			
Dry Cargo Vessels[2]	84	81	61	54
Dry Cargo Vessels and Tankers	80	76	53	47
	Percent of World Fleet Based on Deadweight Tons			
Dry Cargo Vessels[2]	73	60	40	26
Dry Cargo Vessels and Tankers	50	41	27	17
St. Lawrence Seaway				
	Vessel Maximum Dimensions (Feet)			
Length	730	730	730	730
Beam	76	76	76	76
Draft, 15 ft to	No Limit	26	No Limit	26
	Percent of World Fleet Based on Number of Ships			
Dry Cargo Vessels[2]	63	37	35	21
Dry Cargo Vessels and Tankers	57	35	28	17
	Percent of World Fleet Based on Deadweight Tons			
Dry Cargo Vessels[2]	33	10	11	4
Dry Cargo Vessels and Tankers	20	7	6	2

Source: Mardata and computer compilations by U.S. Army Corps of Engineers, Water Resources Support Center, Institute for Water Resources, Jan 1989.

(1)Based on stated maximum dimensions for existing and on-order vessels.

(2)Containerships, general cargo vessels, RO-RO vessels and dry bulk carriers.

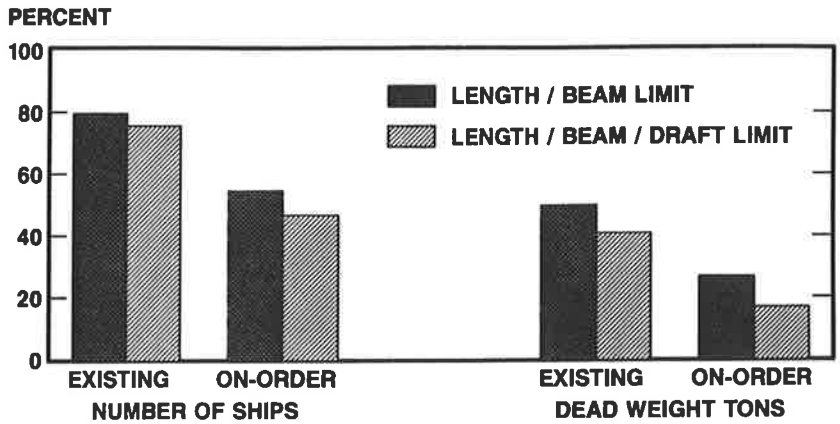


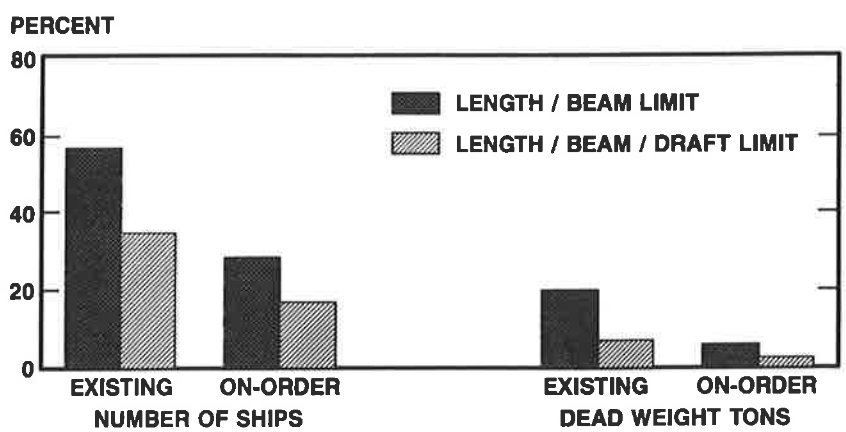
FIGURE 29 Percent of world fleet able to transit Panama Canal: existing and on-order for major vessel types.

limitation of draft is added, assuming fully loaded ships, that 80 percent reduces to about 76 percent. However, looking at future ships on order for the next 5 years, this figure drops to 53 percent of the world's ships, based on length and beam, or about 47 percent if the draft limitation is added. Based on deadweight tonnage, as shown in the right-hand-side of Figure 29 of the existing ships, only 50 percent would be able to navigate the Panama Canal based on length and beam, and only 41 percent with draft limitation. For ships on order, this drops to 27 percent of the ships based on length and beam limitation and 17 percent based on addition of the draft limitation. The percentages are all a bit higher if only dry cargo vessels are included in the analysis, as noted in Table 2.

The data for the St. Lawrence Seaway are shown in Figure 30. Based on the number of ships in the existing world fleet and on length and beam limitation, 57 percent of the world fleet could transit the St. Lawrence Seaway. However, if the limitation of the draft is added for fully loaded ships, this decreases to 35 percent of the world fleet that can transit the St. Lawrence Seaway. For ships on order, based on number of ships, only 28 percent of those would be able to transit the Seaway based on length and beam and a further drop to 17 percent is noted if a draft limitation for fully loaded ships is added. Based on deadweight, even lower percentages are noted as follows. Based on beam and length limitations, only 20 percent of the ships can transit the Seaway, and only 7 percent of the world fleet if the draft limitation is added. For ships on order and based on the deadweight category, only 6 percent of the world's fleet could transit the seaway based on beam and length limitations, and only 2 percent if the draft limitation is included. A slightly higher percentage of the world fleet that can transit the Seaway based on dry cargo vessels only is shown in Table 2. The impact of the increasing size of vessels and the problem of the fixed dimensions of canals limiting the fleet that can transit those canals is obvious.

SUMMARY

The following briefly summarizes the major factors previously noted: the ship size, the containerization, and the minibridge, which includes the double-stack. Affecting the Panama Canal is the pipeline moving crude petroleum from the Pacific to the Atlantic. For the St. Lawrence Seaway, the technological



Source: MARDATA NETWORK.

FIGURE 30 Percent of world fleet able to transit St. Lawrence Seaway: existing and on-order for major vessel types.

changes in the steel industry, including taconite, have had a profound effect. Agricultural development abroad and the green revolution have severely affected grain exports. An additional factor, although not necessarily technological, is deregulation, which, along with the unit train and 100-ton car, has had a great impact on the St. Lawrence Seaway. In summary, technological changes have produced more efficient transportation and have shaken the existing transportation routings to create entirely new patterns of commodity movements.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the general guidance and support provided by James R. Hanchey and Lloyd G. Antle of the Water Resources Support Center. They also wish to thank James Gould, Leigh Skaggs, Robert Swett, and Shandra Myers for valuable technical assistance in compiling this paper.

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Publication of this paper sponsored by Committee on International Trade and Transportation.

Use of Advanced Train Control Systems in Scheduling and Operating Railroads: Models, Algorithms, and Applications

PATRICK T. HARKER

Presented in this paper is an overview of a series of models and algorithms that have been developed for use with advanced train control systems technology on railroads to improve the reliability and costs of operations. After the conceptual framework of a hierarchy of control models is described, examples are used to illustrate the use of the various models at each level.

The railroad industry in the United States is currently undergoing major restructuring of its technology and management practices. Before the deregulation of the industry in 1980 through the Staggers and Motor Carrier acts, railroads were dominated by their operating departments; that is, they were focused on cost reductions at the expense of good marketing techniques [see Keeler (*1*) for a comprehensive review of the state of the rail industry before deregulation]. Such a situation of low cost-low quality (as measured by reliability of arrivals, loss and damage of freight, and so on) was very profitable when the U.S. economy was dominated by bulk commodity production. However, the movement toward the production of high-valued goods and the implementation of more efficient (e.g., just-in-time) inventory policies created a demand for highly reliable and flexible freight transportation services. As a result, railroads today are reinvesting in technology and restructuring their management practices to respond to the market's demand for better transport service.

Recent technological developments in advanced train control systems (ATCS) and high-speed computers have provided railroads with a unique opportunity to automate many functions in rail operations and thus to restructure their management systems. The Burlington Northern (BN) Railroad is precisely in this situation. The BN is one of the largest railroads in the United States, with approximately 25,000 mi of track covering the northwestern and central portions of the country. The BN is considered to be a very "progressive" railroad by most in the industry because of its development of many innovative technologies and management practices. For example, the BN has the highest revenue per employee at corporate headquarters (*2*).

The BN, however, has the same data problem that faces all major railroads. Of the 25,000 mi of track, one-third is "dark territory," in the sense that whenever a train enters this portion of the rail network, the dispatcher knows its position only through voice communication with the train crew. In addition, signal blocks on a railroad like the BN can be long (30 mi), and when a train enters such a block all other trains are prohibited from using that portion of track. Obviously, such a system does not make maximum use of the available track capacity. Furthermore, congestion at yards (terminals) that is caused by too many trains arriving within a short time period is a direct result of poor planning of traffic throughout the rail network and leads to sometimes dramatic underuse of yard capacity.

To overcome the difficulties mentioned above, the BN, in conjunction with Rockwell International, is in the process of developing the Advanced Railroad Electronics System (ARES). As described by Welty (*3*), ARES uses the NAVSTAR Global Positioning System, which is being developed by the U.S. Air Force to provide locational information (plus or minus 50 ft) for each train or maintenance of way vehicle on the system at any point in time (750 to 2,500 trains). In addition to this location information, ARES includes the EMS locomotive system, which provides automated procedures for train handling and energy conservation, and the ROCS dispatching system, which uses the location information from each train to help the dispatchers do a better job of operating the rail lines. Of course, any fully-implemented ATCS system will provide a similar wealth of information.

Thus, an ATCS like ARES provides a wealth of data heretofore not available to railroad management. However, this "wealth" can be more like a "flood" if the proper models and associated algorithms are not available to use this information effectively. The purpose of this paper is to provide an overview of an ongoing research project at the University of Pennsylvania that is attempting to develop such models and algorithms. An overview of the series of problems being studied is given in the first section, details on two of these models are given in the next two sections, and a summary of the progress to date and an overview of future research are given in the last section.

THE CHASE FOR MODELS

In order to use the information generated by an ATCS effectively, a series of models and computational procedures are necessary:

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Schedule policy evaluation
↕
Tactical scheduling of trains
↕
Real-time scheduling
-trains
-locomotives
-crews
-cars
↕
Computer-aided dispatching
↕
Optimal train control

Each level of this model hierarchy is briefly discussed in the following paragraphs.

The first question to ask when implementing an ATCS is whether or not a railroad should run scheduled operations. At first glance, this seems to be a rather odd question, particularly for those accustomed to European or Japanese railroads. However, substantial cost savings can be achieved if a "tonnage" operation is run; that is, trains depart from a yard when sufficient traffic has accumulated. Of course, reliability as measured by the variance of travel time will suffer under such a system compared with a scheduled operation. In either case, the question of which policy to follow in the scheduling of trains should be made at the long-term planning level by incorporating the tradeoffs of crew and equipment costs, service quality, and the ability to affectively route empty cars and locomotives. The ability to address this long-term question requires the development of detailed simulation and analytical models that incorporate a total view of rail operations, not simply a model that focuses on the movements of loaded trains between two points.

Once an overall schedule policy has been decided, this policy must be implemented on a weekly or monthly basis. This tactical scheduling of trains differs from the previously mentioned strategic question in that all trains at the tactical level will have schedules. Thus, for those trains that must be scheduled (passenger, intermodal, etc.), the tactical scheduling procedure will create a set of feasible schedules; that is, a set of schedules that are logically consistent in the sense that an operating plan exists that can achieve the times stated in the schedules with high probability, given the delays encountered by each train as a result of random occurrences (wind, breakdowns, etc.) and interference with other trains. For trains that run on a tonnage basis, scheduled slots would exist. That is, trains would not be permitted to depart at random but instead must depart within a stated time window if they are to be operated on a given day. Thus, a tactical scheduling system must also have the capability to create such slots and check that they are feasible when considered alone and when combined with the other scheduled traffic.

Given the tactical schedules, the purpose of the real-time models is to develop operating plans that will achieve the stated schedules as well as possible, given that events have occurred (breakdowns, crew shortages, etc.) that disrupt the plan of operations on which the tactical schedules are based. For trains, the aim is to develop a plan of arrival and departure times at each major yard or, more generally, at each point at which the planning of the train operations changes (that is, a boundary of the dispatchers' territories). For crews, locomotives, and cars, their movements are planned to guarantee that sufficient resources are available at each yard to achieve the tactical schedule plan.

After defining the arrival and departure times of the trains at the boundaries of the dispatchers' territories (i.e., a planning line), the computer-aided dispatching system attempts to schedule the meets and passes along a rail line along with planned arrival and departure times at intermediate points (sidings, beginnings, and ends of double track, etc.) to assure compliance with the times passed from the train-scheduling model. Several approaches have been proposed for this function (*4*), but all tend to ignore the fact that significant fuel savings can be achieved by pacing trains; that is, to have the trains travel at less than maximum velocity to save fuel. In addition, the planning of meets and passes along with a planned pacing of trains will tend to increase the probability of arriving at the destination on time because it is possible to speed up if disturbances do occur. Planning at maximum velocity does not provide this flexibility.

Finally, the dispatching system provides each train with a specific goal for the time and velocity at which it should reach each point on its path. The engineer and the on-board computer system must then calculate a velocity profile (a combination of throttle and dynamic-air brake settings) that will achieve this goal in a safe and fuel-efficient manner. Again, a pacing problem must be solved for the train, a problem that is now much more complex because of the nature of train forces and handling techniques.

This discussion has described the flow of information down the model hierarchy. Of course, the reverse flow is also very important. The train must constantly inform the dispatching model of its location and performance, the dispatching system must inform the network control model of the status of planning lines, and the performance of the network control system (the interline planner) must be monitored to assess the long-term viability of various schedule policies.

At present, the research program underway at the University of Pennsylvania is attempting to address all of these issues. In the following paragraphs, two topics will be discussed: (a) the computer-aided dispatching system and interline planning model, and (b) a new decision-support system for tactical scheduling. Because of length requirements, all of the details of these models cannot be discussed in this paper. However, reference is made to the relevant technical reports that are available from the author.

TACTICAL SCHEDULE VALIDATION AND CREATION

Given the overall policy concerning the frequency of train departures, the tactical scheduling problem is to create schedules for all trains that are logically consistent; that is, that there are operating plans that can achieve these schedules with high reliability. As described by Assad (*5*), many simulation and optimization models exist for the analysis of rail operations. However, no model exists that can answer the simple question: Is a given set of schedules feasible under the best operating conditions in the sense that there exists a plan of operation that can achieve the scheduled times? If not, what minimal changes can be made to the schedules to make them feasible? If they are feasible under the best circumstances, what is the reliability of achieving these scheduled times when adverse conditions exist? Note that a large-scale optimization model could be developed that would attempt to find optimal schedules, given well-defined cost or profit criteria (see, for example, Crainic et al. (*6*). However, the definition of such an objective function is extremely difficult, given the tradeoffs of marketing concerns, costs, crew, and equipment use. Thus, the approach taken in the Schedule Analysis (SCAN) system (*7*) is to provide a decision-support tool that answers the logical questions of whether or not schedules are feasible, and leaves the marketing-cost tradeoffs to the analyst. As designed, SCAN is meant to support weekly or bimonthly updates to the stated schedules.

SCAN is an interactive decision-support system that contains three modules: a data base system for the updating of track and train data as well as train schedules, an algorithm for checking whether or not a given set of schedules is feasible, and a Monte Carlo simulation technique for the calculation of the reliability of a given set of schedules. The feasibility algorithm takes as input the train schedules, track topology, and the free (unobstructed) meetpoint-to-meetpoint running times for each train, which are calculated by one of many train performance simulators (TEM, TPS, etc.). Given this data, the feasibility algorithm searches for a meet-pass plan that can achieve this given set of schedules. If no plan can be found, the schedules are labeled infeasible and the algorithm presents the plan that would require the minimal change to the schedules to become feasible. The details of this integer-programming-based algorithm can be found in Jovanović and Harker (*7*). If the analyst wants help in changing the schedules to achieve feasibility, SCAN contains a set of heuristics to attain this goal. However, the analyst is encouraged to make these changes manually because of the complex tradeoffs mentioned previously.

Once the schedules have been modified so that they are feasible in the best case, the analyst may wish to know how often feasibility would be maintained under more adverse conditions (adverse weather conditions, breakdowns, etc.). SCAN answers this question through a simulation technique in which probability distributions of the free-running times for the trains are used as input to a Monte Carlo model. The result of this simulation is the percentage of time adherence to the schedules under variable operating conditions can be expected.

To illustrate the working of the SCAN system, consider the example given in Figure 1; this shows the track topology on the vertical axis, the time of day on the horizontal axis, and the schedules for each train as straight lines connecting the departure and arrival times. Looking quickly at this set of schedules, it is tempting to conclude that they are feasible, given the spacing of the schedule lines. However, the analysis of these schedules with SCAN first uncovers the problem that some trains are scheduled to operate faster than is physically possible (i.e., in time lower than the free-running time). Once these problems are resolved, SCAN begins to uncover more subtle problems. For example, in Figure 2, no plan exists that could have Train 3 and Train 34 both arrive on schedule; in the best case, Train 34 would be late by 10 min. Thus, the schedule of Train 3, Train 34 or both must be changed to become feasible. After many such changes, a feasible schedule is achieved, as indicated by the feasible meet-pass plan shown in Figure 3. Once these feasible schedules are found, a simulation analysis finds that the schedules are not very reliable; that is, the schedules were feasible in only 8 percent of the cases in which random delays to the trains were introduced. Thus, more time must be added to certain train schedules to increase this reliability. The details of several other examples that illustate the various features of SCAN can be found in Jovanović and Harker (*7*).

SCAN is currently being used to reschedule a major U.S. railroad as well as to analyze various capital improvements and maintenance policies. The ability to achieve a given set of schedules is obviously influenced by the track topology. The impact of changes in track layout on the performance of the train movements should be carefully considered; with SCAN, this relationship can be made explicit and seems to be a major use of such a system. For example, consider the situation shown in Figure 4, which is a portion of double-tracked railroad with two small pieces of single track. In analyzing this situation with SCAN, the problem that is uncovered is not necessarily that single track exists but, rather, that the speed limits on the portion of single track between MTPNT-2 and MTPNT-3 continually create infeasibilities in the schedules (note the shallow slope of the lines in Figure 4 on this portion of the track). Thus, one way to resolve this problem is to upgrade the single track to allow higher speed limits and not to go to the expense of adding an additional track at this point.

REAL-TIME CONTROL OF TRAIN MOVEMENTS

Once the tactical schedules have been set for the day, the purpose of the real-time scheduling system is to attempt to achieve the times stated in the schedules with a high degree of certainty. In practice, events (breakdowns, accidents, etc.) will occur that may inhibit the system from attaining the scheduled goals. Thus, the real-time models attempt to minimize the deviations from these goals, and, at the same time, operate the trains in a safe and fuel-efficient manner. In this section, two such models will be described, along with the results of preliminary empirical studies.

Network Control of Train Movements: Interline Planning

The interline planning model attempts to minimize the deviations of arrival-departure times at various points on the rail network for each train from the times stated in the tactical schedules. As described by Harker and Kraay (*8*), this problem can be formulated as a large-scale mathematical program. This model takes the following general form:

Minimize disruptions to schedule + block switching delays

+ costs for work rule violations

Subject to:

Crew change constraints

Physical constraints of the trains

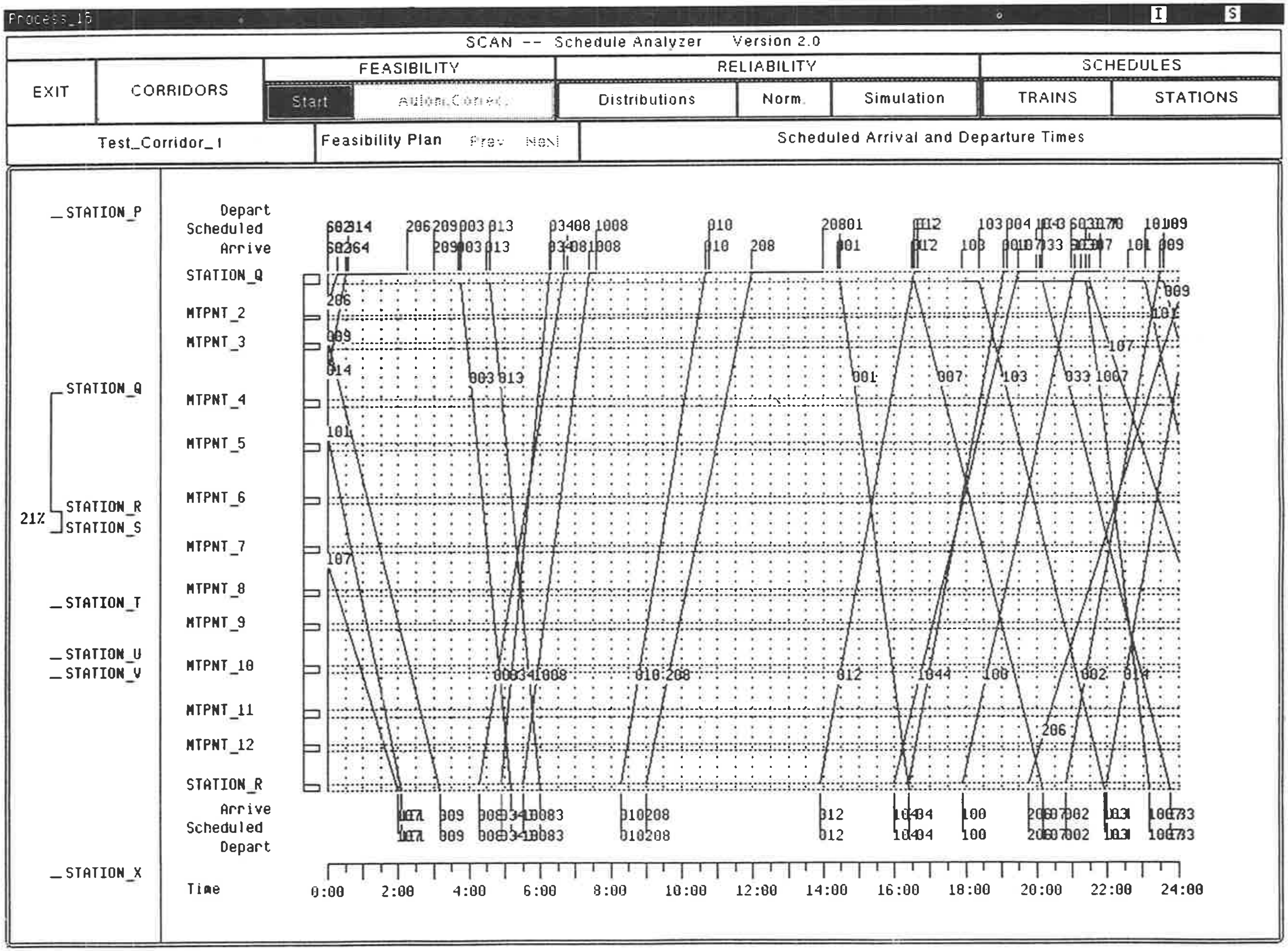

FIGURE 1 Schedules for SCAN example.

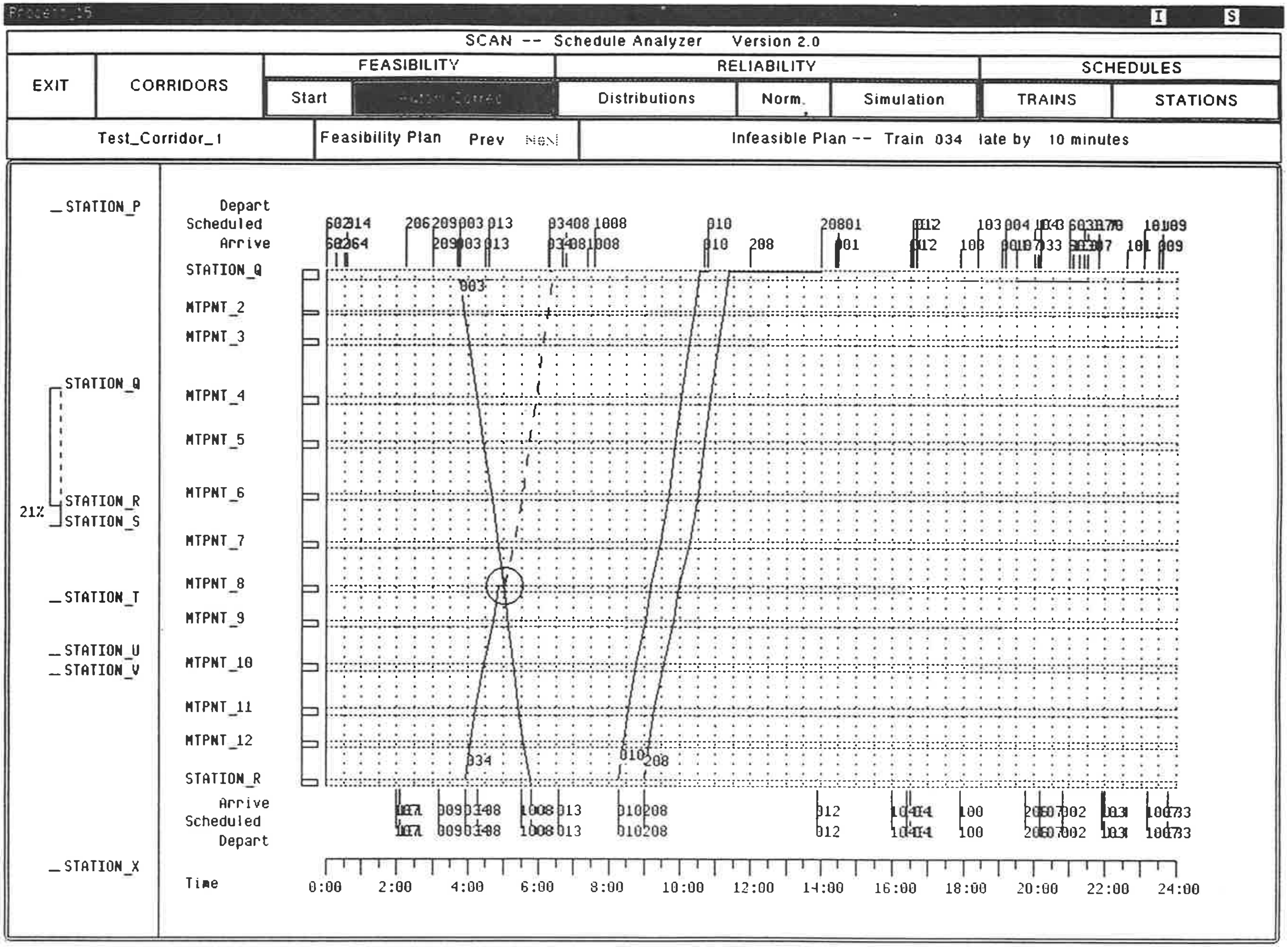

FIGURE 2 Infeasibilities uncovered by SCAN.

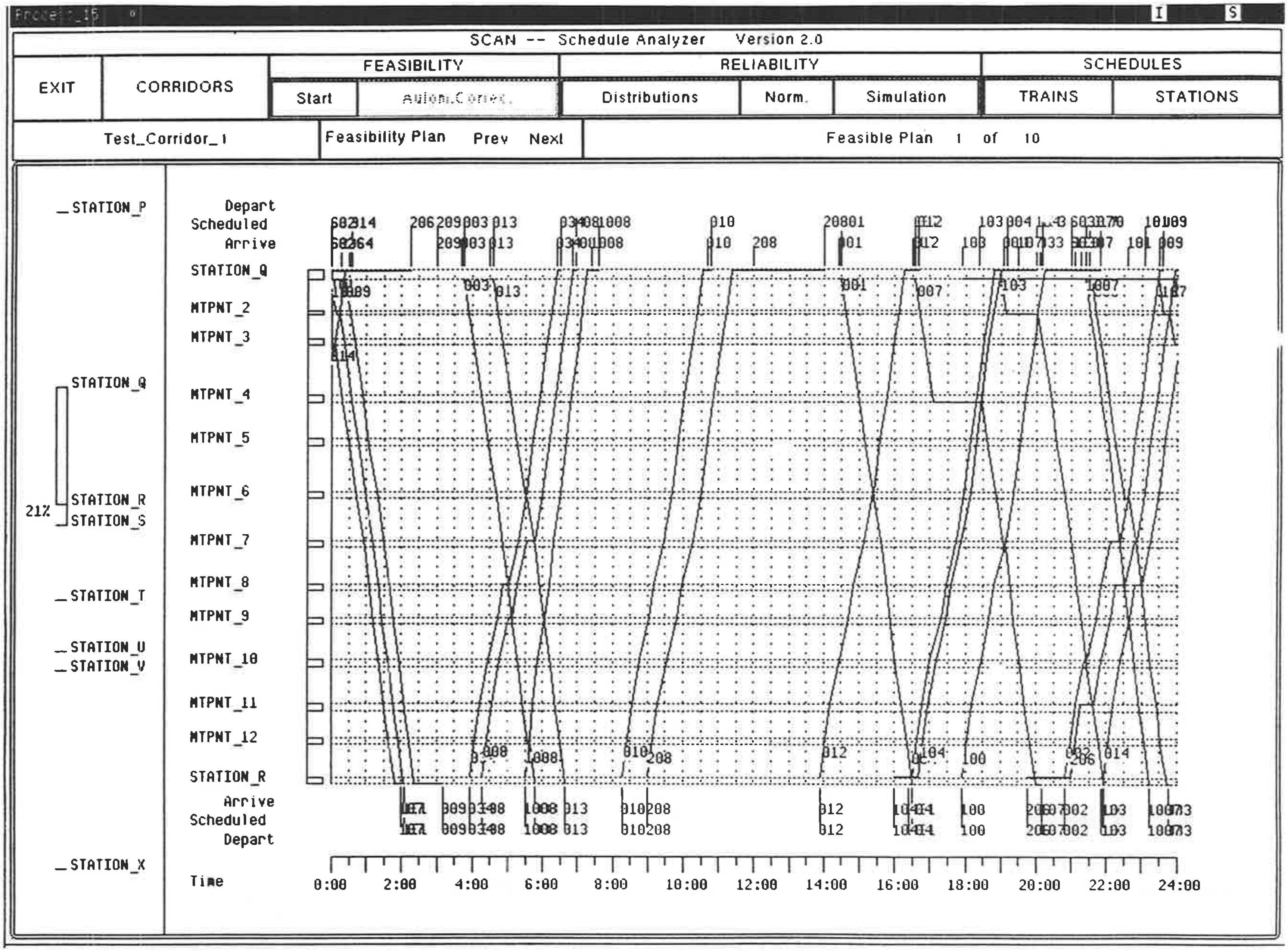

FIGURE 3 One of several feasible operating plans.

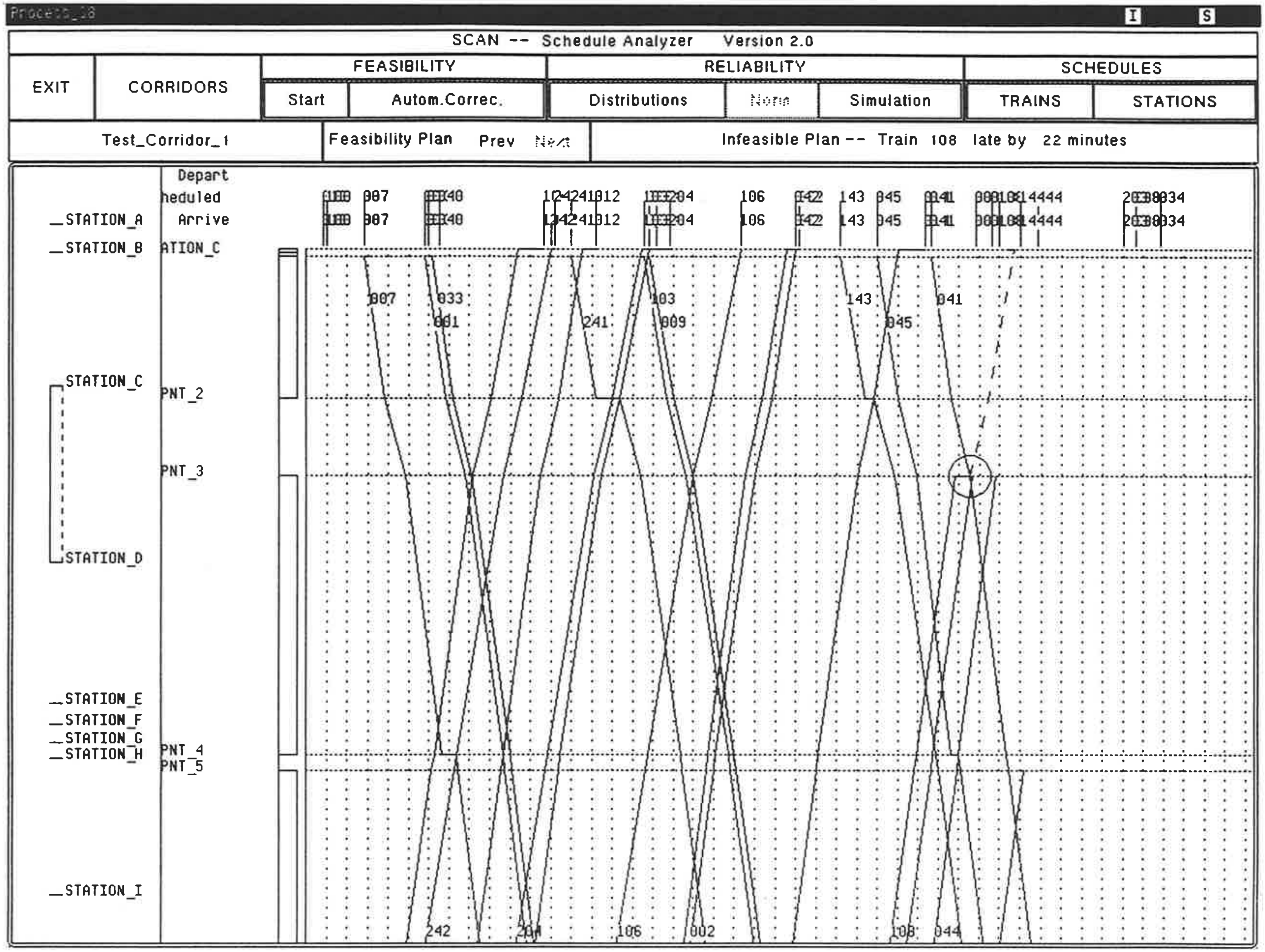

FIGURE 4 Double-track bottleneck example.

Arrival time ≥ departure time + free-running time + delays

Logical constraints

The disruptions to schedule can be any metric of the time of arrival-departure at a point (the variables) and of the stated times in the schedule (the data from a SCAN-like system). In particular, these metrics may be weighted because for a given point, it may not be crucial that a particular train arrive on time, but for another train its on-time arrival may be vital. The cost of block-switching delays refers to the fact that cars will most likely have to switch trains at least once in their journey from origin to final destination. Blocks of cars are often scheduled to travel on one train and then switch to another train at a predefined yard. Thus, a precedence relationship is defined for the arrivals of trains at a particular yard by these block-swapping conditions. Of course, if a block of cars misses a particular outbound train, it can travel on another departing train, but with a possible increase in the total travel time for the cars. The cost of the block swapping reflects this increased cost resulting from cars missing their planned connection at a yard. Finally, train crews are required by law to work no more than a prespecified number of hours. If the crews reach this limit, various penalties are assessed; these penalties define the last term of the objective function.

The first set of constraints simply states that crews must be changed at prespecified points on the network. The physical constraints of the train assure that each train departs after it arrives from a particular point, that sufficient time is given to the train if it must perform work at a given point (picking up and setting out cars, maintenance, etc.), and other such conditions. The third set of constraints states that the total running time of a train (arrival at point $i + 1$ minus the departure from point i) must be greater than or equal to the free running time of the train plus any interference delays caused by the meeting and passing of other trains on the system. Finally, the logical constraints ensure that if two trains are scheduled to meet or overtake on a specified portion of the network, then this activity will occur at the stated point.

The interference delays used in the third set of constraints merit discussion. There exists a large amount of literature dealing with the delays encountered by trains operating on single- or double-track railways. However, these models all assume that trains depart randomly according to a uniform or Poisson distribution. In reality, the trains that are considered within the planning horizon of the interline planning model will depart at or near the planned departure time. That is, the departures are not purely random but rather occur with some error around the stated departure time. To correct for this inaccuracy in the literature, Chen and Harker (*9*) have developed a model of delay for scheduled traffic that is formulated as a system of nonlinear equations. Using the successive approximation algorithm, Chen and Harker show how the mean and variance of travel times and hence the reliability of on-time arrival can be efficiently calculated.

The model just described is formulated in Harker and Kraay (*8*) as a mathematical program with a nonlinear objective function, nonlinear constraints because of the delay functions, and integer variables arising from the logical constraints. Research is currently under way to develop algorithms for this problem that are suitable for parallel-computing environments. A preliminary discussion of this research can be found in Herker and Kraay (*8*).

Computer-Aided Dispatching: the Pacing Problem

Once the interline planning model computes the time windows (targets) for the arrival and departures of each train in the network, the goal of a computer-aided dispatching system is to derive a meet-pass plan for the operation of a given planning line (the portion of the rail network between two specified points that makes up a dispatcher's region of authority). There have been many attempts at developing such a system (*4, 9*). All of these methods try to minimize some measure of cost while assuring that the line is operated safely. Typically, this cost consists of fuel consumption and the cost of arriving early or late at the ends of the planning line. The algorithms are typically simple branch-and-bound methods that implicitly enumerate all feasible plans.

Two problems exist with the current state-of-the-art in computer-aided dispatching. First, by treating the arrival times as a cost rather than as a hard constraint, the models provide the dispatchers with a great deal of freedom to operate their line efficiently. Such freedom typically evolves into a system in which trains are given absolute priorities and some trains are made very late at the expense of others. Furthermore, the dispatchers are often too busy to consider the impacts of late or early arrivals on the performance of the rail network outside their regions of authority. However, it may often be the case that a high-priority train may be delayed to expedite the arrival of a late train even if the latter train has a low priority; priorities are therefore endogenous rather than specified a priori. Also, the minimization of cost along a single planning line may lead to a suboptimal operating plan for the entire network unless the impacts outside the planning region are taken into consideration.

The second problem with the current state-of-the-art involves the hurry up and wait philosophy on which most rail systems operate. Consider, for example, Train 007 in Figure 3. At MTPNT-3, this train arrives 1½ hr earlier than necessary in order to meet the two northbound trains. Because fuel consumption rises as the square of velocity according to the David formulae (*10*), it is far better to pace this train to MTPNT-3 so that it will travel at a lower speed from STATION-Q to this point. Thus, one can simply slow down a train to arrive on time at a planned meet. Can it be done even better? Consider Trains 103 and 100 on the right-hand side of Figure 3. Note that Train 103 arrives approximately 1 hr early at MTPNT-2 for its meet with Train 100. Train 100, on the other hand, arrives 1½ hr early at its destination, STATION-Q. Why not simply slow down both trains? If this were done, Train 100 would not make its meet with Train 007 at MTPNT-7, Train 103 would be late for its meets at MTPNT-10 and MTPNT-11, and so forth. The problem with changing the times of Trains 100 and 103 is that the locations of the meets have been decided, a priori, rather than making this decision simultaneously with the times of arrivals at each meetpoint (and hence, the planned velocity of each train).

The pacing model, as defined by Kraay, Harker, and Chen (*11*), is a mathematical program that attempts to simultaneously find the meet-pass plan (where trains meet or pass) and velocity profiles for each train (their arrival times at each meet-pass point), which minimizes the cost of operating a rail line subject to the scheduled time windows and at the same time conforms to the various operating policies of the railroad. In addition to conserving fuel, this notion of pacing may increase the reliability of train operations. If plans are made in such a way that all trains travel at maximum velocity, then any disruptions can propagate throughout the line, delaying many other trains. By pacing, late trains may have excess power, which will permit them to travel faster than planned to achieve the stated arrival times if disruptions do occur.

The pacing model selects the locations for each meet and overtake, as well as the time of arrival of each train at each intermediate point in the planning line so as to

Minimize cost of fuel + operating penalties

Subject to

Meeting the scheduled time windows at the ends of the planning line

Physical constraints of the trains

Speed restrictions

Logical constraints

The objective function of this model is nonlinear because of the fuel consumption term and the various forms that the operating penalties can exhibit. The time windows simply state that each train should not be permitted to leave the origin yard before the time defined by the interline planner, and should not arrive early or late to the destination yard. The physical constraints portray the physical capabilities of the train vis-à-vis acceleration and deceleration, and the speed restrictions ensure the safe operation of each train. The logical constraints are used to ensure that siding capacities are not exceeded; headways between following trains are maintained; various priority rules are observed; and that any other "reasonable" conditions, such as following trains being permitted to pass one another once at the most (i.e., no leap frogging) are observed. Thus, the pacing model is a large-scale, mixed integer, nonlinear program that must be solved in real time and with a range of solutions—not just one. This latter condition is essential if the model is to be used effectively, because dispatchers may often reject the optimal solution in favor of some other, less optimal solution because of circumstances not considered by the pacing model.

In Kraay et al. (*11*), several alternative algorithms were considered. The best solution procedure is a rounding heuristic in which a velocity profile for each train is computed for each train by not considering the interaction with any other trains. This problem becomes a much smaller nonlinear program that has a special structure. Once these "unconstrained" velocity profiles (and hence, arrival times for each train at each point) have been computed, any conflicts that occur at infeasible points (e.g., a meet in the middle of single track) can be moved to the nearest siding and all of the necessary logical constraints can be obeyed at the same time. This rounding procedure can be accomplished through a modification of the SCAN feasibility algorithm described in the previous section. Once a feasible meet-pass plan has been found via this rounding procedure (the places where trains are scheduled to interact), a nonlinear program with additional constraints is solved in order to compute the times of arrival. This last step is necessary because of the interactions between all trains previously described in the case of Trains 100 and 103; that is, the algorithm must attempt to adjust all the times simultaneously to avoid infeasibilities. In certain cases, this simple rounding procedure can be proven to produce the optimal solution. In other cases, the experimental work reported by Kraay et al. (*11*) shows that this heuristic is quite good.

Preliminary empirical evidence suggests that significant fuel and delay costs can be achieved through the use of this model. In the analysis of current practice, dispatchers tend to become overburdened when many trains are placed under their control. In such cases, they tend to follow the simple practice of dealing first with the highest priority trains, and then progressively moving toward those trains with low priority. The pacing model, by treating all of these decisions simultaneously, often yields significant cost savings. The details of this empirical work will be reported in a subsequent paper. Finally, this notion of pacing extends to many other areas of transportation. For example, the scheduling of barge and ship traffic in a canal (*12*) fits well into this paradigm; these topics will also be explored in the future.

Optimal Control of Train Movements

The pacing model provides the train with the time at which it must reach the next point on its path as well as the velocity at which it should pass this point. The goal of the onboard computer system is to help the engineer achieve this time and velocity constraint in a safe and fuel-efficient manner. This problem has been formulated by Harker and Chen (*13*) as a nonlinear optimal control problem. In fact, both a deterministic model and a stochastic model that take into account the random nature of train performance caused by engine problems, wind, other weather conditions, and so on, have been formulated and analyzed. Research is now underway to develop fast and effective solution procedures for these models.

Summary and Future Research

The hierarchy of models presented in this paper has one goal in mind: to smooth the flow of traffic in rail networks by effectively using the wealth of information available from an ARES-like positioning system. In order to achieve this goal, a simple principle applies: keep it simple! Major policy tradeoffs are made at the top, the SCAN system attempts to implement these policies through the development of tactical schedules, and the real-time control systems develop operating plans that achieve these goals while optimizing performance. Note that this flow of authority is quite different from that typically seen in railroad control systems in the United States; in such systems, cost is typically the driving force. In the schema presented in this paper, the marketing-customer concerns drive the schedules and thus the entire operating philosophy. Simplicity is achieved by clearly stated goals: dispatchers are to obey time windows, engineers the arrival times given by the dispatcher, and so on.

The research that is currently under way at the University of Pennsylvania involves the fleshing out of this hierarchy through the development of the necessary models and algorithms. In addition, various cost-benefit studies are being pursued to ascertain the ability of such a system to improve the reliability and costs associated with freight railroading. In addition, extensions of these concepts to other modes of transportation and, in general, manufacturing processes are currently being explored.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation Presidential Young Investigator Award and by a grant from the Burlington Northern Railroad. The comments of David Kraay, Dejan Jovanović and the staff at the Burlington Northern Railroad are warmly acknowledged.

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Publication of this paper sponsored by Committee on Electrification and Train Control Systems for Guided Ground Transportation Systems.