TRANSPORTATION RESEARCH

RECORD

No. 1313

Freight Transportation

Freight Transportation: Truck, Rail, Water, and Hazardous Materials 1991

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1991

Transportation Research Record 1313
Price: $24.00

Subscriber Category
VIII freight transportation

TRB Publications Staff
Director of Publications: Nancy A. Ackerman
Senior Editor: Naomi C. Kassabian
Associate Editor: Alison G. Tobias
Assistant Editors: Luanne Crayton, Norman Solomon
Graphics Coordinator: Diane L. Ross
Production Coordinator: Karen S. Waugh
Office Manager: Phyllis D. Barber
Production Assistant: Betty L. Hawkins

Printed in the United States of America

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

Freight transportation: truck, rail, water, and hazardous materials 1991.
p. cm.—(Transportation research record, ISSN 0361-1981 ; no. 1313)
Papers presented at the 70th Annual Meeting of the Transportation Research Board held in Washington, D.C. in 1991.
ISBN 0-309-05124-X
1. Freight and freightage—Congresses. I. National Research Council (U.S.). Transportation Research Board. II. National Research Council (U.S.). Transportation Research Board. Meeting (70th : 1991 : Washington, D.C.) III. Series: Transportation research record ; 1313.
TE7.H5 no. 1313
[HE199.A2]
388 s—dc20 91-41574
[388′.044] CIP

Sponsorship of Transportation Research Record 1313

GROUP 1—TRANSPORTATION SYSTEMS PLANNING AND ADMINISTRATION
Chairman: Sally Hill Cooper, Virginia Department of Transportation

Multimodal Freight Transportation Section
Chairman: Richard A. Staley, Richard A. Staley Consulting

Committee on Inland Water Transportation
Chairman: Michael S. Bronzini, Pennsylvania State University
Secretary: I. Bernard Jacobson, North Ferry Company, Incorporated
George Antle, Kenneth C. Bush, Joedy W. Cambridge, Gary N. Dicer, Gerrit Gort, Lowell D. Hill, Anatoly Hochstein, Kevin H. Horn, William F. Huneke, Marvin L. Jacobs, William F. McFarland, Howard E. Olson, R. Barry Palmer, Craig E. Philip, Larry J. Prather, Miles H. Sonstegaard, Robert N. Stearns, Martin Toyen, Edward F. Tralka

Committee on Freight Transportation Planning and Marketing
Chairman: Anne Strauss-Wieder, Port Authority of New York and New Jersey
Secretary: Peter M. Montague, Federal Railroad Administration
W. Bruce Allen, A. Don Bourquard, Russell B. Capelle, Jr., Leland S. Case, Garland Chow, John Glover, Paul C. Hanappe, Susan Henriques-Payne, J. Augustine Hsu, L. Michael Kenny, Bernard J. La Londe, Ah-Chek Lai, Robert M. Landry, George F. List, Ronald A. Mauri, Thomas H. Maze, Edward K. Morlok, Stephen C. Nieman, Howard E. Olson, Edwin P. Patton, Jossef Perl, Charles D. Sanft, John R. Scheirman, Anthony E. Shotwell, Judith L. Truax, Joe Tsai, Robert K. Whitford, Marcus Ramsay Wigan

Committee on Motor Vehicle Size and Weight
Chairman: C. Michael Walton, University of Texas at Austin
Secretary: Kenneth L. Heald, Western Highway Institute
Arthur J. Balek, Philip J. Barbato, John R. Billing, Robert M. Clarke, Alan M. Clayton, Alan C. Courtney, Peter Davies, Philip H. Decabooter, John W. Fuller, William D. Glauz, Peter Griskivich, Loyd R. Henion, Burkhard E. Horn, Bill M. McCall, Dan R. Middleton, John L. Reith, Susan K. Sheets, Brian H. Vogel, Patricia F. Waller, Arthur L. Webster II

Committee on Ports and Waterways
Chairman: Arlene L. Dietz, United States Army Corps of Engineers
William D. Ankner, Pat Broocks-Ross, William R. Coles, Harry N. Cook, Robert Cuellar, Erik T. Ferguson, Donald R. Gibson, Herbert R. Haar, Jr., I. Bernard Jacobson, James A. Johnson, Christopher A. Kane, Keith L. Kirkeide, Keith A. Klindworth, Martin E. Lipinski, Donald C. McCrory, Gary S. Misch, Harold W. Parker, Peter L. Shaw, Mark D. Sickles, Wayne K. Talley, Stanley L. Vale

Task Force on Freight Transportation Data
Chairman: Rolf R. Schmitt, Federal Highway Administration
Secretary: David L. Greene, Oak Ridge National Laboratory
James M. Aanestad, David L. Anderson, Michael S. Bronzini, Bernard Campbell, Russell B. Capelle, Jr., Arlene L. Dietz, Samuel E. Eastman, Loyd R. Henion, T. Q. Hutchinson, David L. Jones, Raphael Kedar, Joseph S. Nalevanko, Joseph B. Riker, Paul O. Roberts, Craig F. Rockey, Frank A. Smith, Anne Strauss-Wieder, Stephen J. Thompson, Anant D. Vyas, George F. Wiggers, Paula C. Young

GROUP 3—OPERATION, SAFETY, AND MAINTENANCE OF TRANSPORTATION FACILITIES
Chairman: H. Douglas Robertson, University of North Carolina, Charlotte

Maintenance Section
Chairman: Jimmy D. Lee, North Carolina Department of Transportation

Committee on Transportation of Hazardous Materials
Chairman: Mark D. Abkowitz, Vanderbilt University
Paula N. Alford, John C. Allen, Ashok B. Boghani, Michael S. Bronzini, Raymond M. Brown, Jonathan W. Cashwell, Robert J. Chipkevich, Sherwood C. Chu, Peter C. L. Conlon, John V. Currie, Richard C. Hannon, Michael Heimowitz, Antoine G. Hobeika, Margorie K. Matthews, William T. O'Brien, Claire L. Orth, Edith B. Page, Dennis L. Price, Paul W. Rankin, William R. Rhyne, Eugene R. Russell, Sr., David Woodbury

GROUP 5—INTERGROUP RESOURCES AND ISSUES
Chairman: William J. Harris, Jr., Texas A&M University

Committee on International Trade and Transportation
Chairman: Stephen J. Thompson, Library of Congress
Alan M. Clayton, John Dumbleton, Martha V. Fernandez, Glenn G. Fuller, A. K. Gupta, Randolph W. Hall, William J. Harris, Jr., Arthur F. Hawnn, Trevor D. Heaver, Marvin L. Manheim, Eisuke Masada, Tillman H. Neuner, James M. Ronayne, Miles H. Sonstegaard

Elaine King, Kenneth E. Cook, and Frank Lisle, Transportation Research Board staff

Sponsorship is indicated by a footnote at the end of each paper. The organizational units, officers, and members are as of December 31, 1990.

Transportation Research Record 1313

Contents

Foreword v

On the Use of Liftable Axles by Heavy Trucks 1
John R. Billing, Fred P. Nix, Michel Boucher, and Bill Raney

Gross Vehicle Weight Distributions as a Function of Weight Limits 11
Alan M. Clayton and Robert G. Thom

1988 Ontario Commercial Vehicle Survey 20
Julius Gorys

Highway Robbery: Social Costs of Hazardous Materials Incidents on the Capital Beltway 27
Theodore S. Glickman, Molly K. Macauley, and Paul R. Portney

Benefit-Cost Evaluation of Using Different Specification Tank Cars to Reduce the Risk of Transporting Environmentally Sensitive Chemicals 33
Christopher P. L. Barkan, Theodore S. Glickman, and Aviva E. Harvey

Abridgment
Hazardous Materials Emergencies in Railyards: Preparedness Guidance for Railroads and Adjacent Communities 44
Marianne Mintz, Kenneth Bertram, Christopher Saricks, and Rachael Rowland

State and Local Issues in Transportation of Hazardous Materials: Toward a National Strategy 49
Mark Abkowitz, Paula Alford, Ashok Boghani, Jon Cashwell, Essam Radwan, and Paul Rothberg

Detailed Inspection of U.S. Army Railroad Trackage and Application to Civilian Short-Line Railroads 55
David G. Brown, Donald R. Uzarski, and Richard W. Harris

Optimal Pricing Policies for Temporary Storage at Ports 66
Bernardo de Castilho and Carlos F. Daganzo

Risk of Dangerous Goods Spills in Abegweit Passage: Ferry Versus Bridge Crossing 75
Peter Bein

Evaluation of Minimum Bridge Span Openings Applying Ship Domain Theory 83
Aksel G. Frandsen, Dan F. Olsen, Henrik T. Lund, and Paul E. Bach

Probability Model of Lockage Stalls and Interferences 91
Harry H. Kelejian

Simulation of Waterway Transportation Reliability 98
Melody D. M. Dai and Paul Schonfeld

Freedom and Trade 106
David T. Hartgen, Gradia M. Gbarbea, and Demetri Baches

Cargo Consolidation: Canada-Caribbean Trade 115
Michael C. Ircha and Barry G. Bisson

Foreword

Freight transportation and international trade are discussed in this Record. Specific topics related to truck freight transportation include a look at issues related to truck size and weight, including the use of liftable axles on heavy trucks; prediction of gross vehicle weight distribution as a function of vehicle weight limits; and methodology for a commercial vehicle roadside survey. Another paper (a corrected reprint of a paper from Record 1241) is rail-related: it presents U.S. Army track inspection techniques and their possible application to shortline railroads.

Also contained in this Record are papers on the transport of hazardous materials. The social costs associated with highway hazmat incidents, preparedness guidance for railyards, and state and local issues in the transportation of hazardous materials are the specific subjects addressed.

Some of the papers in this Record are on water transportation. The port and waterway management issues of pricing for port sheds and evaluation of minimum bridge span openings are considered. Modeling and analysis of inland waterway projects are also topics of papers, including probability modeling of lockage stalls and interfaces and simulation of waterway transportation reliability.

A final group of papers deals with the freedom of international trade and consolidation of Canadian-Caribbean cargo shipments.

On the Use of Liftable Axles by Heavy Trucks

JOHN R. BILLING, FRED P. NIX, MICHEL BOUCHER, AND BILL RANEY

Options to increase the gross weight of heavy trucks are being addressed through studies on size and weight in the United States. These options would require more axles per truck. If the truck configuration and equipment are not tightly controlled by regulation, many of these axles would be liftable axles, and the trucks would be similar to those used already in central and Atlantic Canada. Allowing heavy trucks to use liftable axles, where the axle load is controlled by the driver, may lead to axle weight compliance problems and, eventually, result in damage to roads and bridges. However, the use of liftable axles does allow truckers to haul heavy loads efficiently, which benefits shippers and consumers with a low-cost transportation service. The economic impact on trucking in central and Atlantic Canada of four alternative regulatory scenarios having different constraints on the use of liftable axles is examined in this paper. Findings indicate that the cost of even the most severe measure, an outright ban, is relatively small, no more than 1.14 percent of total industry cost. This is because there are alternative trucks with comparable payload and operating costs, but without liftable axles, to which the freight can be diverted. A few trucking operations could be faced with hauling cost increases as high as 10 to 13 percent.

Recent studies in the United States on truck weight and dimension regulations have been focused on options that increase the gross weight of large trucks (*1,2*). This would require more axles to be used, if axle loads are unchanged or are reduced, to minimize pavement wear. Unless the regulations that would give rise to these heavier trucks control configuration and axle arrangements carefully, it is likely that many of these additional axles would be liftable axles, axles that can be removed from contact with the ground by the driver. Such axles are in use in several states in the United States and are in widespread use in central Canada (Ontario and Quebec) and Atlantic Canada (four provinces). The experience with liftable axles in Canada is the subject of this paper.

Ontario has a form of regulation, based purely on a bridge formula, that does not control either vehicle configuration or the number of axles, but allows more weight to be carried within a given length if more axles are used, or if those axles are more widely spaced. This has given great freedom to the development of diverse configurations, equipped with multiple, widely spaced axles that can carry heavy payloads (*3*). Quebec and the Atlantic provinces have regulated truck configuration more closely than Ontario, but their regulations embody principles similar to those of Ontario. Trucks with multiple, widely spaced axles have difficulty turning on dry roads. Industry has resolved this difficulty through the use of liftable axles, which can be raised or lowered by the driver, usually with air pressure. The driver customarily raises a liftable axle when a turn is being made and lowers it when the turn is completed. These axles can also be raised while cruising along the highway, which might be done by a driver to improve fuel consumption and reduce tire wear when running empty or lightly loaded.

Regulations tolerate liftable axles, with no specific limitations beyond the general requirement for axle-weight compliance. Liftable axles came into use in the early 1970s, and their use has grown steadily since. The growth has resulted in quite complicated trucks that have two or more liftable axles. The use of liftable axles may reduce a truck's stability in many situations (*4*). Their use makes compliance with and enforcement of axle-load regulations difficult, so there are concerns about the use of liftable axles and damage to roads and bridges. These concerns were great enough that liftable axles were excluded from the truck configurations covered by the 1988 Memorandum of Understanding between the Canadian provinces and territories that established uniform national heavy truck weight and dimension regulations (*5*). The 1988 agreement, developed under the auspices of the Roads and Transportation Association of Canada (RTAC), recognizes six specific truck configurations (*6*). Limits on axle loads, gross weight, axle arrangements, axle spacings, and a variety of other dimensions are tailored to ensure superior stability for each configuration. These are referred to as the RTAC rules. The ten provinces and two territories are currently at various stages in the integration of the RTAC rules into their own regulations. Ultimately, standard RTAC trucks will operate from coast to coast on designated highways. Although the RTAC rules prohibit use of liftable axles on any of the RTAC configurations, the 1988 agreement does not require any province to ban the use of liftable axles. Provinces are free to continue to allow these and other existing non-RTAC truck configurations to operate. The six eastern provinces therefore will retain many aspects of their earlier regulations and local trucks, which include the wide range of trucks currently using liftable axles.

Liftable axles do add a great deal of payload to a truck for a small increase in vehicle cost. Shippers of heavy commodities benefit from the lower transportation costs resulting from the use of liftable axles.

J. R. Billing, Vehicle Technology Office, Transportation Technology and Energy Branch, Ministry of Transportation of Ontario, 1201 Wilson Ave., Downsview, Ontario, M3M 1J8, Canada. F. P. Nix, Canadian Institute of Guided Ground Transport, Queen's University, Kingston, Ontario, K7L 3N6, Canada. M. Boucher, Ecole nationale d'administration publique, Université du Québec, 945, avenue Wolfe, Saint-Foy, Québec, G1V 3J9, Canada. B. Raney, Provincial Transportation Systems Office, Ministry of Transportation of Ontario, 1201 Wilson Ave., Downsview, Ontario, M3M 1J8, Canada.

A preliminary exploration of the use of liftable axles in central and Atlantic Canada is presented in this paper. The concerns of highway and truck engineers are summarized and findings from a recent study on the economic impact of hypothetical changes to regulations that would constrain the use of liftable axles are presented.

TRUCKS WITH LIFTABLE AXLES

Configurations

Configurations are described generically by the following notation. Note that x is the number of axles on a vehicle unit and y is the number of liftable axles; the designation RTAC, used later in the paper, denotes a configuration complying with RTAC rules.

Notation	*Configuration*
Tx	Straight truck (T4 has a tandem-steer axle);
Tx,yL	Straight truck with liftable axles;
Tx-x	Straight truck and trailer;
Tx-x,yL	Straight truck and trailer with liftable axles;
x-Sx	Tractor-semitrailer;
x-Sx,yL	Tractor-semitrailer with liftable axles;
x-Sx-x	A-train double (single drawbar dolly);
x-Sx-Sx	B-train double (two semitrailers, no dolly); and
x-Sx=x	C-train double (double drawbar dolly).

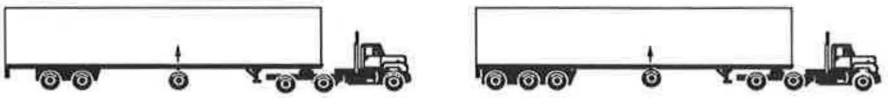
The configuration 3-S2, the 18-wheeler, is the most common large truck in both the United States and Canada. Figure 1 shows some typical configurations that use liftable axles. The most common is the 3-S3,1L triaxle semitrailer, used in Ontario, Quebec and the four Atlantic provinces, which has a fixed tandem axle at the rear of the semitrailer, and an independently suspended liftable axle (the belly axle) some distance ahead of it. The quad-axle semitrailer, allowed only in Ontario and Quebec, may have a single liftable axle and a fixed tridem axle (3-S4,1L). In Ontario, it may also have one of several arrangements of two liftable axles with a tandem axle (3-S4,2L). Semitrailers with five axles are used only in Ontario and a small number with more than five axles, in a variety of axle arrangements and usually with at least two liftable axles, operate between Ontario and Michigan. In Ontario, there are also triaxle straight trucks, T4,1L, with a liftable axle between the steer axle and the tandem drive axle. There are also small numbers of trailers that have liftable axles and are pulled by straight trucks.

Table 1 shows the large payload advantages of flatdeck semitrailers with liftable axles in the three regions. Other body styles have slightly smaller payloads, but the relative increase in payload remains about the same for each as liftable axles are added. Adding a liftable axle to the standard 5-axle tractor-semitrailer increases its payload by over 8 t (17,640 lb) in some cases, for only about a 1 t (2,205 lb) increase in tare weight. The payload increase diminishes as each additional axle is added.

Usage

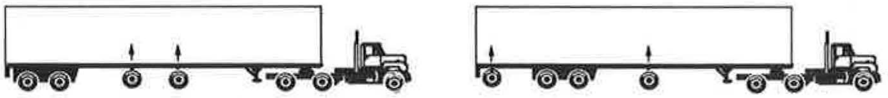
Information on the use of liftable axles is available from roadside surveys, conducted by the provinces in different years, which are of varying quality.

Ontario conducted a large survey in 1988; a summary of the more important statistics is shown in Table 2. Just less than 17 percent of the trucks on the highways had liftable axles, and these accounted for one quarter of all freight hauled. The most important use of liftable axles is on 6-axle configurations, most of which are tractor-semitrailers. Vans (including refrigerated vans), flatdecks, and stake-and-rack trailers account for 80 percent of all liftable axles.



6-Axle Tractor-Semitrailer 3-S3, 1L

7-Axle Tractor-Semitrailer 3-S4, 1L



7-Axle Tractor-Semitrailer 3-S4, 2L

7-Axle Tractor-Semitrailer 3-S4, 2L

8-Axle Tractor-Semitrailer 3-S5, 2L

8-Axle Tractor-Semitrailer 3-S5, 2L

9-Axle Tractor-Semitrailer 3-S6, 2L

Straight Truck T4, 1L

FIGURE 1 Common truck configurations that use liftable axles.

TABLE 1 PAYLOAD GAINS FOR TRACTOR-SEMITRAILERS WITH LIFTABLE AXLES (FLATDECK TRAILERS, PAYLOADS IN TONNES)

Region	**Payload**	**3-S2**	**3-S3,1L**	**3-S4,1L**	**3-S5,2L**
Ontario	Typical	27.0	35.7 (+32.2%)	39.6 (+10.9%)	42.5 (+7.3%)
	Maximum	32.0	40.0 (+25.0%)	45.8 (+14.5%)	46.6 (+1.7%)
Quebec	Typical	27.0	35.7 (+32.2%)	37.8 (+5.9%)	
	Maximum	33.8	42.4 (+25.7%)	39.6 (-6.8%)*	
Atlantic Canada	Typical	25.0	32.7 (+30.8%)		
	Maximum	28.8	36.5 (+26.7%)		

* Quebec recently decreased the GVW of a 3-S4,1L from 57.5 to 55.0 tonnes, but the 3-S3,1L is still allowed 57.5 tonnes, which could give it a higher payload.

TABLE 2 USE OF LIFTABLE AXLES IN ONTARIO AND QUEBEC

	Ontario		**Quebec**	
	Trucks	**Freight**	**Trucks**	**Freight**
Trucks without Liftable Axles	83.3%	74.8%	79.1%	67.6%
Trucks with Liftable Axles	16.7%	25.2%	21.2%	32.4%
Configuration				
Tractor-semitrailer	15.3%	22.7%	20.2%	30.9%
Double trailer	0.9%	1.9%	0.8%	1.1%
Straight truck	0.3%	0.2%	0.0%	0.0%
Truck-trailer	0.3%	0.6%	0.2%	0.4%
Body Style				
Van	7.9%	9.9%	7.0%	8.2%
Flatbed & stake	5.6%	9.4%	8.0%	13.2%
Dump	1.5%	3.0%	1.7%	5.8%
Tanker	0.9%	1.6%	3.3%	3.4%
Other	0.9%	1.4%	0.2%	0.3%
Number of Axles				
5 or fewer	2.2%	2.1%		
6	9.5%	13.4%		
7	1.8%	3.4%		
8 or more	1.8%	3.4%		

Quebec completed a roadside survey in 1989; the preliminary results in Table 2 show the use of liftable axles is even more widespread in Quebec than in Ontario, although the variety of trucks using them is more limited. Liftable axles are used almost exclusively by 6- or 7-axle tractor-semitrailers (as compared with double-trailer or truck-trailer combinations), particularly those with van (including refrigerated van), flatdeck, or stake-and-rack body styles.

Data from Atlantic Canada are limited. However, on the basis of results of a 1984 roadside survey, 41.3 percent of all configurations on the highway were tractor-semitrailers with 6 or more axles, mostly of 3-S3,1L configuration. It is estimated (crudely) that they accounted for 24.5 percent of truck freight tonnage in the region. In all of central and Atlantic Canada, then, something in the order of 27 to 31 percent of total truck freight tonnage, depending on how the numbers are summed, is carried by equipment with liftable axles.

Operational Considerations

All liftable axles are equipped with a valve beside the axle allowing it to be raised or lowered while the truck is stationary. In addition, most trucks and tractors come with a control that allows the driver to raise or lower the liftable axle from the cab. In some cases, a regulator in the cab also allows the driver to adjust the axle load.

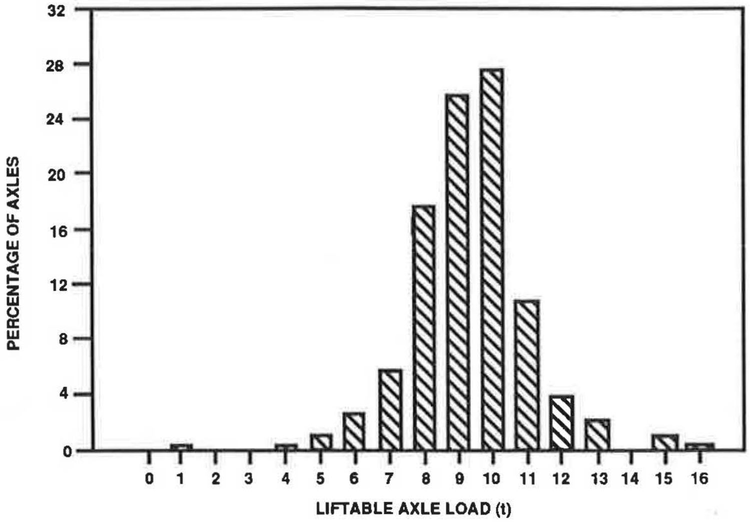


FIGURE 2 Liftable axle load distribution of 260 3-S3,1L.

Vehicle manufacturers and truckers both readily admit that life would be easier if liftable axles were banned. Load compliance is more difficult and maintenance costs are higher when these axles are used. However, shipper demands and competitive pressures require that they be used in the absence of any regulatory limitation to the contrary.

The semitrailer with liftable axles usually has tare weight and price advantages over the comparable double-trailer combination. There are cases where the B-train double can be more efficient, but in general, the long semitrailer has an operational advantage for most freight. The B-train may not split well for some loads, and it is not practical for long loads such as beams or reinforcing bars. Semitrailers also have a distinct advantage over double trailer combinations for some body styles. The cost of refrigeration units and insulation and pressure vessels increases substantially per cubic meter of trailer in switching from single to double trailers.

In on-off road operations, such as logging and mining, raising the liftable axle is considered necessary to transfer loads to the tractor drive axles to provide traction for off-road mobility. The ability to raise the liftable axle and increase the drive axle traction is also considered a safety factor when driving on a slippery road or climbing an icy hill.

Weight Compliance Considerations

Weigh-scale staff in Ontario report that two-thirds or more of all weight infractions occur on trucks with liftable axles. This is not surprising. These trucks are designed to carry the heaviest loads and operate close to their allowable gross weight, so they are at greatest risk of incurring an infraction. However, the actual loads carried by liftable axles are also a major factor in the number of infractions. The liftable axle load is controlled by the driver, who can adjust it to any level. If the liftable axle load is too high, the liftable axle is overloaded. If it is too low, other axles may be overloaded. Weigh-scale data show that actual liftable axle loads may vary from zero, when the axle is raised, to 16 t (35,273 lb) or more. A typical distribution is shown in Figure 2, from a survey conducted by the Ontario Ministry of Transportation. The trucks in this sample are all virtually identical 3-S3,1Ls, within 5 percent of their allowable gross weight. However, fully 48 percent had their liftable axles sufficiently far off the 10 t (22,046 lb) load that there would be an axle weight infraction, even if the load were perfectly distributed. Unfortunately, fines for weight infractions in Ontario and Atlantic Canada are small, and provide little incentive for tight control of liftable axle loads.

Roadway and Bridge Considerations

The number of equivalent single axle loads (ESALs) generated by a truck with liftable axles varies with the load on the liftable axle, as shown in Figure 3 for five typical heavy truck configurations under Ontario axle and gross weight regulations. Axle load equivalencies are based on the fourth-power law, with 5 t for a front axle with single tires, and 10 t for a single axle, 17 t for a tandem axle, and 24 t for a tridem axle with dual tires (*7*). Figure 3 shows further that whenever the

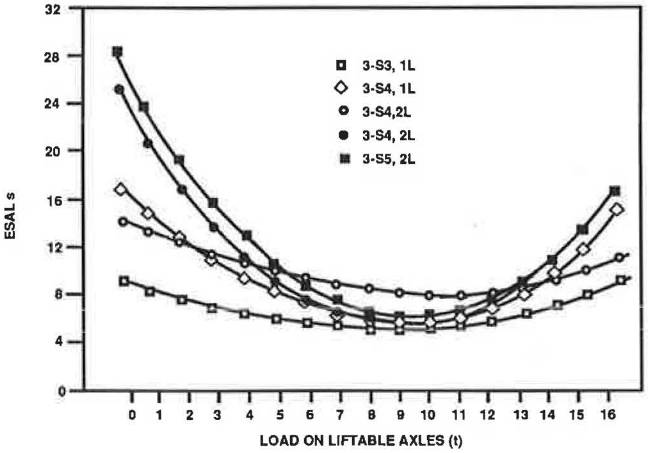


FIGURE 3 Heavy truck ESAL dependence on liftable axle load.

truck is operated with a significant liftable axle overload, or an underload that overloads the remaining fixed axles, there is an increase in the number of ESALs it generates. This is because the increase in ESALs for an overloaded axle is always greater than the reduction in ESALs for the corresponding underloaded axles. When liftable axles are raised, the number of ESALs per truck may increase by a factor between two and four. The high numbers of ESALs arising from trucks whose liftable axles are incorrectly loaded is considered to be a major contributor to rutting and other load-related damage to highways and municipal roads.

Figure 4 compares the bridge loading effects of various trucks with liftable axles against the Ontario bridge formula (OBF), the current technical basis for regulation in Ontario. Even with liftable axles properly deployed, the regulations allow loads on some configurations that exceed the OBF by a small amount. However, with the liftable axles raised, there are a number of axle groups whose loads exceed the OBF by 10 t (22,046 lb) or more, with a legal load distribution on the truck when the liftable axles are properly deployed. Gross weight overloads, or improper load distribution, simply make the situation worse. The high overloads occur primarily on tandem and tridem axles, and particularly affect the deck structures of some designs of bridge, and the main longitudinal members of short span bridges.

Vehicle Stability Considerations

The use of liftable axles on long semitrailers allows considerably more load to be carried, as shown in Table 1. For commodities of moderate density, such as lumber, grocery and food products, bulk liquids, and powders, this results in a considerable increase in the height of the payload center of gravity. This, by itself, tends to reduce the rollover threshold of the truck, and to deteriorate other aspects of its dynamic performance. With the liftable axles deployed, the truck cannot turn, and may be at risk of a jackknife when trying to turn on a wet and slippery pavement. When liftable axles are raised so that the truck can turn, the truck's resistance to rollover may be substantially reduced (*4*). This is when the truck is most susceptible to rollover. This clearly introduces a safety hazard for which the driver must compensate by reducing speed. Drivers of these trucks appear quite cautious when traversing freeway ramps.

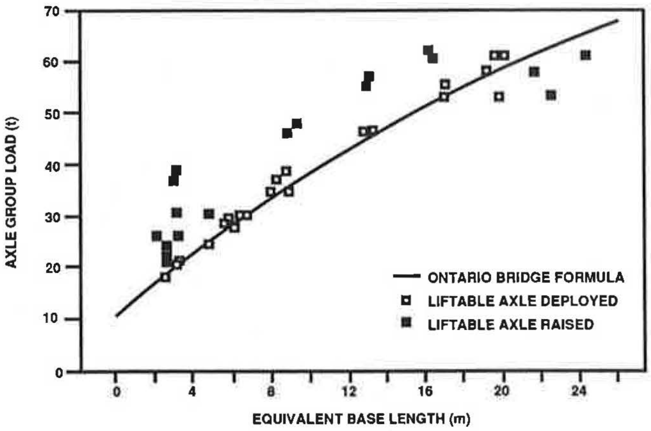


FIGURE 4 Heavy truck axle group load comparison with OBF.

Summary

When trucks are allowed to operate with liftable axles and when there are no means to ensure control of axle loads, there is a loss of compliance with axle weight law. In some cases, axle loads on trucks whose liftable axles are raised can exceed the allowable load by over 10 t (22,046 lb). These trucks impose considerably more road and bridge damage than if they operated with liftable axles properly deployed. There are also serious dynamic performance deficiencies of heavy truck configurations equipped with liftable axles, which gives rise to concerns about the safety of this equipment. Trucks equipped with liftable axles can, at the will of the driver, operate far outside the technical limits set for roadway design, bridge safety, and intrinsic truck safety.

ECONOMIC ANALYSIS OF TRUCKS WITH LIFTABLE AXLES

Regulatory Scenarios

Concerns about performance of trucks with liftable axles have led Ontario Ministry of Transportation, Ministère des Transports du Québec, and Transportation Development Center of Transport Canada to undertake a joint program of research to explore technical options that might provide opportunities for tighter regulatory control. This section summarizes aspects of one study in this program (*8*). It documents the cost of trucks with liftable axles, the operating costs of such trucks, operational considerations that go into the decision to use such an axle, and how the cost and operational factors compare with trucks that do not use liftable axles. Five scenarios are developed as a basis for this study. There are large differences between the scenarios to test the sensitivity of truck choices and trucking costs to changes in regulations. The scenarios are

1. The base case, where use of liftable axles is uncontrolled within the gross and axle load limits of each province.
2. RTAC rules are added to the current regulations, and the allowable load on liftable axles is reduced from 10 to 8 tonnes.
3. RTAC rules are added to the current regulations and the allowable load on liftable axles is further reduced to 6 tonnes.
4. RTAC rules are added to the current regulations and use of liftable axles is prohibited.
5. The base case, except each vehicle in Ontario is limited to one liftable axle, as in Quebec and Atlantic Canada.

Scenarios 2, 3, and 4 include the addition of RTAC rules, because only one of the six provinces in central and Atlantic Canada has actually completed the necessary steps to adopt these rules formally. The others are in the process of adoption, and in the meantime are allowing RTAC trucks to operate under permit.

The study looks only at trucking costs. The high axle loads possible with liftable axles raised exceed the technical standards for roads and bridges by such a wide margin that technical reasons alone demand constraints on the use of liftable axles. The study therefore did not examine road, bridge, or safety costs.

Costing Methodology

A detailed costing methodology was developed for evaluation of the impacts of the five regulatory scenarios. The intent was to compare the relative costs of one truck configuration with another, and then to use these results to predict the consequences of each of the regulatory scenarios. The methodology is based on the widely used biannual computation of trucking costs undertaken for Transport Canada by Trimac Consulting (*9*). Because Trimac procedures only consider a limited number of configurations, many modifications had to be made to allow the costing process to be sensitive to the changes in trucking costs because of the large variety and number of configurations in this study. The result is a series of models that develop costs by

- Region: Ontario, Quebec, and Atlantic Canada.
- Regulatory scenario: 1 to 5, as listed previously.
- Configuration: 24 basic configurations (e.g., 3-S3,1L, T3-4, etc).
- Body style: one of seven (e.g., van, refrigerated van, flatdeck, etc).
- Gross Vehicle Weight (GVW): a typical maximum, using the maximum axle loads allowed by each province's regulations, although these may be rarely seen, and a high, from axle loads typical of trucks that carry dense commodities.
- Tare weight: a typical high and low tare weight; there are trucks outside this high-low range.
- Payload: a maximum calculated by subtracting the low tare weight from the maximum GVW, and a high payload calculated by subtracting the high tare weight from the high GVW.

Additional inputs are built into the model to describe factor prices, productivity, and other aspects of operation. While the analysis is conducted for particular values of these inputs, they may be varied to examine the sensitivity of the model and its results to the assumptions. Factor prices are standard 1988 Trimac values for such things as labor rates and fuel prices, equipment prices supplied by manufacturers, and others, such as the cost of capital or the level of overhead as user-supplied data. The basic productivity relationships used by Trimac are retained for such things as cargo load-unload rates. However, new relationships are developed to assess the range of configurations being considered, such as how fuel consumption is affected by GVW, the effect of an empty backhaul on GVW, the effect of wide-spread axles on tire and maintenance costs, and the effect of axle load on tire and maintenance costs. Finally, annual utilization as determined by the annual hours of operation and the extent of non-trip distances, the trip speed, and empty or full backhaul is specified by the user. Users are able to specify any haul distance, but most of the published results use the base 160 km (100 mi) found in Trimac's procedures.

The models compute costs in terms of dollars per tonne, dollars per kilometer, dollars per tonne-kilometer, and annual costs. Dollars per tonne-kilometer is the principal measure used in the subsequent analysis. Table 3 shows an example of the results from this costing procedure. Because not all 24 configurations are allowed by all provinces, it contains only 53 costs for one truck body style. There are actually 3,710 costs, from 53 configurations over the three regions, for two weights, under five scenarios, and seven body styles. Important aspects of Table 3 are as follows:

- Body style is van;
- High GVW and high tare weight, so payload is high;
- Haul distance is 160 km (100 mi);
- Backhaul is assumed;
- 2,000 annual hours of operation;
- Non-trip distance is 5 percent of total;
- Load and unload rates are Trimac's, for bulk freight (30.27 and 32.72 t/h);
- Regulatory scenario is the base case;
- Average trip speed is 80 km/h (50 mi/h);
- Axle spreads over 1.8 m (71 in.) increase maintenance and tire costs by 10 percent;
- Axle spreads over 2.0 m (79 in.) increase maintenance and tire costs by 20 percent;
- Axle loads over 8 t (17,637 lb) increase maintenance and tire costs by 20 percent;
- Axle loads over 9 t (19,841 lb) increase maintenance and tire costs by 30 percent;
- Fuel consumption is a function of GVW;
- Overheads are 23.4 percent of truck operating costs; and
- Pre-tax cost of capital is 20 percent.

This analysis is concerned only with dense freight. The comparison of costs is not valid for LTL freight, automobiles, livestock, or any other commodity whose density is less than about 320 kg/m^3 (20 lb/ft^3). Costs are shown as a percentage of 3-S2 costs within each region, as this is the most common large truck configuration in Canada, although it is not used widely to haul dense commodities in the area of this study.

This analysis of trucking costs, with all factors except configuration held constant, leads to a number of observations. First, the RTAC configurations, as originally set out in the 1988 agreement, cannot haul freight at anywhere near the cost of some of the current liftable axle equipment in Ontario, and only the RTAC 3-S3-S2 B-train is competitive in Quebec and Atlantic Canada. The multi-axle semitrailer combinations (mainly in Ontario) are quite efficient haulers of heavy, dense commodities, in respect of truck operating costs.

A second observation is that operating cost is not the only factor in a carrier's decision to use one configuration instead of another, there are a range of operational considerations that also influence the choice. Sectors of the trucking industry using owner-operators have difficulty switching to truck-trailer equipment, as owner-operators own tractors so they can haul anyone's trailer; some shippers require that trailers be left for extended periods of time for loading or unloading, which also militates the use of truck-trailers; and some freight cannot be easily handled by double-trailer combinations.

A third observation is that a regulatory scenario that simply reduces the allowable loads on liftable axles may not be ef-

TABLE 3 SUMMARY OF TRUCK WEIGHTS, PAYLOADS, AND TRUCKING COSTS

	Ontario			Quebec			Atlantic Canada		
	GVW	Payld	Cost	GVW	Payld	Cost	GVW	Payld	Cost
Trucks	(t)	(t)		(t)	(t)		(t)	(t)	
T3	24.9	15.6	132%	25.0	15.7	130%	24.0	14.7	134%
T4, 1L	34.9	24.3	93%						
T4	33.9	23.3	99%	34.0	23.4	98%			
T3-2	42.9	28.4	95%	44.0	29.5	91%	42.0	27.5	92%
T3-3	53.0	37.4	79%	53.0	37.4	78%	51.0	35.4	77%
T3-4	61.7	44.8	71%	57.5	40.6	74%	56.5	39.6	73%
T4-4, 1L	63.5	45.3	70%						
3-S2	42.0	26.1	100%	42.0	26.1	100%	40.0	24.1	100%
3-S3	47.3	30.3	90%	48.0	29.0	88%	47.0	30.0	86%
3-S3, 1L	52.0	35.0	83%	52.0	35.0	83%	49.0	32.0	81%
3-S4	60.1	42.0	76%						
3-S4, 1L	57.3	39.2	78%	55.5	37.4	80%			
3-S4, 2L	60.1	42.0	76%						
3-S5, 1L	61.5	42.1	73%						
3-S5, 2L	61.5	42.1	73%						
3-S6, 1L	61.5	40.8	76%						
3-S6, 2L	61.5	40.8	76%						
3-S3-S2	61.5	40.4	81%	59.0	37.9	84%	56.5	35.4	84%
3-S3-S2, 1L	61.5	40.4	81%	59.0	37.9	84%			
3-S2-3	61.5	39.7	82%	57.5	35.7	89%	50.0	28.2	101%
RTAC 3-S3	45.0	28.0	92%	45.0	28.0	92%	45.0	32.5	86%
RTAC 3-S2-S	256.0	36.0	90%	56.0	36.0	90%	56.0	36.0	85%
RTAC 3-S3-S	262.0	40.9	80%	62.0	40.9	79%	62.0	40.9	75%
RTAC 3-S2-3	58.5	37.2	86%	58.5	37.2	86%	58.5	37.2	82%

fective where excess axle load capacity exists, as it does in many of the configurations with two liftable axles. Carriers claim that, while these configurations do not necessarily allow any payload advantages, they do allow tolerance in loading commodities such as coils of steel to meet axle weight laws.

Finally, under any of the regulatory scenarios examined, reasonable alternatives to liftable axle trucks do exist for most freight. That is, if load limits for liftable axles are reduced, liftable axles are restricted to one per combination, or are banned altogether, there are alternative configurations to carry freight without a large increase in hauling costs. There are some circumstances in which this generalization does not hold. For example, carriers using refrigerated vans with liftable axles may face fairly large cost increases if they switch to double-trailer configurations. But these cases aside, it is generally true that most freight can be hauled by alternative configurations with only a small increase in hauling costs under the regulatory scenarios examined. Indeed, in some cases, hauling costs could actually fall under some of the scenarios to the extent that the change in regulations encourages operators to switch to truck-trailer combinations. The T3-4 can haul dense freight at the lowest cost in all three regions, though there are institutional and operational factors that may make the use of such equipment difficult.

Impact of Regulatory Scenarios on Freight Costs

The final stage in the evaluation of the regulatory options is to integrate the results of the costing model with a large-scale model of freight flows in central and Atlantic Canada. This is difficult, as Statistics Canada data on freight flows (*10*), and road-side survey data on vehicle configurations are only weakly related. The methodology is as follows.

First, a detailed examination is made of every configuration under each of the five regulatory scenarios. Where hauling costs increase for equipment with liftable axles, it is assumed that freight shifts to the nearest alternative configuration. For example, if in Scenario 3 the reduction in liftable axle loads to six tonnes increased the hauling costs of the 3-S3,1L to a point higher than the 3-S3, it is assumed that some or all freight would shift to the 3-S3. Some of this 3-S3,1L freight would also shift to the 3-S4,1L and some might shift to the T3-3 configuration. Generally, but not always, a freight shift implies an increase in trucking costs for shippers. This step, the reassignment of freight, was the key to the whole analysis.

The data from roadside surveys shown, in part, in Table 2, are used to construct a distribution of the freight hauled in each region by each configuration, and an index of cost-per-tonne is constructed from the cost model for each configuration.

The frequency distribution of freight volume given by the roadside survey is used to distribute annual tonnes of originating truck freight measured in Statistics Canada's surveys: 106 299 144 tonnes for Ontario; 55 779 124 tonnes for Quebec; and 20 448 510 tonnes for Atlantic Canada. Having obtained a measure of the annual tonnes carried by each configuration, each of these numbers is multiplied by its respective cost index. Those numbers are summed and a new frequency distribution of costs-per-tonne times total tonnes is obtained. Those percentages are then multiplied by Statistics Canada's 1987 measure of total operating expenses of carriers domiciled in each region: $5.5 billion for Ontario, $2.5 billion for Quebec, and $0.9 billion for Atlantic Canada.

Finally, the regulatory scenarios are evaluated by taking the minimum/maximum change in costs (as a result of the freight shifts) times the estimated total annual trucking costs attributed to each configuration. This evaluation does compare changes affecting under one-third of all freight, those dense commodities now carried by trucks with liftable axles, with total industry costs. This was done because the demarcation between dense freight that would be affected by the changes in regulatory scenario, and the freight unaffected, is not known with precision.

A summary of the results, Table 4, shows the total impact of any of the regulatory scenarios is relatively small in relationship to total trucking costs in central and Atlantic Canada. The main reason is that under any of the scenarios examined, there always exists some configuration capable of hauling the heavy payloads displaced from the trucks made uneconomic or eliminated by that scenario. None of the regulatory options closes off the ability of truckers to haul payloads in the

TABLE 4 SUMMARY OF INCREMENTAL COSTS OF SCENARIOS

Millions of 1987 Canadian Dollars

	Ontario		**Quebec**		**Atlantic Canada**		**Total**	
Scenario	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
2-8 t axle	-4.3	13.9	-0.4	12.9	-0.9	1.1	-5.6	27.9
3-6 t axle	-8.7	28.2	-0.8	26.1	-1.8	2.2	-11.3	56.5
4-Ban axle	-13.8	53.2	-0.7	45.4	-2.7	3.2	-17.2	101.8
One axle	15.0	52.6	-------	-------	-------	-------	15.0	52.6

------ no effect

Percentage of Total Trucking Cost

	Ontario		**Quebec**		**Atlantic Canada**		**Total**	
Scenario	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
2-8 t axle	-0.08	0.25	-0.02	0.51	-0.11	0.13	-0.06	0.31
3-6 t axle	-0.16	0.51	-0.03	1.03	-0.21	0.26	-0.13	0.63
4-Ban axle	-0.25	0.96	-0.03	1.80	-0.32	0.38	-0.19	1.14
One axle	0.27	0.95	-------	-------	-------	-------	0.17	0.59

------ no effect

40-tonne range. Indeed, in Atlantic Canada, the new RTAC B-train allows much higher payloads than any existing equipment with liftable axles. Further, the analysis may over emphasize the impact in Quebec. The roadside survey does not reflect more recent changes in regulation which make the B-train much more attractive. Table 3 shows it can haul freight at lower cost than any liftable axle equipment. A trend to use of these B-trains could reduce substantially the impacts shown in Table 4 for Quebec.

Although the overall impact appears to be relatively small, there are some operators or commodities that do not have a ready alternative truck configuration of near comparable cost. Refrigerated vans, propane tankers, and end-dump trailers are all trucks that could see significantly increased costs under any of the scenarios. Some commodities could see costs increasing by as much as 10 to 13 percent (or, in isolated cases, even more).

A sensitivity analysis for both the assumptions employed in the cost model and the model of freight flows was concluded. Although the full results are complex, it should be noted that the values shown in Table 4 maximize the potential impact of the regulatory scenarios. That is, the minimum/maximum values shown have been deliberately set very far apart. The true impact if the scenarios were actually implemented, if any, would be expected to lie somewhere within this range.

There are weaknesses in this methodology. There is no strict relationship between freight flows measured by Statistics Canada's survey of shipping documents, according to the origin or destination of the freight, and financial data computed by Statistics Canada from a census survey based on the province of domicile of carriers. Further, the measure of total operating expenses includes many activities not related to the movement of the freight, such as international activity, storage, and warehousing. There are many assumptions and parameters used in the cost model, from the factor prices used, to the fuel consumption specified, to trip length chosen for the analysis. Finally, no account was taken of transitional (changeover) costs for truck operators. These costs are believed to depend strongly upon how the changes would be implemented. If liftable axles were banned outright on short notice, there is little doubt that transition costs would be very high. However, if existing equipment was allowed to continue operating under a grandfather clause, transition costs would be quite low because carriers would not be forced to buy new equipment until the existing equipment became uneconomic to operate. These and other weaknesses aside, the study does provide an initial estimate of the range of changes in costs that would be expected from a change in regulations regarding liftable axles.

Summary

The economic analysis has a wide range of uncertainty. However, even with the most pessimistic of assumptions, none of the regulatory scenarios used in this study has a major impact in terms of total trucking costs. Even the most draconian measure, an outright ban on liftable axles, results in a cost change between reduction of 0.19 percent and an increase of 1.14 percent. These percentages have been calculated in terms of total private and for-hire truck operating expenses; in fact, the regulatory options examined would affect only a portion of this activity—that involved with the hauling of dense freight. Some of these operators could experience cost increases of as much as 10 to 13 percent (or in isolated cases, even higher). Whatever the case, the overall minor impact of the scenarios, and the limited cases of more serious impacts, needs to be weighed off against the technical impacts of liftable axles on the infrastructure.

CONCLUSIONS

There are serious weight compliance, roadway wear, bridge loading, and intrinsic truck safety issues associated with the use of liftable axles on heavy trucks. There is a solid technical basis for regulatory measures that would limit the application and use of liftable axles. The trade-off, however, is the benefit shippers and consumers derive from the lower transportation costs made possible by the use of trucks with liftable axles. Clearly, regulatory change is not contemplated without careful consideration of this trade-off.

Findings from a study that is part of the process of weighing this trade-off have been presented in this paper. It found the impact of four regulatory scenarios, even one which banned liftable axles altogether, to be quite small in terms of overall trucking activity in central and Atlantic Canada. This is because there are already alternative trucks of comparable payload that could replace those with liftable axles. It was also found that scenarios that simply reduced allowable loads on liftable axles may have no impact where operators already have excess axle capacity over allowable gross weight.

In Canada, the issue is how their current widespread and uncontrolled use of liftable axles might be curtailed. There are clearly major drawbacks to both highway agencies and truckers if liftable axles come into widespread use, because control of axle loads cannot be guaranteed. Alternative vehicles can be configured to provide high gross weights without the use of liftable axles. This task can be achieved in a manner that provides an improvement in both intrinsic truck safety and system safety, as well as providing the productivity improvement of higher gross weights.

ACKNOWLEDGMENT

The economic analysis upon which this paper is largely based was sponsored by the Ministry of Transportation of Ontario as part of a technical study of liftable axles being conducted by the Ministry of Transportation of Ontario, the Ministère des Transports du Québec, and the Transportation Development Center of Transport Canada.

REFERENCES

1. *TRB Special Report 225: Truck Weight Limits: Issues and Options.* TRB, National Research Council, Washington, D.C., 1990.
2. *TRB Special Report 227: New Trucks for Greater Productivity and Less Road Wear.* TRB, National Research Council, Washington, D.C., 1990.
3. A. C. Agarwal and J. R. Billing. *The Effect of Ontario's Weight*

Regulations on Commercial Vehicle Design. Presented at International Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, B.C., June 1986.

4. J. R. Billing, C. P. Lam, and J. Couture. Development of Regulatory Principles for Multi-axle Semitrailers. Presented at 2nd International Symposium on Heavy Vehicle Weights and Dimensions, Kelowna, B.C., June 1989.
5. *Memorandum of Understanding on Interprovincial Heavy Vehicle Weights and Dimensions*. Roads and Transportation Association of Canada, Ottawa, Feb. 1988.
6. *Recommended Regulatory Principles for Interprovincial Heavy Vehicle Weights and Dimensions*. CCMTA/RTAC Vehicle Weights and Dimensions Study Implementation Committee Report, Roads and Transportation Association of Canada, Ottawa, Sept. 1987.
7. J. T. Christison. *Pavement Response to Heavy Vehicle Test Program: Part 2—Load Equivalency Factors*. CCMTA/RTAC Vehicle Weights and Dimensions Study Technical Report Volume 9, Roads and Transportation Association of Canada, Ottawa, July 1986.
8. F. P. Nix and M. Boucher. *Economics of Liftable Axles on Heavy Trucks*. Report CV-90-04, Transportation Technology and Energy Branch, Ministry of Transportation of Ontario, Nov. 1990.
9. Trimac Consulting Services Ltd. *Operating Costs of Trucks in Canada—1988*. Transport Canada, Ottawa.
10. *Trucking in Canada 1987*. Statistics Canada, Catalogue #53-224, Ottawa, 1988.

Publication of this paper sponsored by Committee on Motor Vehicle Size and Weight.

Gross Vehicle Weight Distributions as a Function of Weight Limits

ALAN M. CLAYTON AND ROBERT G. THOM

Weight limits are a principal determinant of the weight characteristics of large trucks. They provide a logical and practical base from which these weight characteristics can be predicted. Such predictions are necessary for evaluating the relative benefits and costs of alternative weight and dimension policies. During the past 20 years, Canada has had a weight limit policy that has stipulated a variety of different weight limit regimes to the same truck type. This has provided an on-road experiment of how weight limits translate into actual truck weights. This experiment has created a large and unique data set that permits relating actual truck weights to governing weight limits spanning a broad range. On the basis of this data set, empirical models linking the distribution of gross vehicle weights (GVWs) of three of Canada's most common large truck combinations to the GVW limit governing these trucks are developed. They assume an idealized complete compliance condition, with no violation of the limit. The three truck types for which models are developed are the 5-axle (3-S2) tractor-semitrailer, the 7-axle (3-S2-S2) B-train combination, and the 7-axle (3-S2-2) A-train combination. The complete compliance condition is of course violated if weight limits are not enforced or overweight operations are allowed by special permit. The predictive capability of the 3-S2 model is examined in relation to the GVW distribution of a sample of 3-S2s operating under a GVW limit different from those used in constructing the model. The predicted and actual distributions compare favorably.

Models for predicting distributions of the gross vehicle weight (GVW) of three truck combinations—5-axle (3-S2) tractor-semitrailers, 7-axle (3-S2-S2) B-trains, and 7-axle (3-S2-2) A-trains—are presented. The models predict these distributions as a function of the governing GVW limit for an idealized complete compliance condition, assuming no violation of the limit. They are constructed from a large data base of the weights of trucks operating on Canadian highways through 1974 to 1990. This period saw important changes in Canada's weight and dimension regulations, which in turn provided an extensive "real-life" experiment concerning the effects of weight limits on the operating weights of trucks.

Truck weight distribution models have three principal applications in highway engineering. One, they are useful for evaluating the benefits (i.e., truck productivity gains) and costs (i.e., infrastructure design and deterioration implications) of alternative weight and dimension limit policies. Developing such estimates has proven difficult in the past (*1,2*). Two, in combination with forecasts of truck movements, they can assist in forecasting total axle loadings for purposes of pavement design and the evaluation of pavement life. In the same vein, they could be helpful in any back-casting effort directed at constructing the likely historical loadings to which a pavement has been subjected. Three, growing use of the load factor design concept in bridge engineering requires more and better information about actual truck loads and load distributions (*3*).

MODELING THEORY

The idea behind these models stems from the observation that weight and dimension regulations are the principal determinant of the types, dimensional features, and—particularly for this work—weight characteristics of large trucks operating on a highway system (*4*).

Specifically, the modeling is based on the hypothesis that the distribution of GVWs of laden trucks can be related to and expressed as a function of governing GVW legal limits. This hypothesis emerged from observing two recurring attributes in Canadian truck weight data (*5*). The first, which is intuitively appealing, is that when the GVW limit for a particular truck type is relaxed, then a proportion of that type of truck's operations will increase payloads. This in turn leads to a new, shifted GVW distribution curve for this truck type. Second, truck weight distributions are reasonably stable for a given weight limit.

Why are these attributes present in truck weight data? The following explanation has been offered (*6*). Truckers try to maximize payloads, subject to the limitations imposed on doing so by the characteristics of the demand for freight movement by truck and the regulations limiting truck weights and sizes. In striving for this goal, some loads "weight-out," some "cube-out," and others—because of various demand considerations—do neither. Given reasonably stable demand with fixed weight limits, a steady-state hauling situation emerges, exhibiting regularity in truck weight distributions. If a higher GVW limit is imposed, increases in the shipment sizes of some weight-out movements take place, up to a level constrained by the new limit. Cube-out movements, on the other hand, must continue to be handled in their original cube-out quantities, at their original GVW levels. The weight limit increase, per se, does nothing to alter the incidence of partial loads. After some period of adjustment, a new steady state, including new weight distribution functions, can be expected to emerge.

RELATED RESEARCH

Yu and Walton (*7*) evaluated a number of methods used to predict truck weight distributions under conditions of chang-

---

A. M. Clayton, Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada. R.G. Thom, University of Manitoba Transport Institute, University of Manitoba, Winnipeg, Manitoba, R3T 2N2, Canada.

ing regulatory limits in the United States. The methods were found wanting on a variety of counts, including the data bases from which they were developed, their conceptual formulations, and their inability to produce adequate predictions. Yu et al. (*1*) accordingly developed the "Texas Shift" method. Similar to the models developed here, the Texas Shift method estimates GVW distributions as a function of governing weight limits.

In using the Texas Shift methodology in the Canadian context, Clayton and Plett (*6*) encountered two difficulties. The first stems from the essence of the Yu et al. methodology, namely extrapolation (by an eye-balling technique) of existing cumulative weight distribution curves to different weight limit circumstances. Different analysts (i.e., different "eyes") can have different results. Secondly, the method relies on an assumption that the ratio of the means of weights of a particular truck type to that truck type's practical maximum GVW is constant and independent of the regulation limit. This assumption was found wanting in the analysis of a large data set involving 3-S2 combinations.

GENERAL CONSIDERATIONS RELATING TO MODEL CONSTRUCTION

Modeling Process

The modeling requires relating measured truck weights to governing weight limits for each truck type, and developing empirical models of these relationships. For the models presented here, this involves four stages, illustrated in Figure 1.

Stage 1 is the acquisition of the truck weight information of interest for each truck type (e.g., the GVWs of 3-S2 tractor-semitrailers) under a series of weight limits (e.g., LIMIT 1, LIMIT 2, etc.). Stage 2 "corrects" these raw data sets by ridding them of overweight observations, thereby creating an idealized complete compliance condition. As discussed subsequently, this stage is necessary in order to retain the inherent rationale of the model. Stage 3 develops empirical models of a common form designed to reproduce the resulting corrected weight distributions for each of the governing limit cases. Stage 4 "marries" these models so as to permit their generalization as a function of the governing limit. The resulting generalized model permits estimating weight distribution curves given the governing weight limit.

Data Base

Models are developed for three common truck configurations operating in Canada, namely the 5-axle (3-S2) tractor-semitrailer, the 7-axle (3-S2-S2) B-train combination, and the 7-axle (3-S2-2) A-train combination. The 3-S2 tractor-semitrailer is the most common configuration in the Canadian trucking fleet. It is used to transport the full range of commodities, in both truckload and less-than-truckload quantities. The 7-axle B-train is a large truck combination comprised of a 3-axle tractor plus tandem-axle semitrailer plus a second tandem-axle semitrailer. B-train combinations are generally used for hauling dense products (i.e., petroleum, lumber, bulk fertilizer, grain), in truckload quantities. The 7-axle A-train is another large Canadian truck combination composed of a 3-axle tractor plus tandem-axle semitrailer plus a second 2-axle trailer. Typical dimensional characteristics for these units are shown in Figure 2.

The models have been constructed from truck weight data obtained from four sources (Manitoba Department of High-

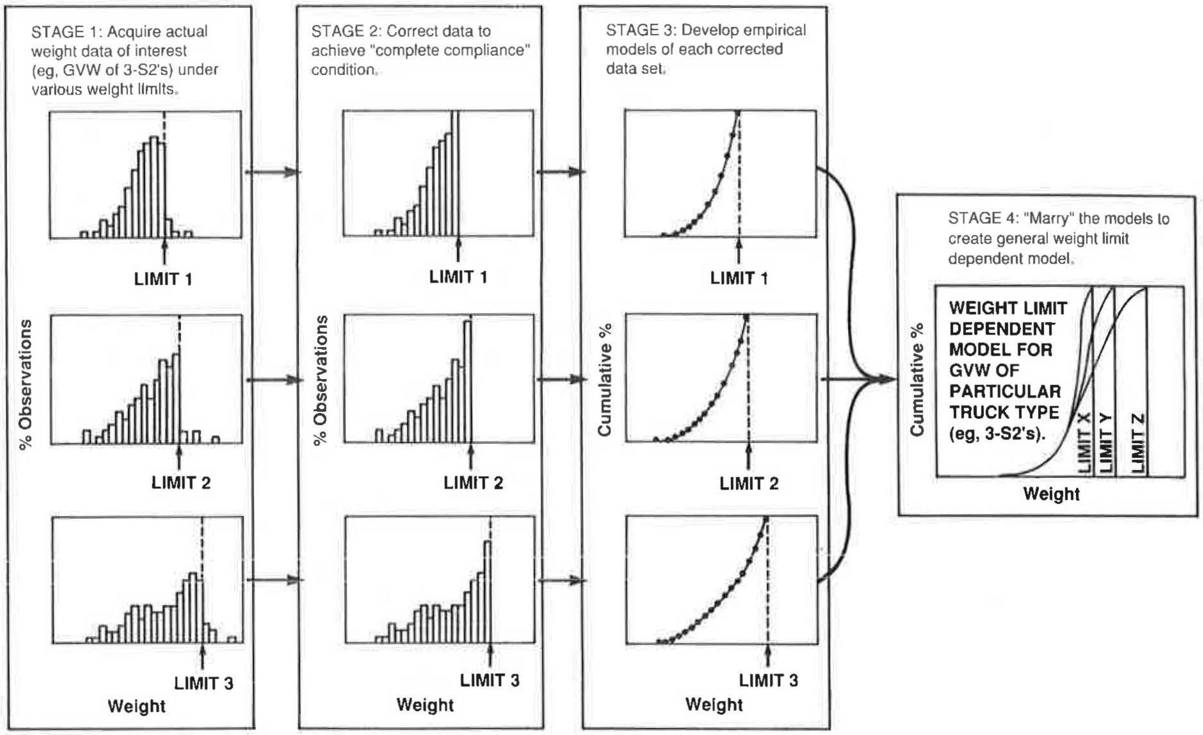


FIGURE 1 Modeling process.

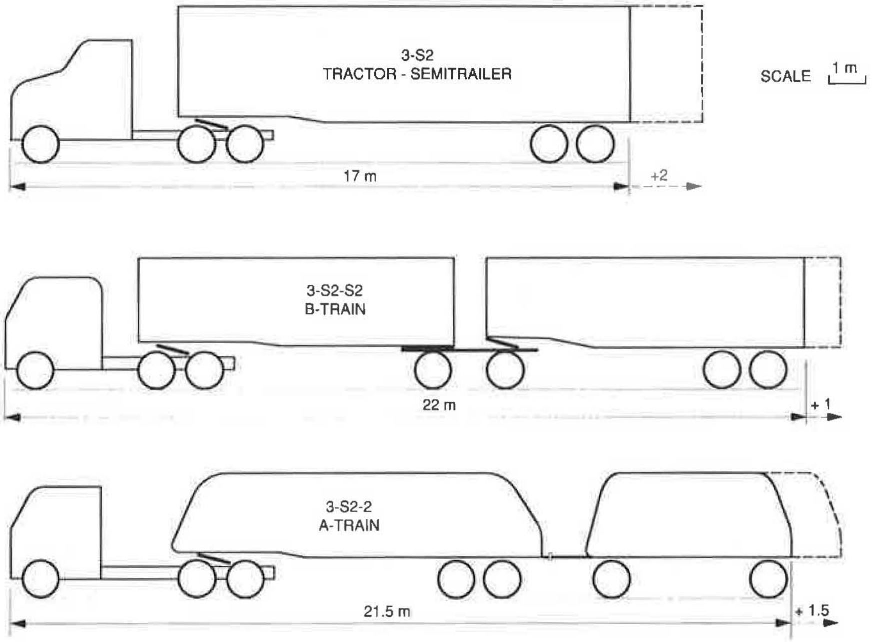


FIGURE 2 Typical truck dimensional characteristics.

ways truck weight surveys between 1972 and 1986; Atlantic Canada Truck Weight Survey of 1985; Saskatchewan Department of Highways truck weight survey of 1986; special winter 1990 surveys conducted in Saskatchewan and Manitoba concerning the weights of Canada's new "RTAC" trucks). Details regarding these data bases are presented elsewhere (*5,6,8,9*). Summary information concerning the content of these data sources is given in Table 1.

To do the modeling, this truck weight data have been related to governing weight limits. Nix et al. (*10*) and Nix (*11*) provide details concerning the weight and dimension regulations applicable during the survey periods considered.

Rationale for Modifying the Raw Data

Many trucks operate overweight (*12*). The extent of overweight trucking is dependent on enforcement policies and practices (*13*), and the extent to which overweight trucking is specially permitted. Policies concerning these matters vary among and even within jurisdictions. In developing the model concept and the resulting formal GVW models, the issue of how to handle overweight observations in the various data sets required special attention.

Two approaches were considered. The first involves retaining the overweight observations in the data sets, and developing general weight limit-dependent distribution models incorporating an overweight element. This was done in the models reported elsewhere (*6*). The problem with this approach is that there is no way of objectively accounting for the effect of variations in enforcement and special permitting on the resulting models. For example, for data obtained under a condition of low enforcement, the relationship between truck weights and weight limits could be expected to be quite different than the same relationship under a high enforcement condition, other things being equal. At the extreme, these relationships might become virtually meaningless under a zero enforcement case (i.e., would a totally unenforced weight limit have any effect on truck loads?).

TABLE 1 SUMMARY OF ORIGINAL DATA SETS

Truck Type	Effective GVW Limit (EGVW) (t)	Axle Limits (t)	Source	No. of Trucks Weighed
3-S2	33.6	5.1/14.6/14.6	Manitoba secondary highways	8,806
	37.3	5.3/16.0/16.0	Manitoba primary highways	12,556
	40.5	5.5/17.0/18.0	Atlantic provinces	4,517
3-S2-S2	50.0	5.3/16.0/16.0/16.0	Manitoba primary highways	46
B-train	53.3	5.3/16.0/16.0/16.0	Saskatchewan 1986 survey	372
	56.5	5.3/17.0/17.0/17.0	Saskatchewan special survey	38
3-S2-2	50.0	5.5/16.0/16.0/9.1/9.1	Manitoba primary highways	78
A-train	53.5	5.5/16.0/16.0/9.1/9.1	Saskatchewan 1986 survey	513
	55.7	5.5/16.0/16.0/9.1/9.1	Manitoba special survey	18

The second approach, and the one selected, is to modify the original data sets—in a consistent, reproducible manner—to make them comply with the governing weight limits. This is done by assuming an idealized condition of complete compliance with the applicable weight rule. The idea behind this is that the developed models should express the ideal weight distributions that could be expected under particular weight limits, assuming compliance. To the extent that a jurisdiction does not enforce its weight limits and specially permits overweight operations, adjustments to the resulting weight distribution models could subsequently be reintroduced in an explicit manner.

The method used to modify data to the complete compliance condition is as follows. Trucks which exceed their legal GVW limit are assumed to have their payloads reduced to a level where their resulting GVWs are just at the limit. This is done by taking all weight observations which are greater than the limit and allocating them to the weight category whose upper boundary is the limit. This allocation method implies that the excess payload associated with overweight observations is removed from and does not influence the resulting complete compliance models.

TERMS

The models make use of two terms requiring definition, namely, the effective GVW limit and the effective steering axle limit. The effective GVW limit (EGVW) is the lesser of: (i) the legislated GVW limit; or (ii) the sum of the axle weight limits, with the steering axle limit being set at the effective steering axle limit. The effective steering axle limit for each truck type is set at the mean weight of that truck type's steering axles observed in the field, plus twice the standard deviation of the sample of steering axle weights from which the mean is derived. Effective steering axle limits for the three truck types modeled here are shown in Table 2.

The effective GVW limit concept is required for this modeling exercise because trucks are often unable to achieve their fully permitted GVW limit either for lack of axles or an inability to shift adequate load to the front steering axle.

(The effective GVW limit used here is equivalent to the Yu et al. (*1*) practical maximum GVW concept. The calculation details are somewhat different, however.)

MODEL DETAILS

5-axle (3-S2) Tractor-Semitrailer GVW Model

This model has been developed from GVW observations for 3-S2s operating under three different (effective) GVW limits (33.6 t, 37.3 t, and 40.5 t). This set of limits covers a GVW range which encompasses the actual limit for these trucks in most countries. Table 1 shows the sources and numbers of truck weight observations used for this model. Details involved in preparing this data set for modeling are given elsewhere (*6,14*).

Figure 3a shows the actual cumulative curves developed from these data sets. Figure 3b shows these same distributions corrected to achieve complete compliance. To illustrate the correction process, consider the 12,556 3-S2 trucks weighed on Manitoba primary highways on which the GVW limit for these units was 37.3 t. Of these 12,556 units, 159 had a GVW level of more than 38 t. These 159 observations were reallocated to the 37-38 t weight category, which in the final model is the weight category 37-37.3 t.

TABLE 2 EFFECTIVE STEERING AXLE LIMITS

Truck Type	Effective Steering Axle Limit (kg)
3-S2	0.08(Tandem Axle Limit in kg) + 4,000
3-S2-S2	5,300
3-S2-2	5,500

Source: after Plett, R. (*15*).

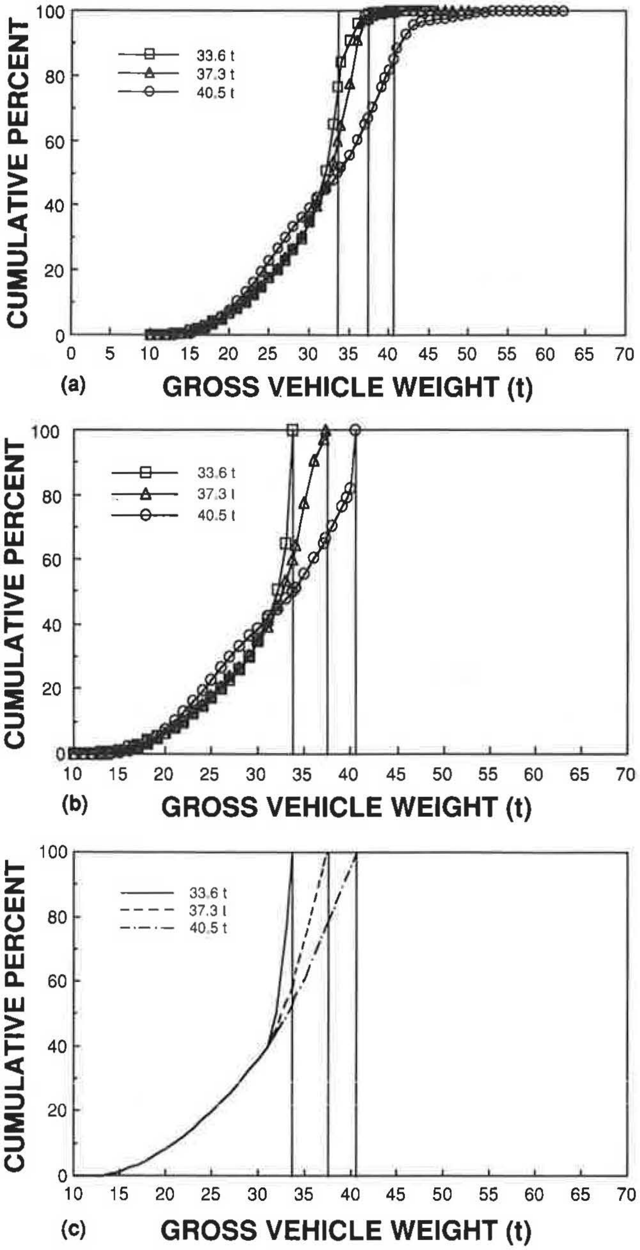


FIGURE 3 GVW Distributions—3-S2s: (a) observed; (b) corrected; and (c) model.

TABLE 3 CUMULATIVE GVW DISTRIBUTION MODELS

Models

Truck Type	x percent less than or equal to on a cumulative curve	$P(x)$ the GVW at which x percent or less trucks operate (in t)
3-S2	for $x > 40$	$P(x) = [\gamma(x - 40)^{\beta} + 31]$
	for $x \leq 40$	$P(x) = 13 + 0.75x - 0.0075x^2$
3-S2-S2	for $x > 25$	$P(x) = [\gamma(x - 25)^{\beta} + 47]$
	for $x \leq 25$	$P(x) = 17 + 2.25x - 0.042x^2$
3-S2-2	for $x > 14$	$P(x) = [\gamma(x - 14)^{\beta} + 45]$
	for $x \leq 14$	$P(x) = 15 + 4.07x - 0.1375x^2$

Parameters

Truck Type	Curve Parameters
3-S2	$\gamma = 3.663908 - 0.18422\ (\text{EGVW}) + 0.002495\ (\text{EGVW})^2$
	$\beta = -9.30265 + 0.498098\ (\text{EGVW}) - 0.00611\ (\text{EGVW})^2$
3-S2-S2	$\gamma = 8.994935 - 0.40784\ (\text{EGVW}) + 0.004574\ (\text{EGVW})^2$
	$\beta = 24.71141 - 0.84735\ (\text{EGVW}) + 0.007462\ (\text{EGVW})^2$
3-S2-2	$\gamma = -382.692 + 14.13420\ (\text{EGVW}) - 0.12944\ (\text{EGVW})^2$
	$\beta = 62.67494 - 2.31392\ (\text{EGVW}) + 0.021433\ (\text{EGVW})^2$

On considering the resulting corrected distributions of Figure 3b, it can be seen that irrespective of the GVW limit, the shape and position of the cumulative GVW distribution curves below the (approximately) 40 percent/31 t position is for all intents and purposes constant. Above this point, on the other hand, the curves diverge. Their divergence is consistent with the model hypothesis that the GVW limit is at work being an important determinant of their shapes and positions (i.e., the higher the limit, the more the cumulative distribution curve shifts to the right).

The fact that the different curves do become more or less the same below some point such as 40 percent/31 t is intuitively reasonable. A certain proportion of trucking activity occurs at GVW levels well below the governing GVW limits. For this activity, whether or not the governing weight limit is higher or lower (within reason of course) has little effect on the loads carried.

It was decided to model this distribution using two components. Below the 40 percent/31 t point, the distribution was assumed to be independent of the weight limit. Above this point, the distribution was assumed to be dependent on the governing weight limit. Note that there is nothing sacred about the 40 percent/31 t point; it is simply the point below which the observed cumulative distribution curves for 3-S2 units are (more or less) common. (While the same general feature—for the same reason—exists for other truck types, the point of commonality does vary.)

Below the 40 percent/31 t point, the distribution has been modeled using a general quadratic expression $P(x) = a + bx + cx^2$, where $P(x)$ and x are defined below. The result is shown in Table 3.

Above the 40 percent/31 t point, the distribution has been modeled as follows. This portion of each distribution curve is defined by two variables, namely:

$$Q(z) = [P(x) - 31] \text{ (in t)}$$

where

$P(x)$ = GVW at which x percent or less trucks operate and
31 = weight below which the curves are constant.

$$z = [x - 40] \text{ (in percent)}$$

where

x = percent less than or equal to on a cumulative curve and
40 = percentage below which the curves are constant.

Note that $P(100)$ on the corrected distribution curves being modeled equals EGVW.

Figure 4 shows the plots of $Q(z)$ versus z used in the modeling for each of the three data sets, at three different GVW

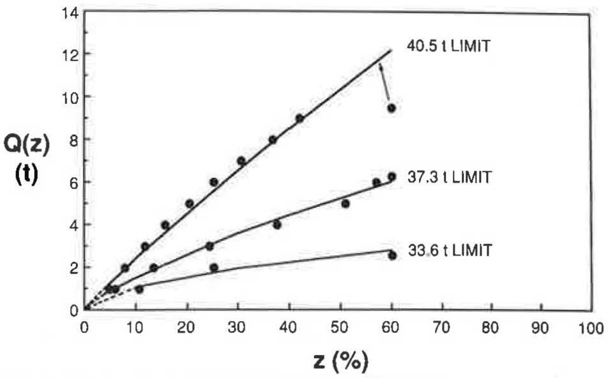


FIGURE 4 *Q(z)* **versus** *z* **for the 3-S2 model.**

limits. These plots are of the form $Q(z) = \gamma z^\beta$, where γ and β are parameters which are dependent on the governing GVW limit.

Alternatively, the relationship could equally be defined by

$$P(x) = [\gamma(x - 40)^\beta + 31], \text{ where } x \geq 40 \qquad (1)$$

The fitted values of γ and β were determined by regression. These fitted values are shown in Table 4. While applying these fitted values to the $P(x)$ function by definition satisfies the 40 percent/31 t constraint, they do not necessarily satisfy the $P(100)$ complete compliance requirement. To satisfy this constraint, the fitted values of β were adjusted so that the combinations of the resulting values of γ (fitted) and β (adjusted), for each GVW limit, would not contravene the complete compliance provision that $P(100)$ must equal the GVW limit. The resulting β (adjusted) values are also shown in Table 4.

To complete the model, the values of γ (fitted) and β (adjusted) had to be related to the governing GVW limit—the determinant variable. It is this linkage which permits generalization of the model, wherein the (complete compliance) cumulative distribution curve (above the 40 percent/31 t point) can be estimated as a function of the governing limit. These relationships were established by regression, and are given in Table 3. These equations can be used to establish the values of γ and β in Equation 1 for a particular EGVW limit. In combination with Equation 1, they constitute the model for estimating that portion of the cumulative GVW distribution curve for 3-S2 units above the 40 percent/31 t point on the curve.

Table 3 then shows all aspects of the resulting, two-component model of the GVW cumulative distribution curve for 3-S2 tractor-semitrailers. Figure 3c shows the distributions predicted by this model for each of the GVW limits used in its formulation (i.e., illustrating the model's ability to predict its origins).

7-axle (3-S2-S2) B-train GVW Model

This model has been developed from three different GVW observations for 3-S2-S2s operating under three different (effective) GVW limits (50.0 t, 53.3 t, and 56.5 t). Table 1 summarizes the sources and numbers of truck weight observations used for this model. These data sets are small compared to those used for the 3-S2 GVW distribution.

TABLE 4 γ AND β VALUES AS A FUNCTION OF EGVW

Truck Type	EGVW (t)	γ Fitted	β Fitted	β Adjusted
3-S2	33.6	0.29109	0.55246	0.53479
	37.3	0.26407	0.76336	0.77475
	40.5	0.29580	0.90931	0.84736
3-S2-S2	50.0	0.04010	1.00529	0.99942
	53.5	0.26992	0.73461	0.73687
	56.5	0.55612	0.65930	0.65734
3-S2-2	50.0	0.40804	0.57331	0.56256
	53.5	2.98670	0.24009	0.22811
	55.7	2.98434	0.28981	0.28666

Figure 5a shows the actual cumulative curves developed from these data sets. Figure 5b shows these same distributions corrected to achieve complete compliance. Visual inspection of these modified distributions led to the decision to model them in the same two-component manner, with the same function forms, discussed for the 3-S2 units in the preceding section. This time, however, the curve break-point was chosen as 25 percent/47 t. The model below this point is deemed to be independent of the GVW limit; above this 25 percent/47 t point, the model incorporates the GVW limit as the determinant variable.

Figure 6 shows the plots of $Q(z)$ versus z used in the modeling for each of the three data sets, at three different GVW limits. Again, these plots are of the form $Q(z) = \gamma z^\beta$, where γ and β are parameters which are dependent on the governing

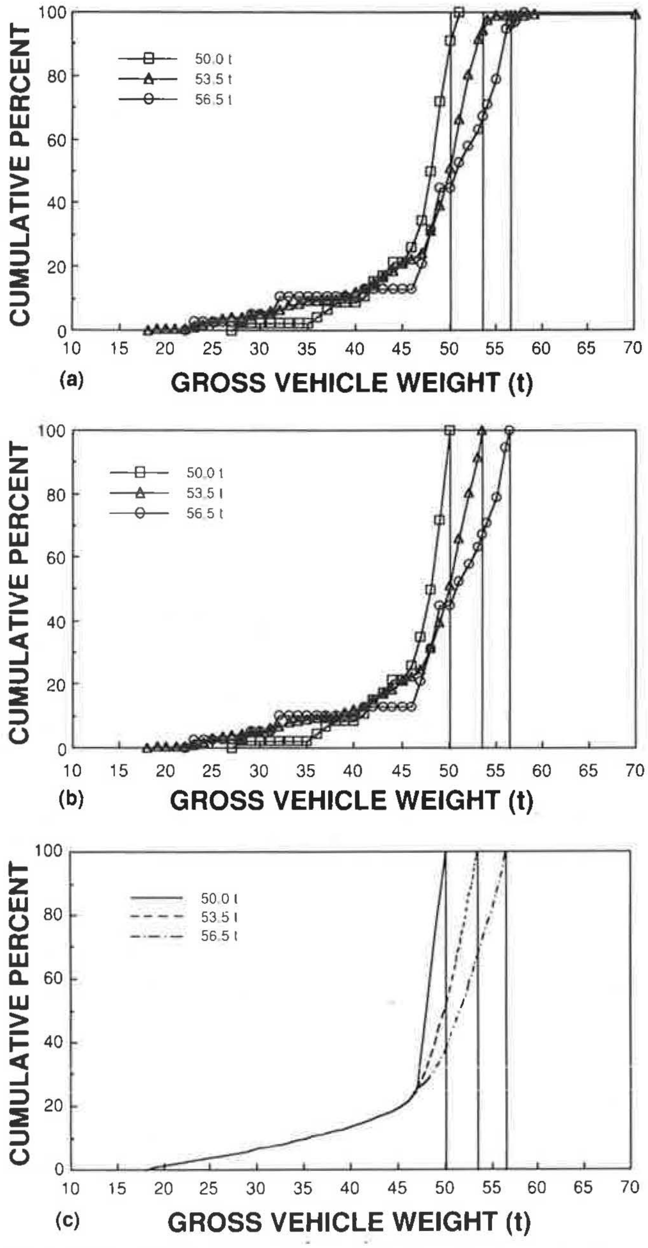


FIGURE 5 GVW Distributions—3-S2-S2s: (a) observed; (b) corrected; and (c) model.

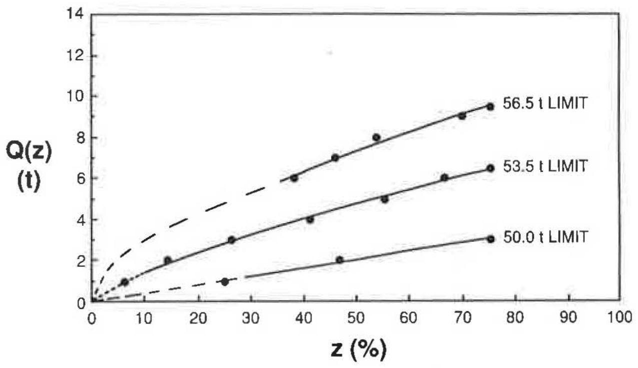


FIGURE 6 *Q(z)* **versus** *z* **for the 3-S2-S2 model.**

GVW limit. The fitted values of γ and β, determined by regression, are shown in Table 4. To satisfy the complete compliance constraint, the fitted values of β were adjusted. The resulting β (adjusted) values are also shown in Table 4.

Table 3 presents the resulting GVW distribution model for these 7-axle B-trains. Figure 5c shows the distributions predicted by this model for each of the GVW limits used in its formulation.

7-axle (3-S2-2) A-train GVW Model

This model has been developed from three different GVW observations for 3-S2-2s operating under three different (effective) GVW limits (50.0 t, 53.5 t, and 55.7 t). Table 1 summarizes the sources and numbers of truck weight observations used for this model. These data sets are roughly of the same size as those used for the 3-S2-S2 model, and much smaller than those used for the 3-S2 model.

This data has been modeled in the same manner described for the other units, using the same methodology. Figures 7a and 7b show respectively the actual and corrected cumulative GVW distribution curves for these units. This time, the curve break-point was chosen as 14 percent/45 t. The model below this point is deemed to be independent of the GVW limit; above this point, the model incorporates the GVW limit as the determinant variable.

Figure 8 shows the plots of $Q(z)$ versus z used in the modeling for each of the three data sets, at three different GVW limits. They are again of the form $Q(z) = \gamma z^{\beta}$, where γ and β are parameters which are dependent on the governing GVW limit. The fitted values of γ and β, determined by regression, are shown in Table 4. The values of β (adjusted) required to satisfy the complete compliance constraint are also shown in Table 4.

Table 3 presents the resulting GVW distribution model for these 7-axle A-trains. Figure 7c shows the distributions predicted by this model for each of the GVW limits used in its formulation.

TESTING THE 3-S2 MODEL

The special surveys referred to in the preceding provided a new data set which permits assessment of the predictive capabilities of the 3-S2 model that was developed, namely GVW data for 3-S2s operating under new (1989) weight regulations applicable on primary highways in western Canada. These new regulations permit a GVW of 39.5 t for 3-S2 combinations, based on axle loads of 5.5/17.0/17.0 t. Figure 9 compares the actual cumulative GVW curve for 3-S2s operating under this 39.5 t GVW limit with the predicted curve based on the model. Visual inspection of the results indicates that the model appears to be able to predict this distribution reasonably well.

This comparison suggests that the model is reasonably able to predict weight characteristics of the *same* 3-S2 unit operating in the *same* region on the *same* highways (i.e., primary highways in western Canada), at a *different* weight limit (i.e., 39.5 t) than the weight limits applicable to the data base used

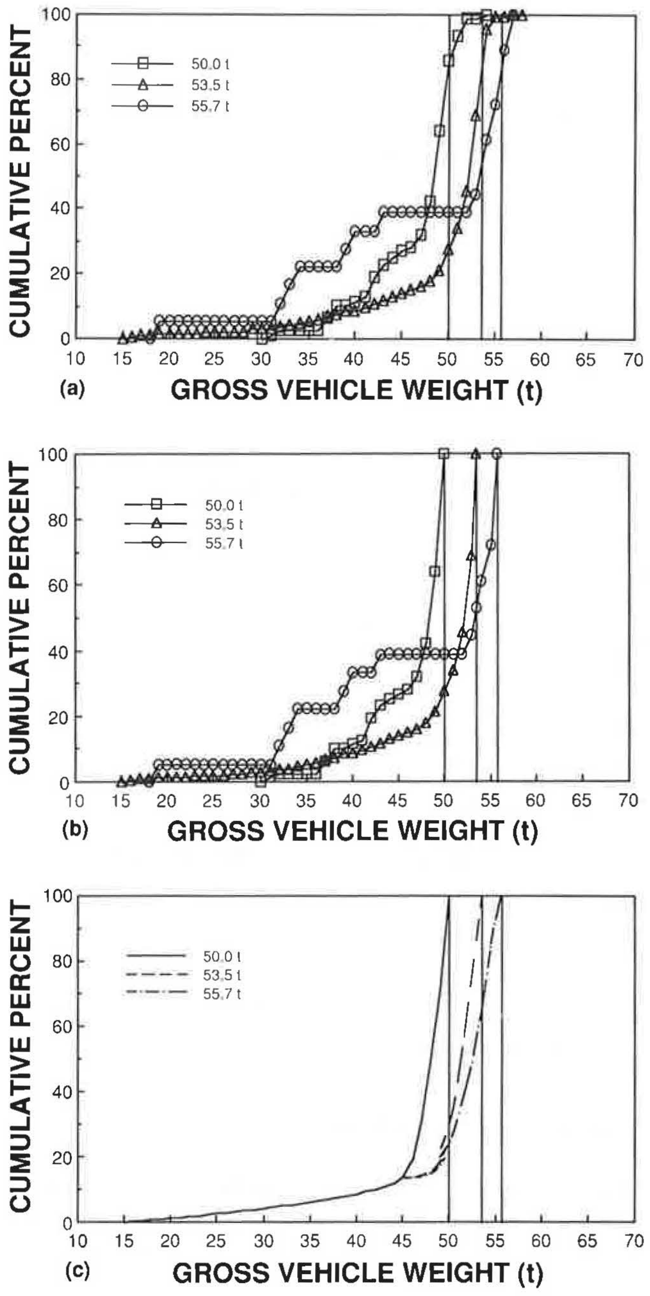


FIGURE 7 GVW Distributions—3-S2-2s: (a) observed; (b) corrected; and (c) model.

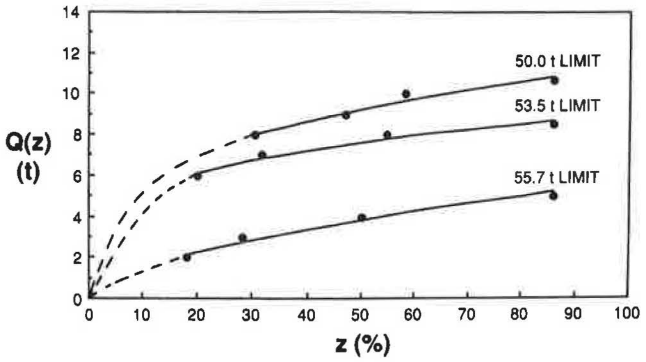


FIGURE 8 *Q(z)* **versus** *z* **for the 3-S2-2 model.**

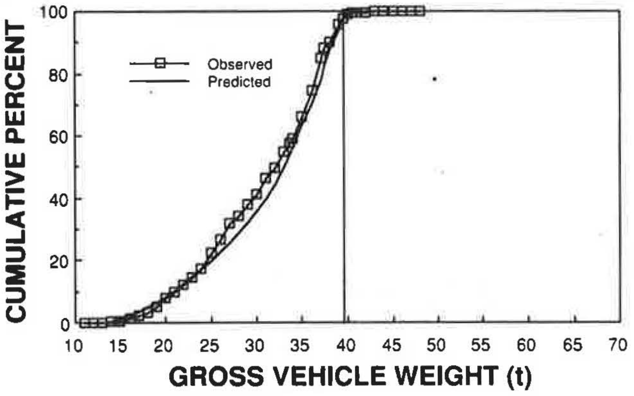


FIGURE 9 Comparison of actual versus predicted GVW: 3-S2s.

in formulating the model in the first place. Its ability to be transferred to other locales has yet to be assessed.

DISCUSSION OF RESULTS

Two important considerations are implicit to the models developed here: (*a*) particular mixes of freight hauled by each of the truck types; and (*b*) particular weight and dimension regulatory situations, with their attendant implications on vehicle design and use. If either of these factors was significantly different from those present in the situation that created the data base modeled, different model characteristics could result.

Concerning the freight demand considerations implicit to these models, the following comments are relevant. The 3-S2 model has been constructed from a very large number of observations of the GVWs of these units hauling a wide mix of commodities. As discussed elsewhere (*6*), the model can be considered of an all-commodity nature, meaning that it represents the weight distribution that might be expected in a highway operation where no one commodity or small number of commodities dominates the freight handlings. At this stage, no objective measure of this all commodity concept is proposed. Suffice it to say that given a highway where one unusual commodity dominated the haul (e.g., feathers or gravel), substantially different weight distributions could be expected to result.

The A- and B-train GVW models have been constructed from much smaller data bases than those used for the 3-S2 model. As such, the commodity-mix-momentum behind the 3-S2 model is not incorporated in these models. For this reason, users of these models should show a greater concern for possible commodity-mix errors than need be shown when using the 3-S2 model. Counteracting the effect of this problem, however, is the fact that, relative to 3-S2 units, 7-axle A- and B-train combinations are normally employed in weight-out type operations. This means that most of the measurements of the GVW of these units tend to be skewed towards the weight limit. As such, to get a good indication on the GVW distribution of these units compared to 3-S2s does not require near as many observations. Put another way, if there is a 7-axle B-train on the road, it is likely that it is either full (on a weight-out basis) or empty. Seldom is it full on a cube-out basis or partly loaded.

Implicit to these models are the detailed weight and dimension regulation systems prevalent in western Canada between 1972 and 1990. The transferability of the resulting models into entirely different regulatory situations (i.e., Ontario's unique bridge-formula-based system) may not be possible.

The models assume the complete compliance condition, or in other words assume that GVW limits are strictly adhered to. To the extent that they are not adhered to (either illegally or legally), variations from the predicted distributions should be expected. At the extreme, if there is no enforcement, these models at the higher weight levels can be expected to exhibit errors.

CONCLUDING REMARKS

1. Empirical models linking the distribution of GVWs of laden 3-S2s, 3-S2-S2s (B-trains) and 3-S2-2s (A-trains) to the GVW limit governing these trucks are presented, for a condition of complete compliance. The 3-S2 model was applied to a situation independent of the data set used in its construction, and was able to produce a quite acceptable prediction.
2. Being complete compliance models, they are intended to be used where truck weights are extensively adhered to. If they are not, the modeled distributions would have to be appropriately modified.
3. The models rely on the existence of stable relationships between truck weight distributions and fixed weight limits, as initially observed in the truck weight data used in their preparation.
4. Implicit to the models are the truck freight characteristics and weight and dimension regulatory systems particular to the data base used in the modeling. It seems reasonable to speculate that locale-specific considerations concerning these implicit factors would necessitate recalibration of the models if they were to be used in significantly different circumstances.
5. The appropriateness of extrapolating the models significantly beyond the weight limit boundaries present in their original data sets has not been assessed and requires investigation.

ACKNOWLEDGMENTS

Funding was provided by the Natural Sciences and Engineering Research Council of Canada and the University of Manitoba Transport Institute. J. Wyatt, Saskatchewan Department of Highways and Transportation; M. Lai, Manitoba Department of Highways and Transportation; and B. Bisson, University of New Brunswick assisted in the provision of data.

REFERENCES

1. C. Yu, C. M. Walton, and P. Ng. Procedure for Assessing Truck Weight Shifts that Result from Changes in Legal Limits. In *Transportation Research Record 920,* TRB, National Research Council, Washington, D.C., 1983.
2. F. Nix and A. Clayton. Assessing the Impact of Weight and Dimension Regulations: Methodological Considerations. *Proc., International Symposium on Heavy Vehicle Weights and Dimensions,* Roads and Transportation Association of Canada, Kelowna Canada, June 1986.
3. ACI Joint Task Force on Load and Resistance Factor Design for Bridges. *Concrete International.* May 1988.
4. R. Lill. Geometric Design for Large Trucks: an Overview of Issues from the Perspective of the American Trucking Associations, Inc. In *Transportation Research Record 1052,* TRB, National Research Council, Washington, D.C., 1986.
5. A. Clayton and M. Lai. Characteristics of Large Truck-Trailer Combinations Operating on Manitoba's Primary Highways: 1974–1984. *Canadian Journal of Civil Engineering,* Dec. 1986.
6. A. Clayton and R. Plett. Truck Weights as a Function of Regulatory Limits. *Canadian Journal of Civil Engineering,* Feb. 1990.
7. C. Yu and C. M. Walton. Estimating Vehicle Weight Distribution Shifts Resulting from Changes in Size and Weight Laws. In *Transportation Research Record 828,* TRB, National Research Council, Washington, D.C., 1982.
8. Saskatchewan Highways and Transportation. *Truck Axle Weight and Commodity Survey: 1986.* Regina, Canada. April 1987.
9. A. Clayton, A. Lansdown, J. Wyatt, and R. Thom. Truck Weight Distributions as a Function of Weight Limits: Western Canada Experience. *Proc., 3rd International Conference on Short and Medium Span Bridges,* Toronto, Ontario, Canada, Aug. 1990.
10. F. Nix, A. Clayton, and B. Bisson. *Study of Vehicle Weight and Dimension Regulations and Canada's Trucking Industry: The Regulations.* Report TP8481E, Transportation Development Centre, Transport Canada. 1986.
11. F. Nix. Canadian Sizes and Weights. *Motor Truck,* Nov. 1989.
12. A. Clayton and R. Girling. Aspects of Overweight Trucking in Manitoba. *Proc., Canadian Transportation Research Forum Annual Conference,* Halifax, Canada, May 1989.
13. J. Wyatt and M. Hassan. Some Tentative Findings about the Effect of Level of Enforcement on Compliance with Truck Weight Regulations. *Proc., Canadian Transportation Research Forum Annual Conference,* Toronto, Ontario, Canada, May 1985.
14. A. Clayton, R. Plett, D. Chan, and P. Klungboonkrong. Predicting Truck Weights from Weight Limits. *Proc., International Conference on Highways and Data Processing,* Ecole Nationale des Ponts et Chaussees, DFCAI Departmement Interational, Paris, France, March 1990.
15. R. Plett. *Weight and Dimension Characteristics of Large Combinations as a function of Regulatory Limits: Manitoba Highways.* M.Sc. thesis. Department of Civil Engineering, University of Manitoba, Winnipeg, Canada, 1989.

Publication of this paper sponsored by Committee on Motor Vehicle Size and Weight.

1988 Ontario Commercial Vehicle Survey

JULIUS GORYS

The Ontario Ministry of Transportation periodically undertakes on-highway surveys of commercial vehicles. In 1988, it surveyed some 19,000 trucks to obtain information for its highway planning and protection mandate. During the course of the survey, the characteristics of the vehicles were documented, and data collected on carriers, area of registration, load utilization, commodity type and weight, and trip origin and destination. As well, a profile of the Ontario truck driver was generated. Surveys were undertaken at 57 locations scattered throughout the province at permanent inspections stations, laybys and some border crossing points. At several of the stations, interviewing was done during each of the four seasons. An outline of the methodology used in the 1988 Ontario Commercial Vehicle Survey and some principal findings are presented in this paper.

The Ontario Ministry of Transportation periodically conducts roadside surveys of commercial vehicle and freight movements on the Ontario highway network to collect information for planning and operational purposes.

The primary objective of the 1988 Ontario Commercial Vehicle Survey was to provide a current profile of trucking activity in the Province for the planning, delivery, and evaluation of Ministry programs. Undertaking the survey during 1988 was done to continue providing trend information and identification on the basis of 5-year intervals (previous such surveys were done in 1978 and 1983).

Beyond the primary objective, the study was also aimed at gathering information on the

- Nature and extent of dangerous goods movement;
- Structure of the industry between private and for-hire carriers;
- Transborder movement of goods, particularly the degree and nature of traffic held by other provincial or U.S. carriers;
- Seasonal variations in transportation and commodity movements;
- Characteristics of commercial vehicle drivers regarding demographic and other considerations;
- Commodity and load characteristics; and
- Measures of efficiency and productivity on the basis of empty truck movements and ton-miles transported.

A survey consisting of 29 questions was composed, to be applied at truck inspection locations and border crossings situated along the principal intercity highway corridors in the province. The methodology used to undertake the survey and an outline of the general characteristics of the operating truck fleet found in the Province of Ontario are focused on in this paper.

Ontario Ministry of Transportation, Policy Planning Branch, 1201 Wilson Ave., 3rd Fl., West Tower, Downsview, Ontario, Canada M3M 1J8.

TRUCKING IN ONTARIO

Trucking is the principal means of transporting goods and services both in the Province of Ontario, and in Canada as a whole. Trucking accounted for 61 percent of total freight revenue in the province in 1987, compared with 20 percent for rail (Figure 1). On the order of 130 million tonnes of freight are moved by trucks in Ontario, compared with 70 million tonnes by rail (*1, p.9*).

The trucking industry employs on the order of 200,000 to 225,000 workers, or 4 to 5 percent of the provincial labor force, although this figure also includes nontrucking-related activities (e.g., retail, utilities, and government). Trucking's share of Canada's real domestic product and Ontario's gross provincial product is also approximately 4 to 5 percent (*1*,pp. 180–186).

There are some 158,000 trucks with a registered weight in excess of 4,500 kg (9,920 lb) in the province. Through license fees, corporate income, and diesel fuel taxes, the trucking industry makes a considerable contribution to provincial government revenue—close to $400 million. In contrast, the rail sector contributes only $27 million, but incurs other costs with respect to the maintenance of their own infrastructure (*2*).

On the order of 43 percent of Canada's exports and 57 percent of Canada's imports were transported by truck in 1989, together representing $136 billion worth of trade. In Ontario, the truck proportion of overall transportation of trade is much higher—59 percent of exports, and 68 percent of imports, representing $94 billion worth of trade (*3*).

In 1989, trucking was used to ship 66 percent of Ontario's $56 billion worth of exports to the United States, and 79 percent of its $48 billion worth of imports from the United States (Figure 2). Some 20 percent of Ontario trucking industry revenues are transborder related (*4*).

Ontario dominates Canadian trucking, accounting for about 40 percent of shipments, employment, vehicle fleet, operating expenses, and tonnes transported. The greater Toronto area alone is the generator or recipient of truck shipments and tonnes transported as much as the next three largest cities in Canada—Montreal, Vancouver, and Edmonton (Figure 3) combined (*1*, pp. 110–111).

A total of 47 truck inspection stations are strategically located throughout the Province of Ontario to monitor and control truck activity on both the principal and secondary intercity routes. As well, enforcement staff have the capability to inspect vehicles at dedicated roadside locations (laybys) along certain stretches of highways. All commercial vehicles are required to enter inspection stations. Information from these areas is supplemented with data derived from other sources (principally Statistics Canada) to assist in policy formulation and program delivery.

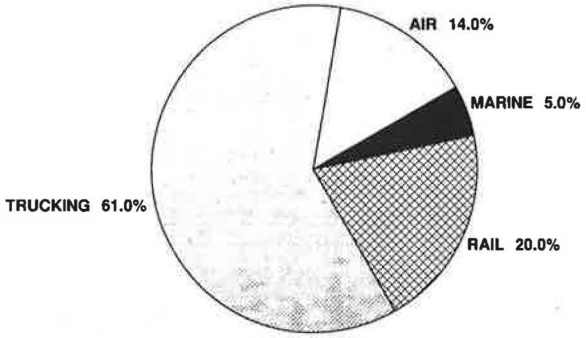
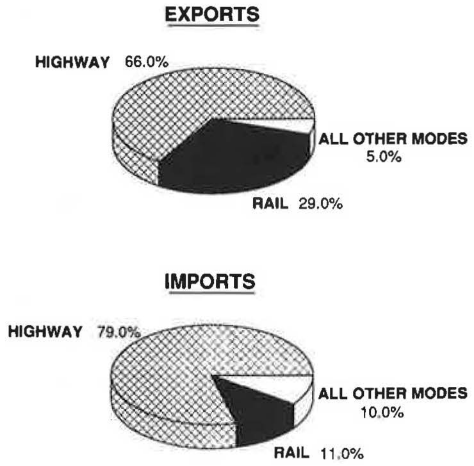


FIGURE 1 Freight revenue generation in Ontario, 1987.



Source: Statistics Canada

FIGURE 2 Value of Ontario's trade with the United States transported by respective freight modes, 1989.

METHODOLOGY

Roadside interviews were adopted to provide time series information consistent with that collected in 1978 and 1983. The survey was carried out during March to November 1988 inclusive, during a 23-week period. The survey was conducted at 57 locations along the principal intercity highway network. Interviews were undertaken on 100 days, but not necessarily for all of the day. In many instances, surveys were carried out at two different locations in the province during the same day. Where possible, surveys were carried out at the same 1983 survey location.

Permanent weighing facilities were available at 41 locations; portable weigh scales were deployed, where possible, at the remaining sites.

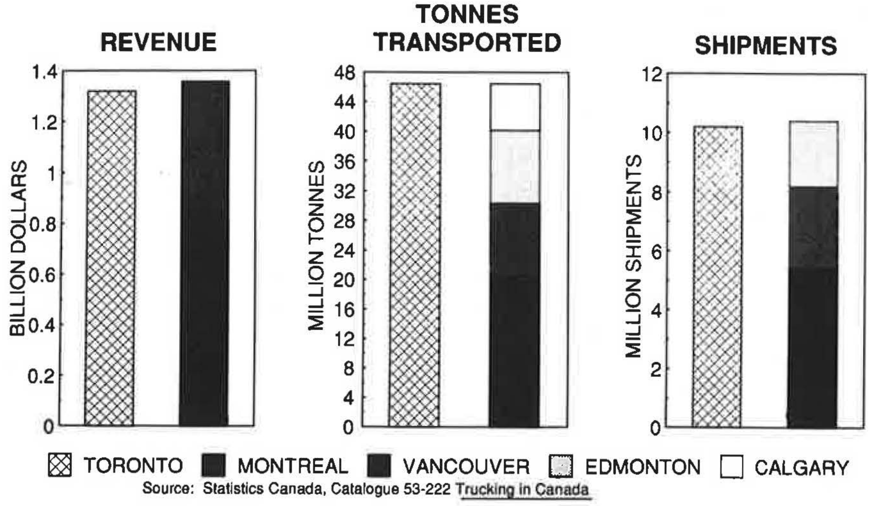
An attempt was made to route as many trucks as possible through the weigh scale platform at the vehicle inspection station. Depending on the respective sizes of the holding area and the interviewing crew, between 2 and 5 trucks would be directed into the station by inspectors. Other trucks were allowed to bypass the station until the interview process was completed, for safety reasons.

Once the trucks were on the scales, inspectors would record the axle weights of vehicles selected for interviewing while a member of the survey crew noted the vehicle plate number, the axle type, and the order of axle weighing. The inspector would then signal the driver to park in the reserved area. Before the actual interview commenced, the surveyor would record the individual truck body and style characteristics (up to 15 features) as shown on Figures 4 and 5.

The interviewer would then approach the trucker, explain the purpose of the survey, and request approval to carry on with the survey. Interviewers relied on the goodwill of drivers who gave generously of their time. Truckers refusing to be interviewed were free to proceed.

For the most part, outright refusals were largely a function of language translation difficulties (i.e., with Francophone drivers) or a cited lack of time by the driver, rather than apprehension at revealing information. After completion of the interview, the bill of lading and other documents related to the carriage of commodities were photocopied if permission was granted to do so. Fully completed interviews lasted between 8 and 12 min; slightly longer when portable scales were deployed.

Drivers were asked several questions pertaining to the vehicle itself: the tare and registered gross vehicle weight, type of fuel propulsion, and whether it was leased or had on-board



Source: Statistics Canada, Catalogue 53-222 Trucking in Canada

FIGURE 3 For-hire trucking, Canadian C.M.A. Rankings, 1987.

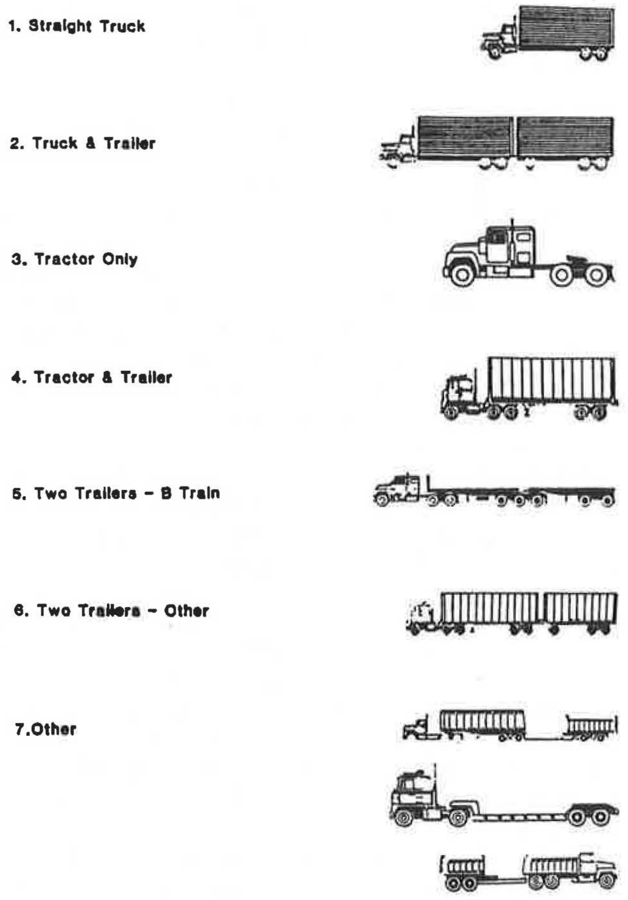


FIGURE 4 Truck types.

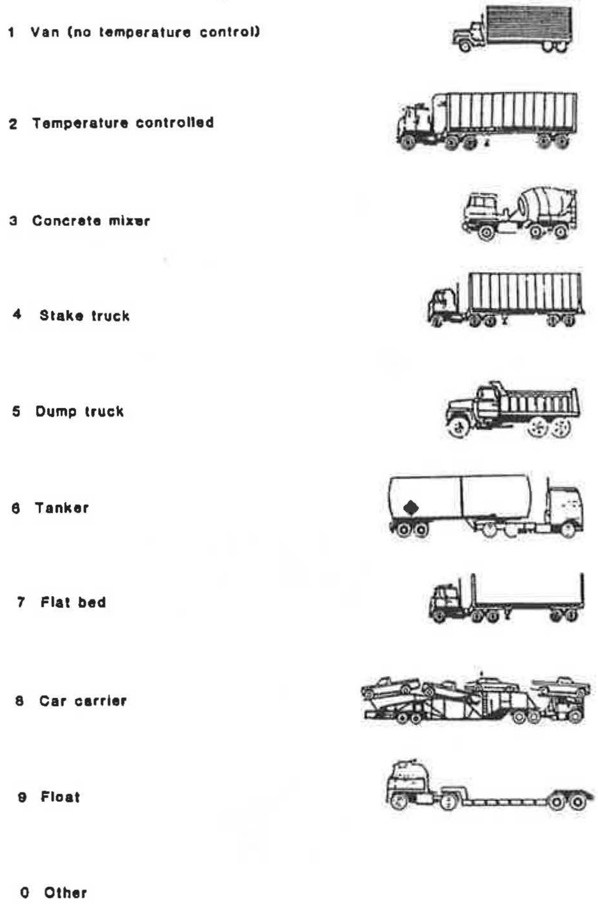


FIGURE 5 Truck body styles.

monitoring devices. Other questions were put forth with respect to the driver employment characteristics, specifically carrier type, union affiliation, method of renumeration, and employee category type.

Information was also collected about the commodities hauled, the degree of utilization level of the vehicle, and the origin and destination of the vehicle and the commodity. This data was crosschecked, where possible, through a review of photocopied waybills. The remaining questions dealt with drivers themselves: their age/sex characteristics, years of experience, recent training, and the number of hours they would be working and driving on the particular trip being surveyed. (A list of questions/variables is found in the appendix to this paper.)

During the duration of the survey, a classification count of vehicles passing by the interview location was also undertaken, to expand the sample to represent a daily average of vehicular movement.

It was planned that each location would be surveyed for 24 hr. At the laybys however, it was determined that because of safety considerations, surveying would be undertaken during daylight hours only. At three-quarters of the survey locations and times, crews were there (but not necessarily surveying) for a full 24-hr period.

All locations were not comprehensively surveyed for the entire intended period because of:

- Inclement weather,
- Heavy traffic that caused unsafe road conditions,
- Malfunctioning of the signalling system or of the portable scales,
- Absence of proper lighting for safe operation,
- Presence of detained vehicles transporting dangerous goods that were leaking that substance,
- Degree of enforcement practiced, and
- Problems associated with staffing logistics.

Fortunately, such incidents were of a minor nature, all things considered.

SAMPLE SIZE AND DATA ADJUSTMENT

In total 19,225 commercial vehicle drivers were interviewed over a period of 1,855 hr at 57 locations (Figure 6), representing an overall sampling rate of 8.6 percent. The sampling rate varied by location, depending on the time of day, and the degree of traffic passing by the respective location. It ranged from a low of 2.4 percent at stations near Toronto, where there were significant volumes, to a high of 100 percent in more remote northern stations.

During another 1,363-hr span, trucks were classified by vehicle type, but there was no truck survey because of weather considerations, absence of enforcement staff, problems as-

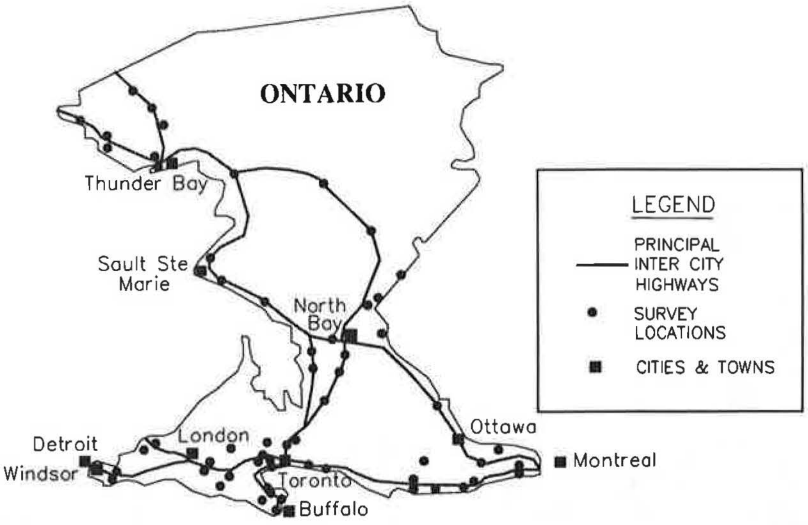


FIGURE 6 Location of survey stations.

sociated with equipment, no trucks for that period, and so on. In addition, to ascertain daily and hourly variations in trip travel, a 7-day, 24-hour classification count was undertaken at a pair of inspection stations west of Toronto.

During the course of the survey, the sample rate varied by day of week as presented in Table 1. The greatest number of surveys were obtained, and vehicular traffic found, on Wednesdays. The Monday and Friday totals were somewhat surprising given a deliberate attempt, by schedule design, to minimize sampling on those two days. It is largely a function of the greater ability to capture truck traffic (given lower volumes generally) on those two days, as the sample rate shows.

The sample rate also varied by time of day (Table 2). Splitting each day into three 8 hour components, it was found that greater success was achieved in sampling trucks during those periods where volumes were less. Truck volumes were found to be highest in the 4:00 p.m. to midnight period.

Care should be used in interpreting this information, however, given the wide area of geographic coverage, and the mix of local versus intercity trips by station site.

Corrections to account for variations in traffic patterns were required to convert the information to an equivalent daily total. Adjustment factors consulted included time series average annual daily traffic information, truck movement trends at international boarder crossings, and the classification counts undertaken at the inspection site while the survey was in progress.

TABLE 1 SAMPLE RATE BY DAY OF WEEK

Day of Week	Surveys Collected	Percent of Total	Trucks Classified	Percent of Total	Sample Rate
Sunday	0	0.0	0	0.0	---
Monday	1,616	8.4	7,078	6.6	22.8
Tuesday	3,722	19.4	17,643	16.5	21.1
Wednesday	5,084	26.5	26,386	24.7	19.3
Thursday	4,542	23.6	33,111	31.0	13.7
Friday	3,623	18.8	20,394	19.1	17.8
Saturday	638	3.3	2,219	2.1	28.8
Total	19,225	100.0	106,831	100.0	18.0

TABLE 2 SAMPLE RATE BY TIME OF DAY

Time Period	Surveys Collected	Percent of Total	Trucks Classified	Percent of Total	Sample Rate
8 to 16	7,356	38.3	50,206	47.0	14.7
16 to 24	6,352	33.0	31,915	29.9	19.9
24 to 8	5,517	28.7	24,710	23.1	22.3
Total	19,225	100.0	106,831	100.0	18.0

The factoring process was undertaken on a individual hour basis, in concert with the 1983 experience, and was largely based on the observed flow of traffic at the individual station. At those stations which were surveyed in each of the four seasons, the factor represented an average of the individual seasons.

A review of the truck proportion of all traffic by hour identified that trucks accounted for between 10 and 58 percent of the vehicular traffic, depending on the hour surveyed (Figure 7). The highest levels were found in the early morning (3 to 5 a.m.). Overall, trucks constituted 17 percent of the total vehicular flow.

Combination vehicles were most prominent during the early morning hours, comprising as much as 85 percent of all trucks. Straight trucks were most in evidence during normal business hours accounting for as much as 22 percent of all trucks.

A 7-day classification count was undertaken as well, at a pair of inspection stations just west of Toronto. From this exercise it was found that Wednesdays had the highest proportion of truck traffic, Sundays the least, and there was a significant difference in volumes between days (Figure 8).

DATA LIMITATIONS

The prime limitation of the data related to the fact that they reflect, at most, a single day's movement of goods by truck during 1988. Unilaterally expanding the results by 250 days

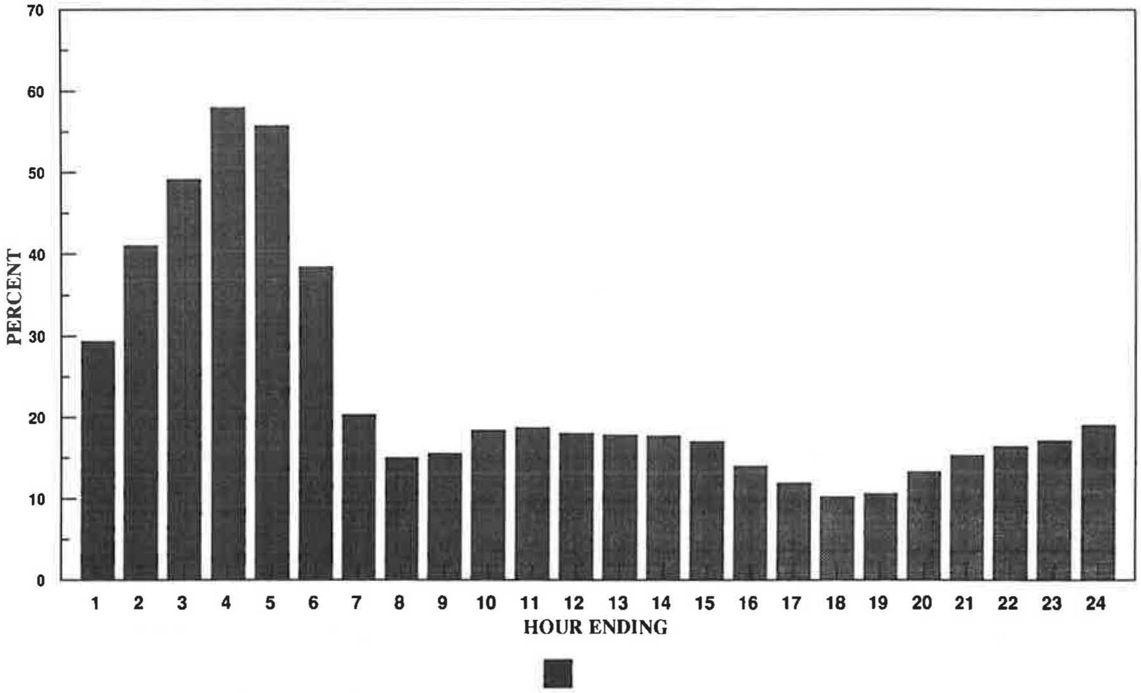
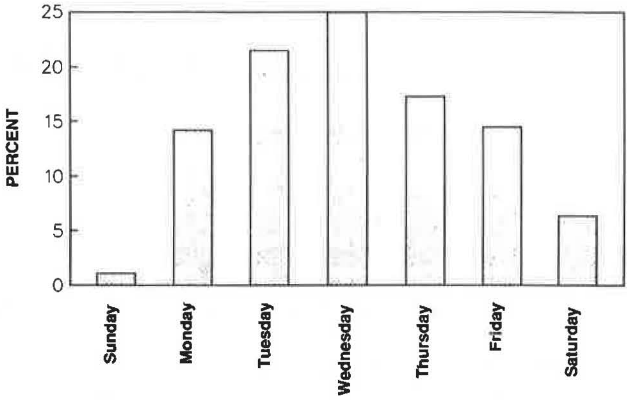


FIGURE 7 Truck percentage by time of day.



Source: Ontario Commercial Vehicle Survey

FIGURE 8 Week-long 24-hr truck classification, Trafalgar Stations, 1988.

or so to represent a yearly flow of truck traffic may present questionable results, and is not recommended given possible seasonal variations. Therefore, the data represent as typical a day as can be possibly surveyed, given observed traffic flows, the logistics of undertaking the survey, and the geographical coverage of sites.

The second limitation is a function of the placement of the interview locations at truck inspection sites: only trucks traveling on the major intercity routes were exposed to the survey. Because the principal purpose of the study was to sample major intercity traffic, this is not a major concern.

The survey does not purport to represent all trucking activity, although a considerable proportion of such rural freeway traffic has an urban origin or destination. There were additional sites on the major secondary routes, so the coverage of truck travel was expanded somewhat, compared with the 1983 survey, but less than was intended. The addition of these sites and expanded coverage at some stations was undertaken to lessen geographic biases.

A related concern with respect to station location citing was that vehicles not in compliance would bypass an open inspection station (and hence avoid being interviewed) because enforcement was being practiced during the duration of the survey. However, selected classification counts on known bypass routes undertaken during the survey found this not to be the case.

Third, only a small proportion of weekend traffic, on Saturdays, was captured. While a bias toward weekday traffic can thus be expected, the results of the week-long classification count at two inspection stations indicated that weekend truck levels were quite low. Saturday travel represented 6.4 percent of weeklong truck traffic; Sunday, a further 1.1 percent.

The fourth limitation reflects the degree of missing values in the survey universe resulting from refusals to divulge information, the provision of misinformation, the absence of a power supply to photocopy waybills, or all of these reasons. Minor variations in the statistical tabulations reflect this. When possible, attempts were made to fill in the blanks through a review of other surveyed information.

Overall, the refusal rate for all of the survey was low (3.5 percent), although moderately higher than was experienced in 1983 (1 percent). This was anticipated because of both the longer survey and the inclusion of potentially controversial questions.

Nonresponses varied considerably by question type and are a function of language translation problems, refusals, misinformation, and in some instances, unawareness. Typically, they were on the order of 9 to 14 percent for each question. There was a higher level of nonresponses pertaining to tare weight (35 percent for nonresident drivers) and driver license identification (44 percent for resident drivers) questions.

PRINCIPAL SURVEY FINDINGS

Structural and operational commercial vehicle fleet information is important for provincial policy formulation, planning and design, and enforcement. The principal survey findings are as follows.

The predominant type of truck in evidence during 1988 was the tractor-trailer combination unit, at 77 percent of the surveyed population. Straight trucks were the next most frequently used truck type at about 16 percent of the surveyed population. Tractors with two trailers only accounted for a further 5 percent of the total, in part a reflection of the greater attractiveness of tractor and semitrailer units (Figure 9).

The van body style accounted for about 60 percent of the truck-trailer units. Two-thirds of all vans were the standard variety, the remainder were temperature controlled (Figure 10). Other frequently occurring identified body types were flat beds (14 percent), and more specialized vehicles such as dump trucks (5 percent) and tankers (8 percent). There were seven body styles that each accounted for less than 2 percent of the overall truck population. The high occurrence of van body styles is a reflection of its operational flexibility, particularly for use in the transportation of general freight. Other body styles reflect a specialized-use or commodity type, which cannot normally be adapted for general use.

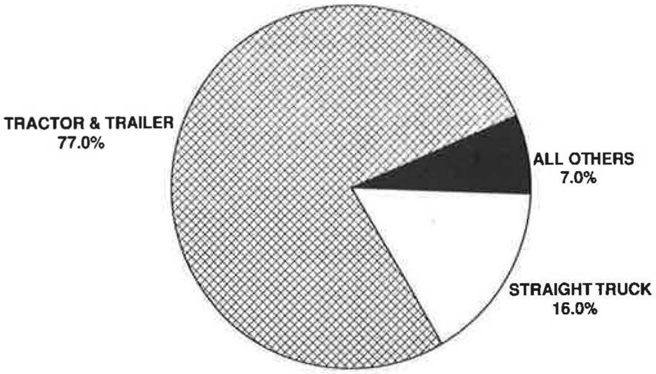


FIGURE 9 Truck types.

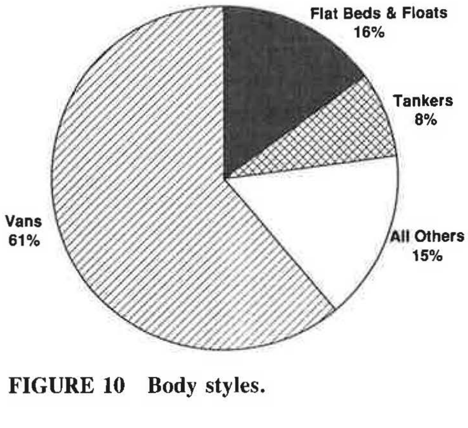


FIGURE 10 Body styles.

An analysis of vehicles by number of axles found that the 5-axle tractor-trailer unit is by far the most numerous vehicle, at about 57.0 percent of the total; the 2-axle straight truck (10.7 percent), and the 6-axle tractor trailer (10.3 percent) represent the two next most frequently used categories of trucks.

An examination of the distribution of trucks by number of axles with the carrier type revealed a greater preference by the for-hire carrier industry for larger vehicles with 6 or more axles. The proportion of for-hire vehicles in this category was 24 percent, compared with 19 percent by private carriers.

To achieve better fuel economy, some trucks are equipped with devices designed to reduce wind resistance to motion. Generally, bubble-type devices are fitted on trailers and van-style straight trucks, while roof-mounted air deflectors and side fairings are installed on the power-tractor units. Results indicated that 38 percent of the vehicles had energy saving devices.

The registered gross vehicle weight (RGVW) of a vehicle is the total weight that the vehicle is registered and licensed to carry within the Province of Ontario under its Highway Traffic Act; it is licensed against the power unit. The maximum RGVW for a vehicle is 63,500 kg (139,990 lb). It was found that the average RGVW of vehicles used in the industry was 39,660 kg (87,430 lb) in 1988. Private carriers used lighter vehicles than for-hire carriers, a function of their different demand pattern.

Where multiple vehicle registrations (including Ontario) were identified, the interviewers were instructed to record the Ontario plate, and not the other jurisdiction. The data indicate that the proportion of Ontario registered trucks/tractors was 81 percent in 1988. The percentage of vehicles registered in the United States was 7 percent.

Although the largest numbers of U.S. vehicles were from the adjacent states of New York and Michigan, the vagaries of U.S. licensing fees, carrier operating practices, and leasing arrangements had resulted in a large proportion of U.S. registered vehicles coming from the states of Vermont and Nevada, while few trips were actually to or from those states. With respect to vehicles registered in other Canadian provinces, those from Quebec and Alberta were the most prominent.

On-board monitoring devices record the timing of movements, distance traveled, and vehicle speeds. They are placed on vehicles to keep track of the trip location, both for clients and for dispatchers. Examples of such devices include logbooks, tachographs, on-board computers, and sophisticated satellite tracking devices.

Logbooks are the principal trip recording devices (53 percent of all vehicles), followed by tachographs (32 percent), and on board computers (4 percent).

Logbooks are the preferred method of record keeping primarily because of cost and because tachographs are not themselves a sufficient substitute for logbooks.

Recent estimates are that approximately 63 percent of the dangerous goods tonnage in the Province of Ontario, or about 25 million tonnes, is being hauled by trucks (Transport Canada, Dangerous Goods Directorate & Ontario Ministry of Transportation, unpublished). In total, about 5 to 6 percent of all truck trips surveyed involved the carriage of dangerous goods. The percentage of trucks engaged in the carriage of dangerous goods varied considerably by individual station but in no instance did it exceed 12 percent on a daily basis.

The most frequently transported dangerous good by truck was flammable liquids (47 percent). Compressed gases (24 percent) and corrosive substances (20 percent) followed. All other commodities were hauled in relatively minute amounts.

SUMMARY

The extent and scope of data collected during the course of the 1988 Ontario Commercial Vehicle Survey were only briefly touched on in this paper. The characteristics of the vehicles themselves and the methodology used to undertake the survey were focused on.

The information collected will be of immediate use. It will precede provincial evaluation of the geometric design of roads, highways and ramps, pavement and structure rehabilitation planning and scheduling, reciprocity arrangements with adjacent jurisdictions, dangerous goods regulation and enforcement efforts, and driver education programs. It will also provide useful information for private sector interests on market opportunities, fleet construction and disposition, and so on.

The reporting of the remainder of the data will be the subject of future papers.

ACKNOWLEDGMENTS

The author wishes to acknowledge the considerable efforts of the following persons involved with the project: R. Tardif, A. Banik, G. Ripley, K. Siwak, P. Dimitriou, J. Tao, D. Gibbons, G. Little, N. Bernier, and W. Raney.

APPENDIX
SURVEY QUESTIONS/VARIABLES

- *Record identification*: record number, location, hour ending, date, direction.
- *Observations:* plate number, base province/state of registration, name on power unit, vehicle configuration (truck type), tractor style, trailer/body style.
- *Features*: roof shield/side fairings/sleeper roof/bubble/headlights on/supersingle tires/dangerous goods placards/lift axle/dimensional load/55 mph decal.
- *Weigh scale data*: vehicle configuration, total axles, raised axles, base length or axle measurement, weight by axle.
- *Questions: vehicle*. Registered gross vehicle weight and tare weight (for non-Ontario plated vehicles), leasing incidence, fuel use. *Features*: logbook/tachograph/on board computer/dimensional load permit/cab accessible lift axle.
- *Questions: carrier*. carrier type, driver employment type, method of renumeration, union/work association membership, energy conservation driving bonus.
- *Questions: commodity*. Waybill existence, commodity type, shipments carried, commodity weight, volume/space utilization, dangerous good class and PIN.
- *Questions: origin/destination*. Community origin and destination of 1st truck/trailer and 2nd trailer, longest trip point in a shuttle trip, number of pickups and deliveries, establishment type at origin and destination, sole driver versus two drivers, commodity origin/destination (if different from the truck).
- *Questions: driver*. Years driven commercially, hours working today, hours driving today, time driving before a break is taken, drivers license number (Ontario drivers only), driver age group and sex, awareness of ministry "trucksave" program. Undertaking of: defensive driver course/first aid course/dangerous goods training course.

REFERENCES

1. *Trucking in Canada 1987*. Catalogue 53-222, Statistics Canada, Supply & Services Canada, Sept. 1989, p. 9.
2. Coopers & Lybrand Consulting Group. *Ontario Moves By Truck. The Role & Contribution Of the Trucking Industry In Ontario*. Ontario Trucking Association, Jan. 1989.
3. *Imports*. Catalogue 65-203, Statistics Canada, Supply & Services Canada, 1990.
4. *Exports*. Catalogue 64-202, Statistics Canada, Supply & Services Canada, 1990.

Publication of this paper sponsored by Task Force on Freight Transportation Data.

Highway Robbery: Social Costs of Hazardous Materials Incidents on the Capital Beltway

THEODORE S. GLICKMAN, MOLLY K. MACAULEY, AND PAUL R. PORTNEY

In the summer of 1988, three major truck incidents involving hazardous materials occurred on the Capital Beltway in Washington, D.C. The delays that were incurred and the social costs of the incidents, which ran into millions of dollars, are estimated in this paper. The impacts of policy options for reducing such delays and the associated costs are analyzed in the context of the three incidents.

In late summer 1988 three major incidents involving hazardous materials occurred on the Capital Beltway in less than a month. Together, they resulted in one fatality, 13 injuries (two truck drivers, three motorists, and eight firefighters), and hours of delay to hundreds of thousands of vehicle occupants. For months afterward, media attention focused on the problem as public representatives and safety experts debated solutions. Hazmat trucks were finally restricted to the two rightmost lanes. Those incidents are looked at more closely in this paper by estimating the delays that were created and the social costs that were incurred. It was observed that the cost of delay could have been reduced substantially if it had been factored into emergency plans and incident management decisions.

CAPITAL BELTWAY

Opened in August 1964, the Capital Beltway is a 63-mi long link in the Interstate highway system. It was originally intended to serve as a bypass around Washington, D.C. for long-distance travelers and, coincidentally, to provide an efficient evacuation route during national emergencies. Its first traffic jam took place on opening day, as eager users were backed up for miles while the ribbon-cutting ceremony was held near the New Hampshire Avenue exit. Since then, as the Washington suburbs have grown, it has become a major commuting artery, handling about 600,000 vehicles per day. Six to ten percent of that volume is trucks, which are involved in 17 percent of the accidents. On an average day, one of the six traffic accidents on the Beltway involves a tractor trailer. In a recent 16-month period, 4 of the 13 major truck accidents on the Beltway involved hazardous materials tankers.

The decision to impose the two-lane hazmat restriction following the three incidents in question was not universally supported. Detractors were concerned that it would tend to increase the density of hazmat tank trucks in the occupied lanes and introduce conflicts with exiting traffic, whereas supporters argued that it would help alleviate safety concerns associated with having small, maneuverable passenger cars occupy the same lanes as large, less maneuverable hazmat tank trucks. In another move made in the wake of these incidents, the Pentagon discontinued its fuel shipments during rush hours and 38 other federal agencies at 120 locations in the metropolitan Washington area followed suit. Other proposals have been made to ban all hazardous materials trucking on the Beltway during rush hours (which would divert tank trucks to other roads) and to introduce centralized tracking of all hazardous shipments (which would be expensive). The American Automobile Association (*1*) has recommended that any trucker causing an accident on the Beltway be fined an amount based on the level of delay that is created and that the proceeds be used to fund public information programs to improve highway safety.

In the future, the Beltway will be equipped with a driver information system whereby incidents will be detected with television cameras and instructions will be relayed to motorists electronically. Plans have also been proposed for carpool lanes that would become part of a regional high-occupancy vehicle network and for Interstate bypasses to the east and west of the Beltway. Considering the projections of 300,000 vehicles a day on some of its 8-lane segments by the year 2010, Beltway drivers will need all the help they can get.

SUMMARY OF INCIDENTS

The first of the three 1988 incidents took place at 3:20 p.m. on Friday, August 12, on the outer loop of the Beltway near Route 193 (Georgetown Pike) in McLean, Virginia. A truck carrying about 10 tons of potentially explosive potassium permanganate in powdered form caught fire while bound for a Fairfax water treatment plant, causing the entire Beltway to be closed down until 6:45 p.m., when the inner loop was reopened. The outer loop remained closed until 9:15 p.m. Eight firefighters were injured and more than 70 persons were evacuated. Traffic in downtown Washington was reportedly slowed by the incident.

On Thursday, August 25, the second incident occurred at 3:55 p.m. when a gasoline tanker on the inner loop hit the rear of a van that was attempting to pass the car in front of it, then crossed the concrete median wall and burst into flames. The location was New Carrollton, Maryland, just north of the

---

Resources for the Future, 1616 P Street, N.W., Washington, D.C. 20036.

Baltimore-Washington Parkway. A motorist traveling on the outer loop was killed when his car ran into the burning truck. Both sides of the Beltway were closed as firefighters spent more than two hours putting out the flames from the 3,000 gallons spilled. The inner loop was reopened at 8 p.m. and two of the four lanes in the outer loop were reopened at 11 p.m. The remaining lanes, 400 ft of which were melted by the fire, were repaved overnight. The drivers of the tanker and the van were both hospitalized, as were two other passengers in the van.

The third incident took place on Wednesday, September 7, at 11:05 a.m. when a gasoline tanker overturned on an entry ramp on the inner loop in Annandale, Virginia, at the intersection of Route 236 (Little River Turnpike), injuring the driver. The ensuing flames, which damaged the steel beams of the overpass, were put out by 12:30 p.m., but the outer loop was not reopened until 2:10 p.m. and the inner loop was kept closed until 5:30 p.m., when three of the four lanes were reopened. Pavement damage in the remaining lane was repaired overnight. The ramp has a high level of tank truck activity because of its proximity to a tank farm in Fairfax City and was previously the scene of a similar accident that proved fatal to the driver, who was apparently taking the turn too fast.

DELAY ESTIMATION

Associated with each incident is a total delay in each direction on the Beltway, as measured by the number of vehicle-hours of waiting time. The Federal Highway Administration (FHWA) has developed an analytical procedure for computing the delay during any kind of freeway incident that reduces the normal capacity of a road for some length of time [see Morales (*2*)]. The FHWA model was used to estimate the delay for each of the incidents, using various sources of data on the traffic volumes, the roadway capacities, and the lane closure times.

In the FHWA model it is assumed that there is a given freeway capacity S_1, which is reduced to an initial bottleneck capacity of S_3 during the time T_1 needed to detect the incident, followed by a capacity of zero during the time T_2 needed to respond to the incident and then an adjusted bottleneck capacity S_4 during the time T_3 needed to clear the lanes. From then on, the capacity is assumed to return to S_1. Any one or two of the times T_1, T_2, and T_3 can be zero. On the demand side, the initial level is S_2, which lasts for a time T_4 (which may be zero), after which the level changes to S_5. These parameters fully determine the total delay.

To estimate the demand flow levels, hourly traffic counts were obtained from the Virginia Department of Transportation for the appropriate days of the week in the preceding July near the locations of the first and third incidents. Similar data could not be obtained for the Maryland location, so Virginia data assumed for the first location were assumed for the second incident. To simplify the calculations, it was determined that the average hourly traffic volume for the "heavy" period from 6 a.m. to 10 p.m. and the "light" period from 10 p.m. to 6 a.m. for each of the two data sets, using the counts for the appropriate days of the week and making separate determinations for the inner and outer loops of the Beltway. Figures 1, 2, and 3 show the traffic counts that were used and the dotted lines show the averages for the heavy and light periods.

Table 1 lists the values of the parameters for the six model runs that were made to estimate the delays and Table 2 presents a summary of the results. In every case, in the absence of information to the contrary, it was assumed that S_3 and T_1 are zero, that is, that every lane was blocked immediately. The values of S_2 and S_5 in Table 1 are the appropriate averages from the traffic count data and the values of S_4 are taken from Owen and Urbanek (*3*). In addition to the total delay, the FHWA model estimates the time to normal flow (TNF), which is the time between the onset of the incident and the moment at which the delay stops accumulating. These estimates are listed in Table 2, along with the estimated delay per vehicle, which was found by dividing the total delay by the total demand during the TNF in each case.

The results in Table 2 show that the total delay ranged from about 350,000 vehicle-hours in the first incident to about 500,000 vehicle-hours in the second and over 1,000,000 vehicle-hours in the third. On a per vehicle basis, the average delay ranged from 2.4 hr in the first incident to 4.2 hr in the second and 6.8 hr in the third. Note that it was assumed in these calculations that vehicles were not free to leave the Beltway once the incident began, hence these numbers are likely to be overestimates. However, given that the delays that each incident induced on other roads were not accounted for, the combined vehicle-hours of delay in this table may in fact be underestimates of the systemwide delay for each incident.

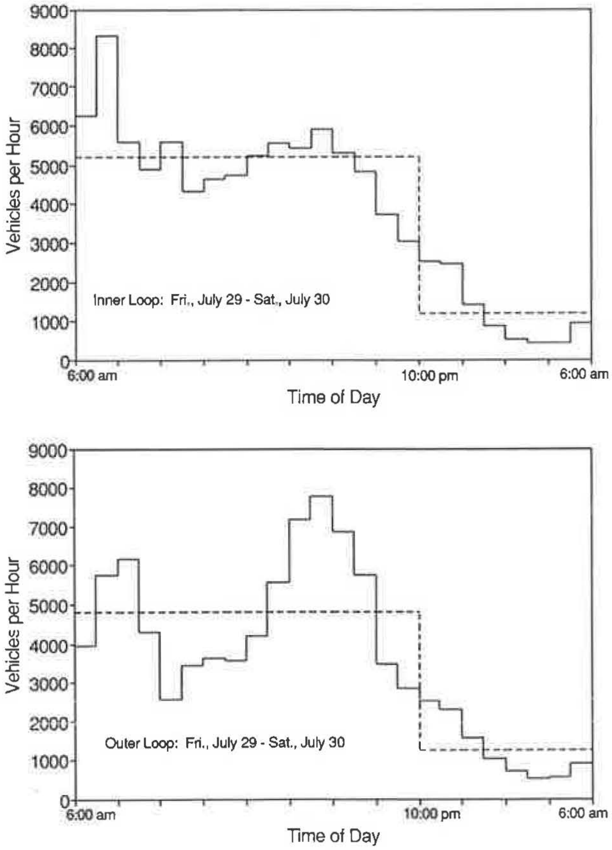


FIGURE 1 Hourly Traffic Counts on the Beltway—Route 193 to G.W. Parkway.

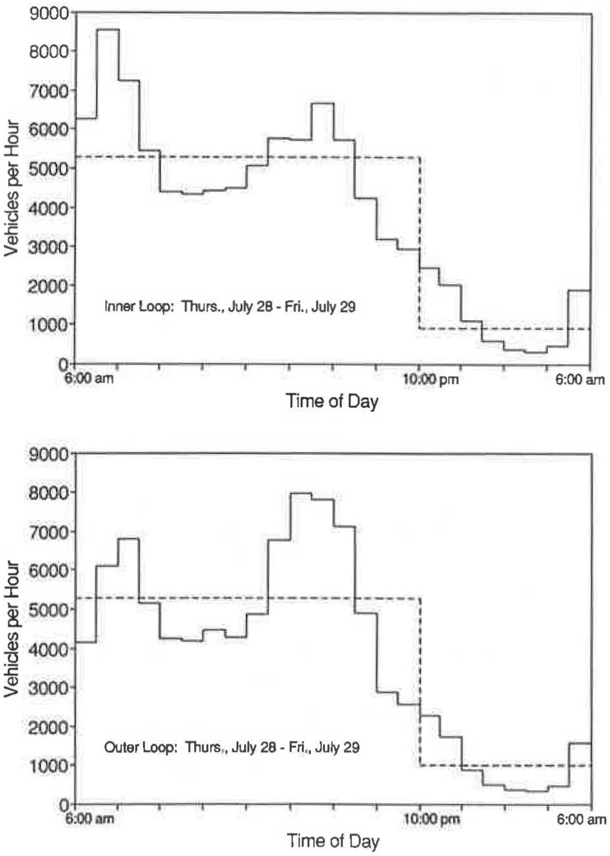


FIGURE 2 Hourly Traffic Counts on the Beltway—Route 193 to G.W. Parkway.

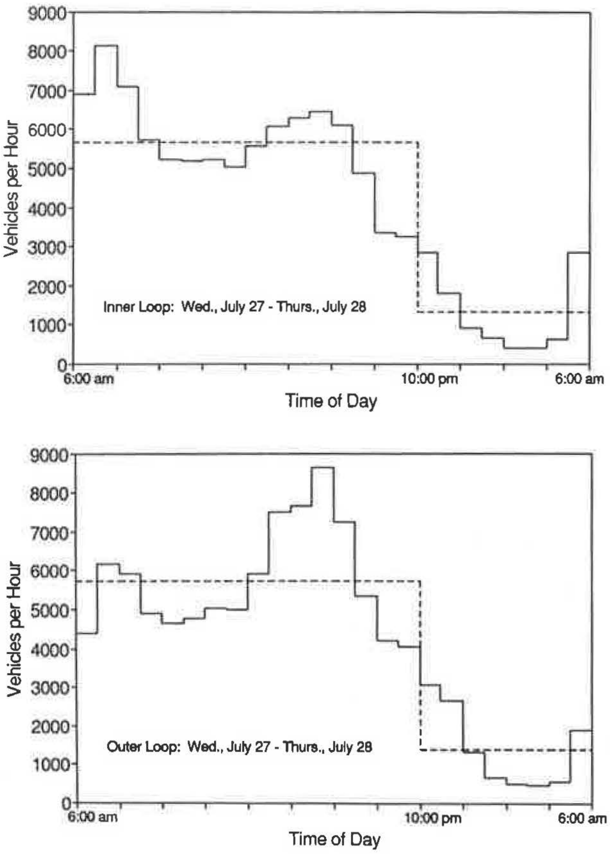


FIGURE 3 Hourly Traffic Counts on the Beltway—Route 236 to G.W. Parkway.

TABLE 1 FHWA MODEL PARAMETERS FOR THE THREE INCIDENTS

	August 12		August 25		September 7	
	Inner Loop	Outer Loop	Inner Loop	Outer Loop	Inner Loop	Outer Loop
S_1	7400	7400	7400	7400	7400	7400
S_2	5219	4820	5278	5262	5657	5714
S_3	0	0	0	0	0	0
S_4	0	0	0	2700	1300	0
S_5	5219	4820	5278	1013	1310	5714
T_1	0	0	0	0	0	0
T_2	205	355	245	425	385	185
T_3	0	0	0	360	690	0
T_4	0	0	0	365	655	0

Note: S values are in vehs per hr and T values are in mins.

TABLE 2 FHWA MODEL RESULTS FOR THE THREE INCIDENTS

	August 12	August 25	September 7
Total Delay (veh-hrs)			
Inner Loop	103,360	153,450	972,750
Outer Loop	241,980	339,720	119,210
Combined	345,340	493,170	1,091,960
Time to Normal Flow (hrs)			
Inner Loop	11.6	14.2	27.1
Outer Loop	17.0	16.7	13.5
Total Demand (vehs)			
Inner Loop	60,510	75,160	82,970
Outer Loop	81,800	42,730	77,330
Total	142,310	117,890	160,300
Delay per Vehicle (hrs)			
Inner Loop	1.7	2.0	11.7
Outer Loop	3.0	7.9	1.5
Combined	2.4	4.2	6.8

Figures 4, 5, and 6 show how the capacity, demand flow and bottleneck flow accumulate over time in each direction during each incident, according to the runs of the FHWA model. The area enclosed by the demand flow and bottleneck flow lines is equal to the total delay in each case.

SOCIAL COSTS OF INCIDENTS

In estimating the social costs of the three incidents, we accounted for: (a) the actual direct costs, and (b) the imputed costs of delay. Information on some of the direct costs was gathered from a variety of sources, including local fire departments, local and state transportation departments, and trucking firms. Table 3 summarizes this information under three categories: emergency response, clean-up, and truck and lading loss. Emergency response costs refer to the value of the time of hazmat units, fire personnel, and traffic controllers, and the equipment and supplies they used (strictly speaking, some of these costs would have been incurred even if no incidents had happened). Clean-up costs are expenses

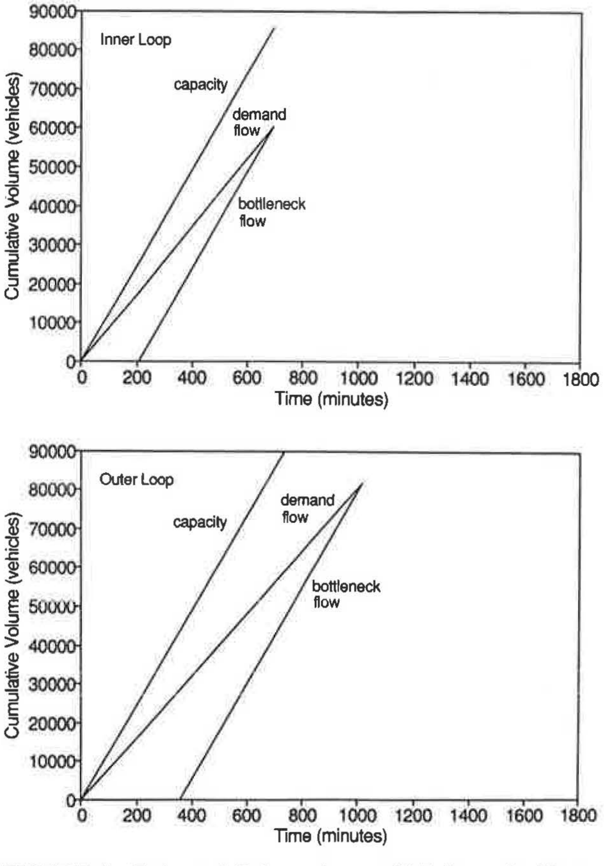


FIGURE 4 Estimated Delay—August 12 Beltway Incident.

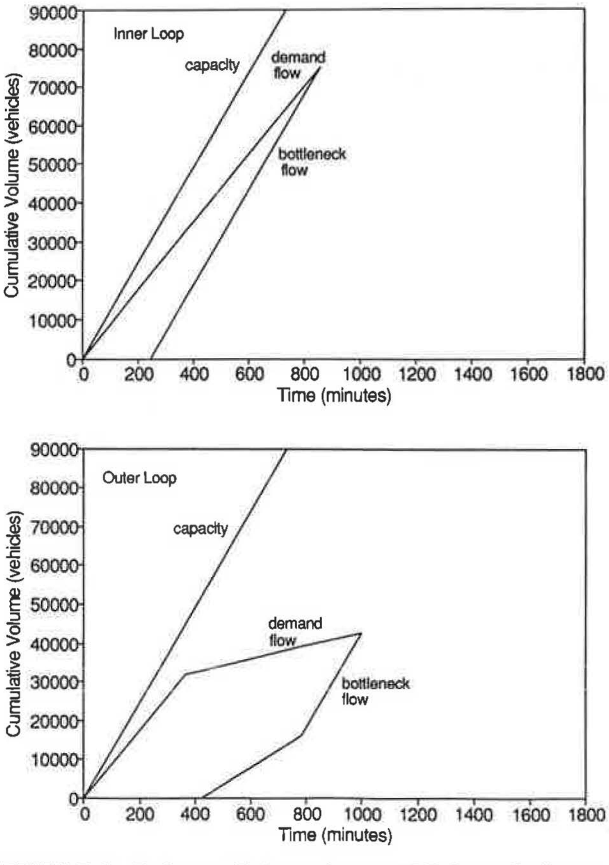


FIGURE 5 Estimated Delay—August 25 Beltway Incident.

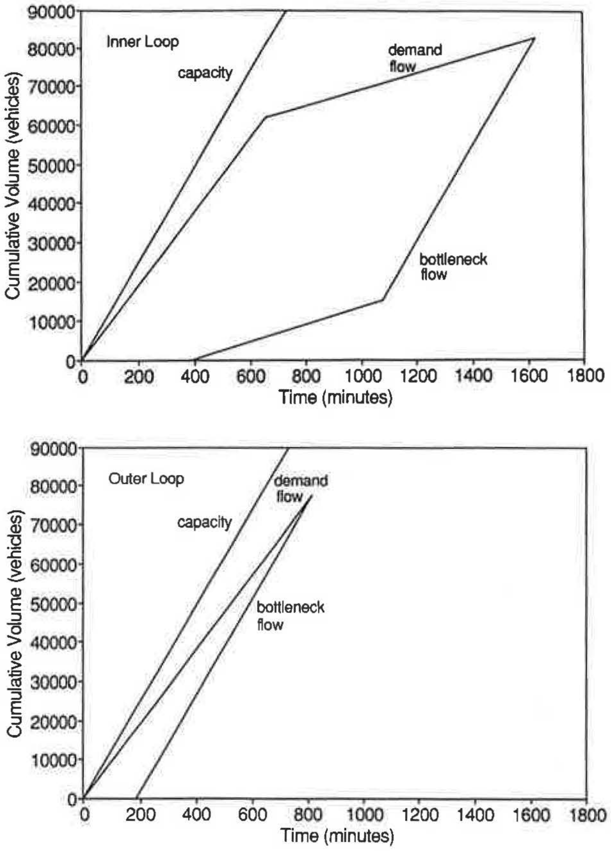


FIGURE 6 Estimated Delay—September 7 Beltway Incident.

for wreckage clearance, spill control and removal, and road repair and repavement. In the case of the third incident, we were only able to obtain a combined total for emergency response and clean-up (the reason this figure is so relatively high is that the damaged bridge had to be repaired). The costs of truck and lading loss, the third category, refer to the value of the truck cabs and trailers that had to be replaced and the cargoes that were lost.

Also under the heading of direct costs are the extra fuel consumption costs for the delayed vehicles. Assuming that all the engines were kept running the entire time in each incident, that idling engines consumed 0.58 gallons per hour, and that the gasoline cost $1.00 per gallon, these costs were calculated on the basis of total delay estimates in Table 2. The idling assumption underestimates the fuel consumption during stop-and-go periods and overestimates it for periods when some engines were shut off, so it was expected to be reasonable on the whole. When these costs are added to the ones above, the total estimated direct costs are seen to vary from about $375,000 for the first incident to about $455,000 for the second and almost $980,000 for the third. Most of these costs were borne by the members of the public who were caught in the traffic jam or whose taxes paid for emergency response and at least some of the clean-up costs. Note that the social costs of death, injury and evacuation were not taken into account [see Fisher, et al. (*4*) on the value of reducing risks of death and Witzig and Shilleen (*5*) on the evaluation of evacuation costs].

Significant as the direct costs may be, they pale by comparison to the monetary value of the delay itself. The estimates of this cost were developed on the basis of an average after-tax wage rate, assuming that this rate reflects the value of unexpected delay [see Deacon and Sonstelie (*6*) for a fuller discussion of the value of waiting time]. According to the Metropolitan Washington Council of Governments (*7*), about two-thirds of all Beltway travel is for trips within the D.C. area. Thus, we assumed an average hourly wage rate of ⅔($9.77) + ⅓($8.06) = $9.20, where $9.77 was the local wage rate in 1988 and $8.06 was the national wage rate. Further, an automobile occupancy rate of 1.24 persons was assumed. [This is the 1985 rush-hour estimate for the Beltway, which is close to the 1.3 figure employed by Teal (*8*) as a national average for all roads]. The results of multiplying the total delay estimates from Table 2 by this wage rate and occupancy rate are as shown in Table 3: about $4.2 million for the first incident, $6.0 million for the second, and $13.2 million for the third. Hence, the total cost of delay is estimated to have exceeded the total direct costs of the three incidents by as little as 11.2 to 1 and as much as 14.5 to 1, or about 13 to 1 on the average. Of course, this ratio could be even higher if successive increments of delay were considered to be increasingly burdensome, as suggested by Larson (*9*).

REDUCING THE COST OF DELAY

The finding that the cost of delay dominates the direct costs of the Beltway incidents by a wide margin raises the issue of

TABLE 3 ESTIMATED SOCIAL COSTS OF THE THREE INCIDENTS

	August 12	August 25	September 7
(1) Direct Costs ($)			
Emergency Response	10,717	4,900	*
Clean-up	40,000	60,081	*
Subtotal	50,717	64,981	237,123
Truck and Lading Loss	124,000	103,000	108,000
Extra Fuel Consumption	200,877	286,039	633,337
Total Direct Costs	375,594	454,020	978,460
(2) Cost of Delay ($)	4,195,840	5,974,656	13,228,877
Total (1) + (2)	4,571,434	6,428,676	14,207,337
Ratio (2) . (1)	11.2	13.2	14.5

*Breakout not available.

TABLE 4 RESULTS OF THE SENSITIVITY ANALYSIS

	August 12	August 25	September 7
Reduction in Delay (%)			
(a) Shorten Duration by 10%	19.0	14.2	15.1
(b) Reduce Demand by 10%	25.1	18.4	19.1
(c) Increase Capacity by One Lane (opposite side only)	11.4	11.8	4.0
Saving in Cost of Delay ($M)			
(a) Shorten Duration by 10%	0.75	0.80	1.88
(b) Reduce Demand by 10%	0.99	1.04	2.38
(c) Increase Capacity by One Lane (opposite side only)	0.45	0.67	0.50

whether enough is being done to avoid such delays. Three general approaches to avoiding delay immediately come to mind: (*a*) shorten the duration of the incident; (*b*) reduce the demand during the incident; and (*c*) increase the capacity during the incident. The first approach requires rapid detection, response, or clearance. The second approach requires improved diversion of traffic away from the incident scene. The third approach, which is more controversial, requires that fewer lanes be closed or that some lanes be opened sooner (or, at least, that a shoulder be opened up to let some traffic through).

By changing the values of the parameters in Table 1, a sensitivity analysis was conducted that uses the FHWA model to show what impacts each of these approaches would have had on the delays (and the costs of delay) estimated for the three incidents. First all T_2 and T_3 values were reduced by 10 percent to shorten the incident duration. Then all S_2 and S_5 values were reduced instead by 10 percent to lessen the demand rate. Finally, to represent the situation in which the far right lane would be kept open throughout the incident on the opposite side of the road, the respective value of S_3 was increased from 0 to 1300 (the capacity when one lane is open), T_2 was reduced to zero, and T_7 was replaced with the former value of T_2.

Table 4 was developed on the basis of the results of rerunning the model with these changes. It shows that fairly modest improvements in emergency management would have yielded substantial benefits, reducing the number of vehicle-hours of delay in an incident by as much as 25 percent (if the demand could have been reduced by 10 percent in the August 12 incident) and saving as much as $2.4 million in the value of the motorists' time lost in an incident (if the demand could have been reduced by 10 percent in the September 7 incident). The most controversial approach is the third one, since even in the relatively cautious case considered here—in which only the very farthest lane on the safer side of the highway is kept open during the incident—it might have led to an increase in risk in order to save waiting time. When (if ever) such tradeoffs are justified and how to evaluate them are questions that are beyond the scope of this paper, but as with other difficult social choices, there may be situations in which the price of extreme caution is too high and some risk must be accepted.

REFERENCES

1. American Automobile Association. *Potomac News*. Falls Church, Va., April 1989.
2. J. M. Morales. Analytical Procedures for Estimating Freeway Traffic Congestion. *Public Roads*, Vol. 50, No. 2, 1986, pp. 55–61.
3. J. R. Owen and G. L. Urbanek. *Alternative Surveillance Concepts and Methods for Freeway Incident Management—Volume 2: Planning and Tradeoff Analyses for Low-Cost Alternatives*. Report FHWA-RD-77-59, FHWA, U.S. Department of Transportation, March 1978.
4. A. Fisher, L. Chestnut, and D. Violette. The Value of Reducing Risks of Death: A Note on New Evidence. *J. of Policy Analysis and Management*, Vol. 8, 1989, pp. 88–100.
5. W. F. Witzig and J. K. Shilleen. *Evaluation of Protective Action Risks*. Report NUREG/CR-4726, U.S. Nuclear Regulatory Commission, June 1987.
6. R. T. Deacon and J. Sonstelie. Rationing by Waiting and the Value of Time: Results from a Natural Experiment. *J. of Political Economy*, Vol. 93, No. 41, 1985, pp. 627–647.
7. Metropolitan Washington Council of Governments. *Solving the Problem of Greater Washington's Main Street*. Washington, D.C., 1986.
8. R. F. Teal. *Estimating the Full Economic Costs of Truck Incidents on Urban Freeways*. Report UCI-ITS-RR-88-3, Institute of Transportation Studies, University of California, Irvine, Nov. 1988.
9. R. C. Larson. *There's More to a Line than Its Wait*. Technology Review, July 1988, pp. 60–67.

Publication of this paper was sponsored by Committee on Transportation of Hazardous Materials.

Benefit-Cost Evaluation of Using Different Specification Tank Cars to Reduce the Risk of Transporting Environmentally Sensitive Chemicals

Christopher P. L. Barkan, Theodore S. Glickman, and Aviva E. Harvey

In response to public concerns about the environment, regulatory requirements for cleaning up spills of certain chemicals have become more stringent and cleanup costs have increased dramatically. Hence, due consideration must be given to environmental sensitivity as an element of transportation risk. Among the environmentally sensitive chemicals of most concern to the railroad industry are 10 halogenated hydrocarbons that are shipped in general-purpose tank cars. The cost of cleaning up spills of these chemicals in 1980 through 1989 exceeded $50 million. This represented more than half of the major environmental cleanup costs resulting from railroad transportation incidents in this period, although shipments of these chemicals accounted for less than 1 percent of the total carload volume of hazardous materials. Investing in more secure tank cars would increase the capital and operating costs but would reduce the risk of these spills. Under current packaging practices, the average liability is estimated to be $788 per carload in 1990 dollars, and this liability will double in 1992 as a result of more stringent hazardous waste disposal regulations. Use of more secure 105A300W or 105A500W tank cars would reduce the 1990 liability to $375 or $129 per carload, respectively. The analytical approach developed in this paper quantifies the benefits and costs of transporting these chemicals in such tank cars. The results indicate that the reduced liability resulting from the use of type 105 tank cars more than offsets the increased capital and operating costs and therefore would be a cost-effective means of reducing the risk.

Industry has a long history of fostering the development of safe equipment and operating practices for the rail transportation of hazardous materials. Over the years, the materials of most concern have been those that pose acute hazards to health and safety, such as poisons, flammables, and explosives. More recently, however, knowledge about environmental degradation has led to increased concern about the impact of releases of chemicals that are hazardous to the environment.

The results of research conducted to identify the highest-priority environmentally sensitive chemicals and evaluate the net economic benefit of replacing the tank cars currently used to transport these chemicals with others that are less likely to release their contents are described in this paper. In general, the direct expenses of environmental cleanup are borne by the carriers, whereas the cars are paid for by the chemical shippers. However, cleanup expenses that are unnecessarily high increase the overall cost of rail transportation and thereby affect shippers as well as carriers. Furthermore, liability may in some cases be shared with the shipper. It is in the interest of shippers, carriers, chemical customers, and the public that the type of tank car used to transport these chemicals be commensurate with their environmental hazard.

IDENTIFICATION OF ENVIRONMENTALLY SENSITIVE CHEMICALS

The process of identifying the environmentally sensitive chemicals of most concern began by evaluating 83 chemicals currently being shipped by rail and authorized by the U.S. Department of Transportation (DOT) for shipment in general purpose tank cars. These chemicals were evaluated for their relative potential to contaminate soil and groundwater in the event of a large, uncontrolled release. This evaluation was conducted by means of a three-stage hazard assessment of each of these chemicals: first, physicochemical models were used to estimate soil and groundwater dispersion; second, environmental engineering models were used to estimate the difficulty of cleanup based on each chemical's properties and the regulatory requirements for its cleanup; third, the results of these models were supplemented by empirical evidence gathered from the railroads. The results of this analysis indicated that 15 halogenated hydrocarbons were among the chemicals posing the highest environmental cleanup hazard. Ten of these chemicals were considered to be the ones posing the greatest risk of a costly environmental cleanup because of current packaging practices (Table 1). Although authorized for shipment in general-purpose tank cars, the other five halogenated hydrocarbons (allyl chloride, dichloropropane, 1,2-dichloropropene, epichlorohydrin, and ethyl chloride) are primarily transported in DOT-specification 105 or 112 tank cars, which exceed the minimum required by regulations and thus pose a lower risk.

BACKGROUND ON HALOGENATED HYDROCARBONS

Halogenated hydrocarbons have become the focus of intense regulatory scrutiny in recent years because they are widely

---

C. P. L. Barkan and A. E. Harvey, Research and Test Department, Association of American Railroads, 50 F Street, N.W., Washington, D.C. 20001. T. S. Glickman, Center for Risk Management, Resources for the Future, 1616 P Street, N.W., Washington, D.C. 20036.

TABLE 1 NUMBER OF CARLOADS OF HALOGENATED HYDROCARBONS

Chemical	1987	1988	1989
Carbon tetrachloride	1,647	1,154	1,029
Chlorobenzene	648	624	952
Chloroform	1,155	1,041	1,250
Dichlorobenzene	73	96	55
Ethylene dibromide	3	4	2
Ethylene dichloride	2,314	2,163	3,462
Methyl chloroform	292	914	1,133
Methylene chloride	227	664	883
Perchloroethylene (PERC)	487	842	964
Trichloroethylene (TCE)	271	227	153
PERC/TCE Mixture	51	28	27
Total Reported Carloads	7,168	7,752	9,910
Estimated Actual Carloads (based upon an 84% reporting rate)	8,533	9,228	11,798

used chemicals that can have negative environmental impacts and create chronic health problems. They were among the first hazardous substances generally banned from land disposal by the Environmental Protection Agency (EPA) in 1986 under the Resource Conservation and Recovery Act (RCRA) amendments. They pose a significant challenge in remediation because they are all denser than water and tend to quickly permeate deep into aquifers and stubbornly resist removal. Moreover, the standards for cleanup of contaminated soil and water are stringent because these chemicals are all suspected carcinogens.

The most familiar halogenated hydrocarbons are chlorinated solvents such as trichloroethylene, methyl chloroform, methylene chloride, and perchloroethylene (*1*). Trichloroethylene (TCE), perchloroethylene (PERC), and methyl chloroform, also known as 1,1,1-trichloroethane (TCA) are the most frequently detected volatile organic compounds contaminating groundwater in the United States (*2*). TCE has been a widely used degreasing agent for many years. It is classified as a probable human carcinogen and is listed as a hazardous air pollutant and is the chemical most often detected at Superfund sites (*3*). TCA has widespread application in metal cleaning for decontaminating and degreasing parts, and in electronics for cleaning circuit boards and semiconductors. Methylene chloride (METH) has diverse uses in paint removers, aerosols and chemical processing. PERC, also known as tetrachloroethylene, is used extensively by the dry cleaning industry and as a vapor degreaser for cleaning electrical equipment.

Table 1 presents the number of carloads of the 10 halogenated hydrocarbons reported for 1987, 1988, and 1989 to the TRAIN II data base, which is the record of rail freight movements maintained by the Association of American Railroads (AAR). The total transportation volume of these chemicals has been increasing in recent years, up to an estimated level of about 12,000 carloads in 1989. On a chemical-by-chemical basis, the trend has been downward or stable in some cases and upward in others. Certain ones are being phased out of production over time (e.g., carbon tetrachloride, which is used as a precursor in freon production), while others continue to be produced and transported at increasing levels [e.g., ethylene dichloride, which is used extensively for polyvinyl chloride (PVC) production]. In some cases, even though domestic demand is declining due to environmental concerns, transportation volume is rising because of export demand.

In 1989 an estimated 1.2 million tank car loads of hazardous materials were shipped in the United States and Canada. The 10 halogenated hydrocarbons accounted for less than 1 percent of this volume. Despite this low percentage, they accounted for approximately 60 percent of the cost of major environmental cleanups (i.e., those costing more than $250,000) from transportation-related spills reported by the railroads in 1980 through 1989, including four of the five most costly ones (Figure 1).

APPROACHES TO RISK REDUCTION

Risk reduction can be achieved by preventing spills from happening or by reducing their impact when they do happen, or both. Spill impacts are reduced by the effectiveness of the remedial response, which for these chemicals is constrained by such factors as ease of access to the spill location, local geology, proximity of remediation equipment and personnel, and spills of other chemicals that may pose a more immediate concern (acute hazards to human life or property). By contrast, the number of spills can be reduced by two approaches: accident prevention and improved resistance to tank car damage.

The first approach, accident prevention, has been a high priority for the railroad industry in recent years. The railroad accident rate has declined substantially over the past decade (*4*). The graph in Figure 2 shows that the annual rate of train accidents dropped by more than 60 percent in the period 1980 through 1989, to a level of about 5 accidents per million train-miles in 1989 (*5*). This reduction can be attributed to investment in physical plant improvements, as well as increased equipment and plant maintenance activities, expanded em-

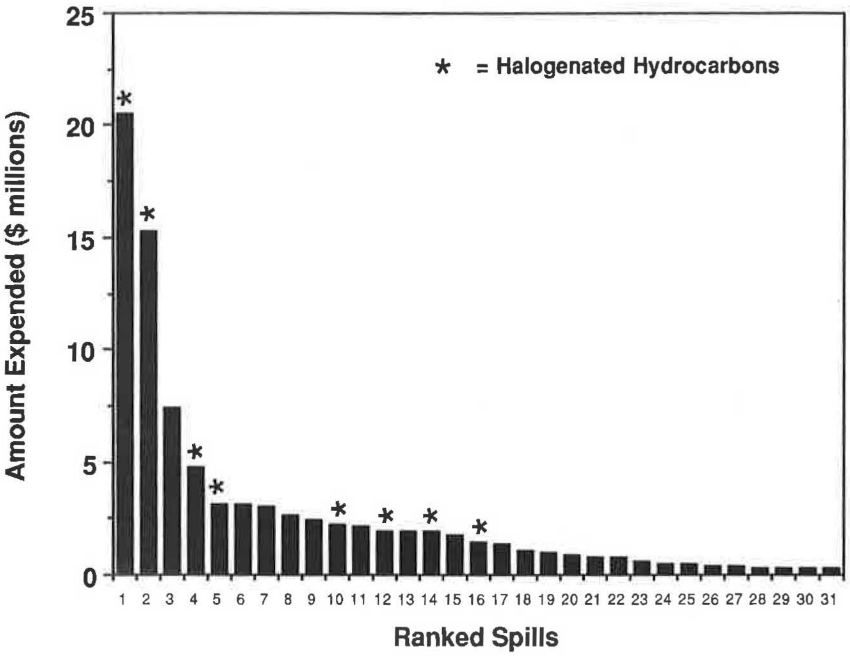


FIGURE 1 Costs of major environmental cleanups from transportation-related spills on railroads, 1980–1989.

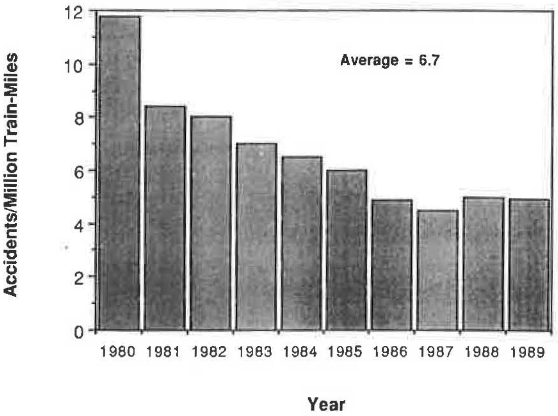


FIGURE 2 Trend in annual accident rate.

ployee training programs and elimination of many low density lines.

The other approach to spill reduction is to use tank cars that are more resistant to damage. The most notable example in recent years is the modification of DOT specification 112/114 tank cars used principally in liquified petroleum gas (LPG) and ammonia service. These cars received head shields, thermal protection, and shelf couplers. Since these changes have been in place there has been a substantial reduction in the frequency of releases from these cars (*6*). General-purpose 111 tank cars have also undergone improvements over the past decade. Since 1978 all 111s in hazardous materials service have received shelf couplers and (where applicable) bottom outlet protection.

Resistance to damage varies among different types of tank cars. DOT-specification 111 tank cars are generally more likely to suffer a release in an accident than are various pressure tank cars such as DOT-specification 105 tank cars (*7*). Most of the cars currently used to transport the halogenated hydrocarbons discussed in this paper are general-purpose, non-insulated tank cars built to DOT specification 111A100W1. These cars have carbon steel tanks and usually come equipped with bottom outlets for convenience in unloading. General-purpose 111 tank cars differ from 105A500W tank cars in several respects related to damage resistance. Most significant are the differences between the thickness and grade of steel used in the tank shell and head. A general-purpose 111 tank car has a 7/16-in. head and shell, whereas a 17,000 gallon 105A500W typically has a head and shell greater than 3/4-in. thick constructed of higher tensile strength steel, as well as a 1/8-in. steel jacket encasing the insulation. As a result, these 105 tank cars have a relatively low likelihood of suffering a puncture in an accident (*8*).

The other major difference is in the top and bottom discontinuities (fittings) and the accompanying protection. By specification, 105 tank cars have no bottom fittings, whereas general-purpose 111 cars usually have a bottom fitting that extends below the tank. All new tank cars with bottom fittings ordered since the beginning of 1978 have been required to have bottom discontinuity protection, and most older cars in hazardous materials service have been retrofitted under a program developed and administered by the AAR Tank Car Committee. All of the top fittings on a 105 tank car are consolidated and encased in a 3/4-in. protective housing, while a general-purpose 111 car may have four or more separate top discontinuities, which are usually not protected [see Figure 3, from General American Transportation Corporation (*9*)]. Top and bottom discontinuities are both vulnerable to damage in accidents, but the lack of any bottom fittings on the 105 and the protective housing encasing the top fittings contribute to the greater release resistance of these cars.

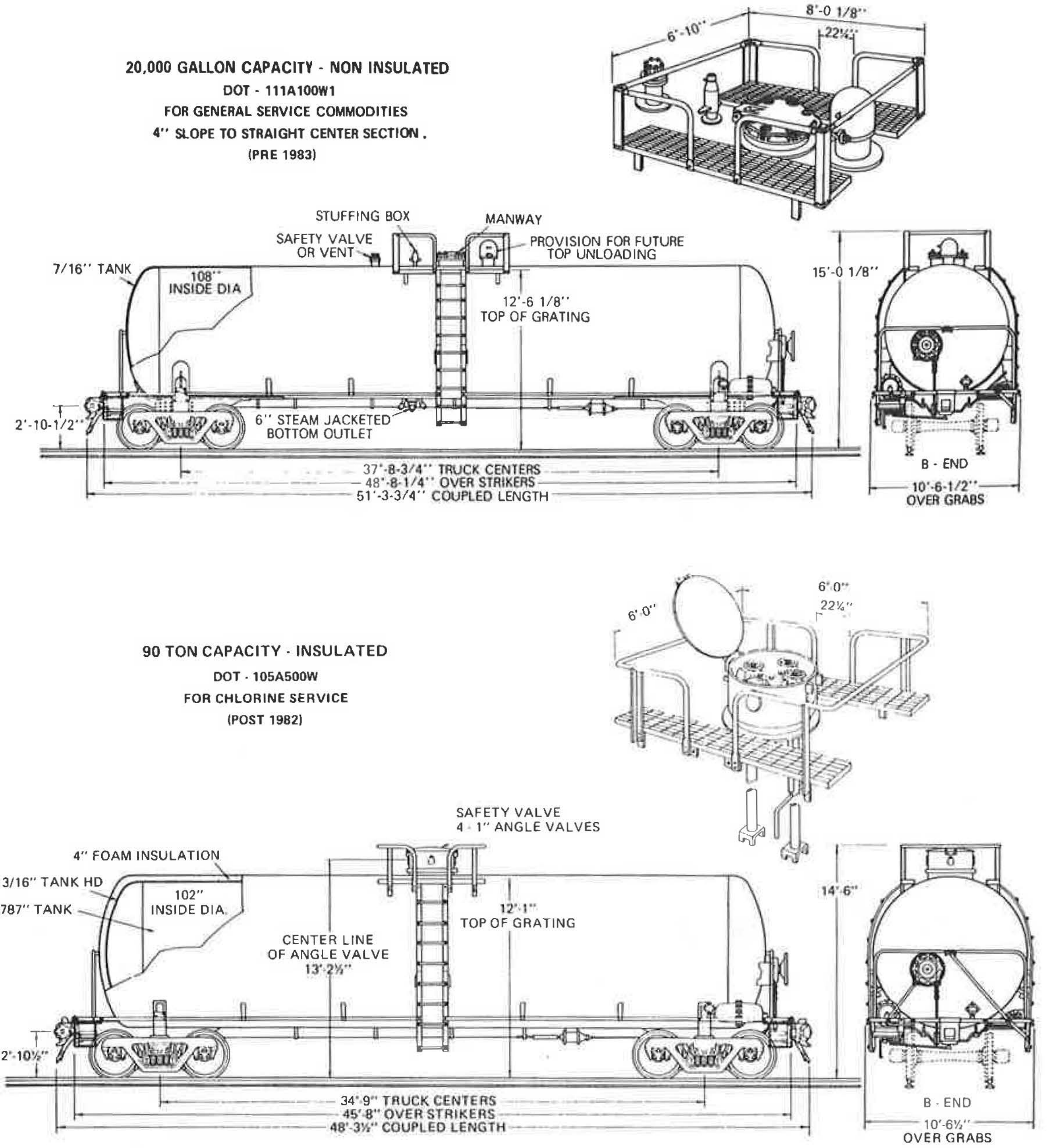


FIGURE 3 DOT specification 111A100W1 (top) and 105A500W (bottom) tank cars.

FORMULA FOR BENEFIT-COST CALCULATIONS

We developed an analytical approach to determine whether the cost of replacing the 111s with the stronger, but heavier and more expensive, 105A500W tank cars would be offset by the benefit of the avoided environmental cleanup expense. The benefit was calculated from data on the cost of cleaning up spills of these chemicals, combined with data on the differences in tank car release probability developed by the Railroad Tank Car Safety Research and Test Project, a cooperative effort of the Railway Progress Institute (RPI) and the AAR. The costs of replacing 111s with 105s are the additional operating expense due to the heavier weight of the 105 tank cars and the net capital expenses associated with putting them in service and retrofitting the terminals for top unloading. We used a net present value (*NPV*) approach because of the relatively long period of time over which the benefits and costs would accrue.

The *NPV* of replacing the 111s with 105s equals the sum of the benefits of car replacement minus the associated costs, calculated over the years during which the benefits and costs are expected to accrue and discounted to constant (year 0) dollars. The equation used for this calculation is:

$$NPV = \left\{ \sum_{n=1}^{N} \left[b \prod_{j=1}^{n} (1 + r_j) - c_t \right] (1 + i)^{-n} \right\} - (c_a + c_m)$$

where

N = expected lifetime of a tank car (30 years);
b = average annual benefit of replacing the 111s with 105s, that is, the expected annual reduction in total cleanup costs from transportation spills;
r_j = real rate of increase in cleanup costs in year j;
c_t = average annual incremental cost of transportation if the 111s are replaced with 105s, that is, the increase in the total variable cost of moving the tank cars;
i = annual discount rate, that is, the annual rate of increase in the real cost of capital;
c_a = net investment required to acquire the 105s, that is, the cost of the new cars minus the lost value of the cars replaced; and
c_m = investment required to modify the terminals to accommodate the 105s, that is, to retrofit the terminals for top unloading.

Several assumptions were made to simplify the calculations. First, it was assumed that all of the cars are replaced at the outset, which means that the benefits and the costs of car replacement are realized throughout the 30-year period. Second, it was assumed that the total volume of the 10 halogenated hydrocarbons shipped each year remains constant at 1989 levels. Although overall traffic growth is anticipated for these chemicals, the incremental risk from increased shipments and the incremental cost of additional 105s are both proportional to traffic volume. Therefore, the *NPV* per tank car will not change. Third, it was assumed that the annual rate of car utilization, that is, the number of trips per car each year, remains constant regardless of the type of car used. In actuality, the higher value of the 105 might provide an incentive to operators and carriers to improve the efficiency of their use of tank cars, which would increase the *NPV* of replacing 111s with 105s. Finally, it was assumed initially that the train accident rate will remain constant. The rapid decline observed in the 1980s appears to be leveling off and unless there are technological breakthroughs in derailment prevention, declines of this magnitude are anticipated in the near future. The implications of removing the last assumption are discussed later. The following discussions of benefit estimation, cost estimation, and future cleanup costs describe how we estimated the factors in this equation.

BENEFIT ESTIMATION

The annual benefit (b) of replacing the 111s with 105s is the average saving associated with having to clean up a smaller expected number of spills each year over the lifetime of the replacement cars. To estimate the magnitude of this saving, the experience of the past decade was reviewed. There were 15 train accidents from 1980 through 1989 in which one of the 10 halogenated hydrocarbons was released from one or more damaged tank cars, involving a total of 41 tank cars. At least 35 other release incidents not caused by train accidents also occurred in this period, most of which involved much smaller spill quantities.

Data from the railroads indicate that 8 of these 50 incidents were especially costly to clean up. Six of the eight were caused by train derailments and two were not (one involved a weld failure and the other a damaged bottom outlet that leaked). The most costly was the result of a derailment on the Illinois Central Railroad that took place on the outskirts of Livingston, Louisiana in 1982. The railroad has already spent over $20 million to clean up the PERC that was absorbed into the soil and released into groundwater. Ongoing water treatment and site monitoring has been costing approximately $25,000 per month. To date the total unadjusted cost of cleaning up the spilled halogenated hydrocarbons in these eight incidents is $50.4 million. Remediation efforts are still ongoing for six of the eight incidents. The present value of the future cost of completing the cleanup at these sites is conservatively estimated to be $5.0 million. On the basis of the recent Superfund experience, however, these costs are likely to increase beyond the current estimates (*10–12*).

To adjust the historical cleanup costs shown in Table 2(a) to 1990 dollars the railroads involved were asked to provide a detailed historical breakdown of the expenditures on these spills (the 1990 figures refer to ongoing remediation efforts from the earlier incidents). This was necessary to account for general inflation and changes in real costs. These costs apply only to incidents that occurred in the period 1980 through 1989. The most quantifiable change in real costs over the years since 1980 has been the more than 700 percent increase in the average cost of land disposal of soils contaminated with these chemicals (Figure 4). This cost has risen from approximately $25 per ton in 1980 to approximately $220 per ton 1990 (*13*). These values were used to adjust the annual cost for soil disposal in each year relative to the cost in 1990. The resulting adjustment factor ranged downward from 8.8 in 1980 ($220/$25 = 8.8) to 1.0 in 1990. Although average monitoring and treatment requirements and their resultant costs have experienced real increases over the past decade, we were unable to satisfactorily quantify the additional effect of these increases on the remediation cost of the specific sites under study. Therefore, all other remediation cost components were adjusted to 1990 dollars using a GNP index based on the general inflation rate; the values of this index increased monotonically from 1.0 in 1990 to 1.529 in 1980. Up to the end of 1990, the total cleanup cost due to spills of the 10 halogenated hydrocarbons in railroad transportation incidents that occurred in the period 1980 through 1989 is estimated to be about $72.1 million in 1990 dollars, as shown in Table 2(b). With the addition of $5.0 million, the present value of the future costs, the total becomes $77.1 million. This estimate is conservative because it does not include all the litigation costs nor any of the real costs of increased site monitoring and more stringent contaminated soil removal standards, other than the unit cost of soil disposal. It also does not include the costs to parties other than the shipper, carrier, and car-owner.

To calculate the per carload liability over this period, the number of carloads of the ten halogenated hydrocarbons shipped from 1980 to 1989 was estimated by fitting a curve to the estimated actual carloads for the 3 years in Table 1 and extrapolating back over the preceding 7 years. This produced a total of 62,600 tank car-loads. Dividing the total of $77.1 million by this number gives an average environmental cleanup liability of $1,232 per carload. This per carload liability estimate then had to be adjusted downward to reflect the safer operating conditions in 1990 compared with the average con-

TABLE 2 CLEANUP COSTS ($ THOUSANDS): (a) ACTUAL AND (b) ADJUSTED TO 1990 DOLLARS

(a)

Year	Soil Disposal	Air Stripped Water	Carbon Treated Water	Other Costs	Total
1980	152	4,833	0	844	5,829
1981	0	4,833	0	0	4,833
1982	1,285	4,834	541	393	7,053
1983	3,625	0	1,855	6,740	12,220
1984	0	5	3,184	403	3,592
1985	0	534	2,666	350	3,550
1986	0	1,812	781	715	3,308
1987	1,386	1,421	520	1,879	5,206
1988	0	202	368	639	1,209
1989	0	265	413	1,668	2,346
1990	0	367	372	540	1,279
Total	6,448	19,106	10,700	14,171	50,425

(b)

Year	Soil Disposal	Air Stripped Water	Carbon Treated Water	Other Costs	Total
1980	1,338	7,390	0	1,290	10,018
1981	0	6,737	0	0	6,737
1982	5,770	6,333	709	515	13,326
1983	*5,097	0	2,339	8,499	15,935
1984	0	6	3,872	490	4,368
1985	0	631	3,149	413	4,193
1986	0	2,086	899	823	3,808
1987	2,345	1,586	580	2,097	6,608
1988	0	218	397	690	1,306
1989	0	275	428	1,730	2,433
1990	0	367	372	540	1,279
Total	**16,622**	**25,628**	**12,745**	**17,088**	**72,082**
Percent	**23%**	**36%**	**18%**	**24%**	**100%**

* This value represents only a partial adjustment because of the unusually high unit cost of soil disposal paid for the 1983 Lake Charles incident.

ditions over the 10-year period used as the basis for the cost calculations. Three aspects of rail transportation of hazardous material safety have improved over the period from 1980 to 1989: train accident rate, non-accident caused release rate, and tank car performance in accidents. The estimate of current liability had to be corrected to account for each of these. Thus, it was noted first that the 1989 train accident rate was 67 percent of the 10-year average (Figure 2). Second, it was determined that the 1989 rate of non-accident caused release incidents was 75 percent of the 10-year average (*14*). Third, calculations based on available data for tank cars indicated that the probability of release from an accident for damaged, non-insulated, general-purpose 111 tank cars averaged 0.25 over the period 1980 to 1989, compared with 0.225 for 1989 alone (*8*). Thus, on the basis of a relative difference of 10 percent, the 1990 accident-caused release probability for 111s damaged in accidents was estimated to be 90 percent of the 10-year average.

Recalling that 6 of the 8 incidents (¾) were due to train accidents and the other 2 (¼) were non-accident caused, the

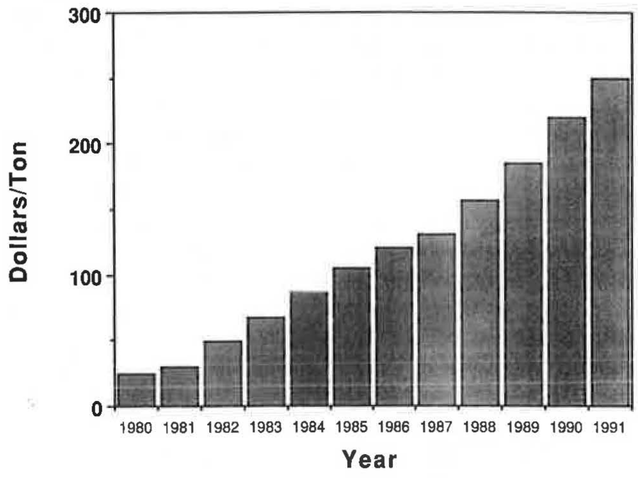


FIGURE 4 Cost of disposal of soil contaminated with halogenated hydrocarbons.

total industry liability in 1990 associated with transporting these ten chemicals was estimated to be [(¾ × 67 percent × 90 percent) + (¼ × 75 percent)] × \$1,232 = \$788 per carload. Multiplying this figure by the 11,798 carloads in 1989 yields an estimated annual industry-wide liability of \$9.3 million due to the rail transportation of these chemicals.

Other things being equal, the average annual benefit of replacing the 111s by 105s is the portion of this cost that would be avoided because of the difference in the release probabilities for the 105 and the 111 tank car. This difference is reflected by the relative reduction in $P(R)$, the probability of a release in a train accident. Assuming that $P(D)$, the probability that a tank car is damaged in a train accident, is the same for both types of cars, the reduction in the conditional probability $P(R|D)$ is equal to the reduction in $P(R)$. The reason is that $P(R) = P(D) \times P(R|D)$ and the $P(D)$ values cancel out when the relative reduction in $P(R)$ is calculated. Given the estimates of 22.5 percent for $P(R|D)$ for non-insulated 111A100W1 tank cars, 10.7 percent for 105A300W tank cars, and 3.7 percent for 105A500W tank cars (*8*), the reduction in $P(R|D)$ is estimated to be (22.5 − 10.7)/22.5 = 52.4 percent for the 105A300W and (22.5 − 3.7)/22.5 = 83.6 percent for the 105A500W. The estimated annual benefit for the 105A300W is \$9.3 million × 52.4 percent = \$4.9 million and for the 105A500W, it is \$9.3 million × 83.6 percent = \$7.8 million. These are the annual, industry-wide liabilities that would be avoided by using the respective kinds of 105 specification tank cars to transport these chemicals, that is, they are the values of b in the NPV equation. In carload terms, these results mean that under current packaging practices, the estimated average liability per carload is \$788, which reduces to \$375 per carload for the 105A300W and \$129 per carload for the 105A500W. (Note that the calculation of the reduction in $P(R|D)$ treated all eight incidents as accident caused although two were not. This approach is reasonable, given that using 105s instead of 111s would have diminished the likelihood of occurrence in one case and virtually eliminated it in the other.)

COST ESTIMATION

The variable cost of transportation, that is, the cost per mile, is about the same for 111s as for 105s, but the reduced capacity of the heavier 105A500W means that more carloads are required to transport the same quantity of chemical. Therefore, the incremental average annual transportation cost (c_t) associated with replacing the 111s by 105s was estimated by taking the product of three factors: the average cost per shipment in either type of car, the percentage increase in the number of cars required, and the current annual number of carloads shipped.

To estimate the first factor, the 1988 Sample of Carload Waybill Statistics of the Interstate Commerce Commission (ICC) for U.S. terminations was used, supplemented by AAR TRAIN II data for Canadian terminations, to determine that the average length of haul for the 10 halogenated hydrocarbons was about 850 mi. Then, using the ICC's Uniform Rail Costing Model, it was determined that, for a tank car having a capacity less than 22,000 gallons traveling 850 mi, the average variable cost per shipment is \$1,606.

To estimate the second factor, a tank car size-and-weight program developed by Union Tank Car Company was used. The size of a tank car is often optimized for individual commodities as a function of the commodity's density. The objective is to maximize the ratio of lading to tank car light weight (tare), so that the loaded car does not exceed the current maximum AAR interchange limit of 263,000 lb for weight on rails. This must be accomplished within the constraints imposed by various DOT and AAR specifications, including, among other things, clearances, tank thickness, and car length. For each of the 10 halogenated hydrocarbons the optimum size and weight of a 111 tank car and a 105 tank car and the percentage loss in capacity because of the heavier weight of the 105 was determined. As Table 3 shows, the results ranged from about 7.2 percent for ethylene dibromide, the heaviest of these chemicals, to 11.2 percent for ethylene dichloride, the lightest. Then, weighting each of these percentages by the corresponding number of 1989 carloads, we determined that the average loss in capacity would be 10.5 percent. This means that about 11.7 percent more shipments would be required to move the same quantity of these chemicals, because the number of shipments is inversely related to the capacity and 1/(1 − 0.105) = 1.117.

The value of the third factor is 11,798 carloads. Hence the product of the three factors is \$1,606 × 0.117 × 11,798 = \$2.22 million. This is the estimated value of c_t under the assumptions of no real increase in the average cost per shipment, no growth in total traffic, and optimally size tank cars. Analysis of the actual loading practices of these products indicates that if current inefficiencies in tank car use were elim-

TABLE 3 CAPACITIES OF NONINSULATED 111A100W1 TANK CARS AND OPTIMIZED 105A500W TANK CARS

CHEMICAL	Density (lbs/gal)	Capacity (gallons) 111A100W1	Capacity (gallons) 105A500W	Percent Reduction In Capacity
Carbon tetrachloride	13.22	15,803	14,338	9.27
Chlorobenzene	9.24	21,890	19,186	12.35
Chloroform	12.41	16,764	15,123	9.79
Dichlorobenzene	10.90	18,876	16,819	10.90
Ethylene dibromide	18.16	11,713	10,873	7.17
Ethylene dichloride	10.45	19,607	17,401	11.25
Methyl chloroform	11.19	18,432	16,464	10.68
Methylene chloride	11.02	18,690	16,671	10.80
Perchloroethylene (PERC)	13.54	15,453	14,049	9.09
Trichloroethylene (TCE)	12.16	17,083	15,380	9.97
PERC/TCE mixture	12.85	16,053	14,544	9.40
WEIGHTED AVERAGE				**10.54**

inated, the 11.7 percent weight penalty would be reduced to approximately 7.5 percent.

As far as fixed costs are concerned, replacing the 111s by 105s will require two major capital expenses: the net cost of acquiring 105s and the cost of modifying the terminals for top unloading of 105s. The second expense is necessary because general-purpose 111s are usually unloaded through bottom outlet valves but these are prohibited on the 105s.

The acquisition cost (c_a) is the difference between the total cost of replacing the existing 111s with new 105s, and continuing to use the existing 111s. According to recent industry estimates, the price of a new 105A500W tank car is approximately $88,000, while a new general-purpose 111 costs approximately $58,000. Assuming that the current rate of car utilization continues at nine trips per year, the number of 111s in question is 11,798/9 = 1,311 and the number of 105s required to replace them is 1,311 × (1 + 0.117) = 1,464.

The cost of continuing to use the existing 111s is the present value of the cost of replacing $\frac{1}{30}$ of the 1,311 cars each year due to attrition. Every such replacement will require a new car to be purchased but will yield a salvage value of the old car equal to 10 percent of the new cost, for a net cost of 90 percent of $58,000, or $52,200. Hence the total annual cost is $\frac{1}{30}$ × 1,311 × $52,200 = $2.28 million. Over 30 years, the total present value of this cost is $21.49 million. The final value of c_a depends on the fate of the existing cars that are displaced from halogenated hydrocarbon service. There are two possible extremes: either all the cars are scrapped or they are all sold or transferred into other service. If they are scrapped, c_a is equal to the cost of the new 105s minus the scrap value of the 111s minus the present value of the cost of attrition-based renewal of the 111 fleet described previously. The calculation is as follows: (1,464 × $88,000) − (1,311 × $5,800) − $21.49 million = $99.74 million. Alternatively, if all of the cars are sold or transferred, the AAR replacement value for a 15 year-old car (the average age of cars in this service) minus the cost of cleaning is used. Under this scenario, the calculation changes to c_a = (1,464 × $88,000) − [1,311 × ($31,900 − $1,000)] − $21.49 million = $66.83 million. Assuming that half of the current fleet would be scrapped and half would be sold or transferred into other service, it was estimated therefore that the average value of c_a would be $83.28 million.

The cost of terminal modification (c_m) derives from the fact that many of the existing terminals which receive these products and are not equipped for top unloading would have to be modified to handle the 105s. The Chemical Manufacturers Association (CMA) estimates that the average cost of retrofitting a terminal for this purpose would be between $10,000 and $20,000. To estimate the number of terminals, we used 1989 AAR TRAIN II data to determine that the shipments of the ten halogenated hydrocarbons went to about 140 destinations in the U.S. and Canada. Some of the terminals at these locations may already have top unloading capability, whereas others may have multiple racks within the same facility. Allowing for this uncertainty and the fact that customer locations might change in the future, requiring some additional cost in constructing unloading facilities, we estimated that 200 terminals would have to be modified. The median value of the cost figures provided by CMA is $15,000 per terminal, resulting in an estimated value for c_m of 200 × $15,000 = $3 million.

FUTURE CLEANUP COSTS

The rate of future increases in cleanup costs will depend on a number of factors, but it is expected that the influence of regulatory requirements will continue to dominate. The response to spills of hazardous substances that is currently required by the federal government comes under the provisions of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), which was revised in 1990 to reflect the 1986 amendments to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). CERCLA requires the Environmental Protection Agency (EPA) to define cleanup criteria known as "applicable or relevant and appropriate requirements" (ARARs). Depending on the hazardous substance and the specifics of the site, an ARAR may call for in situ remediation or removal and treatment of contaminated soil and groundwater. Effective in 1992, federal law will generally prohibit the disposal in landfills of soil that has been contaminated with halogenated hydrocarbons. More expensive alternative treatment methods such as high-temperature incineration or vitrification will usually be required when soil contaminated with halogenated hydrocarbons must be disposed of. Water treatment is also expected to become considerably more expensive within the next few years because of Title III of the Clean Air Act of 1990 (CAA). The most commonly used technique for treating contaminated water, known as air stripping, in which the volatile contaminant is removed from the water and released into the astmosphere, will no longer be allowed for the halogenated hydrocarbons. More costly methods will be required in which air pollution control devices are employed or activated carbon filtration is used. The unit cost of these methods can range from two to ten times the unit cost of air-stripping (*15,16*). In addition, state requirements for site remediation continue to become more stringent, driving cleanup expenses still higher.

These recent regulatory and legislative developments mean that contaminated soil and water, the two principal disposal and treatment components resulting from spills of these chemicals, will be much more expensive in the near future. Soil incineration is considerably more expensive than disposal in a hazardous waste landfill (*17*). A survey of major hazardous waste disposal firms conducted for the AAR (*13*) found that the average cost of incineration in 1990 was 5.5 times greater per unit of soil disposed than the average cost of landfilling. Analysis of the cleanup expense showed that soil disposal accounted for 23 percent of the total cost of site remediation in 1990 dollars [Table 2(b)]. To calculate the real rate of increase due to the full implementation of the land ban in 1992, we multiplied this fraction by 5.5 in year one. The result was a 104 percent increase in the overall cost of remediation (r_1 = 1.04). In order to quantify the effect of the CAA on remediation costs we determined from Table 2(b) that approximately 36 percent of the total cost of remediation was accounted for by water treatment using air stripping.

EPA has not yet promulgated the regulations mandated by the CAA prohibiting this method of water treatment. Its timetable for implementation of Title III ranges from three to seven years after its passage in 1990, depending on the chemical (*18*). A median value of five years and a four-fold increase in water treatment costs was assumed. The impact will be an additional 52 percent increase in the overall liability in year five ($r_5 = 0.52$). As mentioned in the section describing benefits, other cost factors are also expected to undergo real increases because of more stringent cleanup standards, greater monitoring requirements, additional third party expenses, and social inflation (*19*). However, because the authors were not able to satisfactorily quantify these factors, $r_j = 0$ for all other years was assumed.

RESULTS

Summarizing the estimates of the factors in the benefit-cost equation, b = \$7.8 million, c_t = \$2.2 million, c_a = \$83.3 million, c_m = \$3.0 million, $r_1 = 1.04$, $r_5 = 0.52$, and all other $r_j = 0$. The discount rate i was assumed to be 0.10, based on the 1988 ICC value of 10 percent for the before-tax real cost of capital. The resulting *NPV* is \$94.7 million. Dividing by 1,464, the number of tank cars required, the corresponding *NPV* per 105A500W tank car is \$64,701. A similar analysis was conducted for the 105A300W by substituting the following values in the formula: b = \$4.9 million, c_t = \$1.0 million, and c_a = \$53.8 million. The total *NPV* for conversion to 105A300W tank cars is thus \$60.5 million. Division of this number by 1,380, the estimated number of 105A300Ws that would be required, yields an *NPV* per tank car of \$43,861.

The effect that a reduction in train accident rate would have on the *NPV* was also estimated. To make these calculations, we inserted the term $(1 - a)^n$ ahead of b in the formula, where a represents the annual percentage decline in accident rate. A 1 percent or 2 percent compounded annual reduction in the train accident rate sustained over the 30-year period resulted in respective *NPV*s of \$75.8 million and \$59.3 million for the 105A500W and \$48.6 million and \$38.3 million for the 105A300W. For either of the two 105 specifications, a 7 percent annual reduction in train accident rate would have to be sustained over the 30-year period to yield an *NPV* of zero (Figure 5). These results do not reflect the additional costs and benefits associated with changes in the accident rate. The effect that the 11.7 percent increase in the number of carloads would have on the probability of accident involvement was not quantified. Although the number of cars derailed increases with number of car-miles, the actual functional relationship between these two variables depends on the accident cause. For example, the most likely impact of more cars would be longer trains. The number of cars derailed per derailment is positively correlated with train length but the rate of change in the functional relationship is much less than one (*20*). The influence of more tank cars would also be counteracted somewhat by smaller expected spill sizes because of the lower capacity and greater strength of the 105s.

The car utilization rate assumed in the model was 9 trips per year, which is lower than that reported by several major chemical shippers. The *NPV* if 105s are used is a positive function of car utilization efficiency because the greater the number of trips per year, the fewer the number of cars required, and the lower the corresponding value of c_a (Figure 6). Better car utilization is in the mutual interest of both industries because it lowers the capital outlay required of the shippers, thereby improving the cost-effectiveness of more secure tank cars while providing industry and the public with the benefits of fewer spills. To achieve better utilization, the railroads can assist by moving tank cars more expeditiously and the chemical shippers can contribute by providing incentives to their customers to unload and return cars promptly.

SUMMARY AND CONCLUSIONS

The 10 halogenated hydrocarbons considered in this analysis are currently transported in general-purpose tank cars because of their relatively low acute hazard to human health and safety. As the general awareness and understanding of environmental hazards and the health effects of chronic exposure to potential carcinogens have increased, so have the requirements for environmental cleanup of these chemicals.

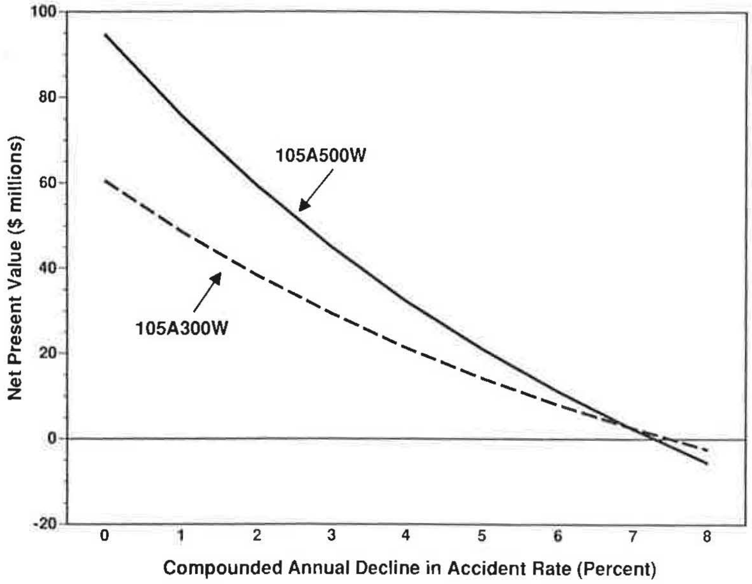


FIGURE 5 **Effect of train accident rate on *NPV*.**

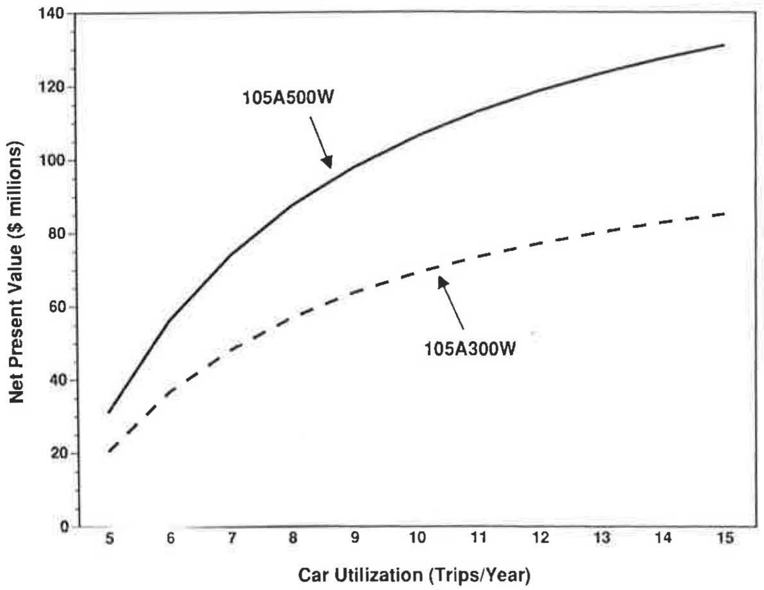


FIGURE 6 Effect of car utilization on *NPV*.

But transportation packaging practices have not kept pace with the environmental and economic impacts of these spills. Another hazard must be considered along with the more traditional hazards of acute toxicity, flammability, explosivity, and corrosivity. This hazard, which is referred to here as environmental sensitivity, needs to be factored in when evaluating the transportation risk of chemicals.

In deciding how to best respond to this need, analogies with packaging practices for other chemicals that rank highly on their respective hazard axes are appropriate. Beginning in 1918, the railroads and the car-building and chemical industries recognized that there was a need to "over-design" tank cars carrying chemicals that "if not contained were dangerous to life" (*21*). This was the reason for the development of the Type V tank car (precursor to the current 105) for transportation of chlorine and sulphur dioxide, and later the 105 car for tetraethyl lead. Subsequent experience with 105 tank cars carrying acutely toxic or flammable materials over the years has been excellent. Because of the wide range in hazards, this degree of over-packaging is not necessary for all chemicals, but the study results suggest that in the case of the 10 selected halogenated hydrocarbons, switching to 105s would be a cost-effective means of reducing risk.

ACKNOWLEDGMENTS

A number of people have contributed to the authors' understanding of this subject. The authors are grateful to the following individuals from the railroad, chemical, and car-building industries for helpful discussion and information: P. C. L. Conlon, B. J. Damiani, J. W. Fleshman, T. A. Gudiness, R. J. Holden, P. G. Kinnecom, D. J. Pasternak, L. W. Pepple, E. A. Phillips, R. E. Phillips, M. J. Rush, M. P. Stehly, C. E. Taylor, A. S. Rivers, K. E. Wolfe, J. E. Waggener, and W. J. Woodall. T. P. Warfield, Q. Huang, and P. B. Williams assisted with the data analysis. Special thanks to the members of the AAR Environmental Committee, Bureau of Explosives Steering Committee, and Tank Car Committee and railroad staff who provided data and insight.

REFERENCES

1. K. Wolf and F. Camm. *Policies for Chlorinated Solvent Waste*. Report R-3506-JMO/RC, RAND Corp., Santa Monica, Calif., June 1987.
2. H. H. Russell, J. E. Matthews, and G. W. Sewell. Remediation of sites contaminated with TCE. *Remediation*, Vol. 1, no. 2, 1991, pp. 167–183.
3. P. H. Abelson. Volatile Contaminants of Drinking Water. *Science*, Vol. 247, no. 4939, 1990, p. 141.
4. A. E. Harvey, P. C. Conlon, and T. S. Glickman. *Statistical Trends in Railroad Accidents*. Publication R-640, Association of American Railroads, Washington, D.C., Sept. 1987.
5. Association of American Railroads. *Railroad Facts*, Washington, D.C., Annual, 1980–1989.
6. E. A. Phillips and H. Role. *Effectiveness of Shelf Couplers, Head Shields and Thermal Shields on DOT 112(114) and 105 Tank Cars*. Publication R-610, Association of American Railroads, Chicago, June 1985.
7. E. A. Phillips. *Analysis of Aluminum Tank Cars Damaged in Accidents 1965–1986*. Publication R-749, Association of American Railroads, Chicago, March 1990.
8. E. A. Phillips and C. P. Barkan. *Open Memoranda on DOT 111A and 105A Tank Cars Preliminary Analyses* P-09-1-1, P-10-1-2 and P-05-1-3. Association of American Railroads, Chicago, April–May 1990.
9. General American Transportation Corporation. *Tank Car Manual*. 5th Ed., Chicago, Ill., 1985.
10. *SUPERFUND: Cost Growth on Remedial Construction Activities*. General Accounting Office, Resources, Community and Economic Development Division, Feb. 1988.
11. T. L. Richardson, P. Dappen, and M. C. Ray. "Estimated versus final costs on hazardous and toxic waste remediation projects." *Proceedings of Superfund '90*, HMCRI, Silver Spring, MD, pp. 230–235, 1990.
12. B. R. Schroeder. "Cost inaccuracies in Superfund projects: Strategies for building better estimates." *Proceedings of Superfund '90*, HMCRI, Silver Spring, MD, pp. 236–240, 1990.
13. Resource Consultants, Inc. *Cost analysis: Disposal of soils contaminated with chlorinated hydrocarbons*. RCI Project 1-3221, Brentwood, TN, March 1991.

14. Bureau of Explosives. *Annual Report of Hazardous Materials Transported by Rail*. Association of American Railroads, Washington, D.C., Annual 1980–1989.
15. J. Q. Adams and R. M. Clark. "Evaluating the costs of packed-tower aeration and GAC for controlling selected organics." *American Water Works Association Journal*, vol. 83, no. 1, 1991.
16. Environmental Protection Agency. *Baseline and Alternative Waste Management Cost Estimates for Third Landban Disposal Restrictions*, October 1989.
17. Environmental Protection Agency-Office of Policy Analysis. *1986–1987 Survey of Selected Firms in the Commercial Hazardous Waste Management Industry*, March 1988.
18. Environmental Protection Agency-Office of Air and Radiation. *Implementation Strategy for the Clean Air Act Amendments of 1990*, January 1991.
19. K. E. Wolfe. "An examination of risk costs associated with the movement of hazardous materials." *Proceedings of the 25th Annual Meeting of the Transportation Research Forum*, vol. 25, pp. 228–240, 1984.
20. Delcan. *Rail Transportation of Dangerous Goods: Relationship Between Train Speed and Incidence and Severity of Accidents*. The Toronto Area Rail Transportation of Dangerous Goods Task Force, December, 1987.
21. B. R. Schroeder. "Cost inaccuracies in Superfund projects: strategies for building better estimates." *Proceedings of Superfund '90*, HMCRI, Silver Spring, Md., pp. 236–240, 1990.

Publication of this paper was sponsored by Committee on Transportation of Hazardous Materials.

Abridgment

Hazardous Materials Emergencies in Railyards: Preparedness Guidance for Railroads and Adjacent Communities

MARIANNE MINTZ, KENNETH BERTRAM, CHRISTOPHER SARICKS, AND RACHAEL ROWLAND

This guidance being developed by the Federal Emergency Management Agency (FEMA) to improve the emergency preparedness of railroad yards that handle shipments of hazardous materials and the communities adjacent to those yards is summarized in this paper. Compared with the volume of hazardous materials that pass through railyards, comparatively few accidents have occurred. However, several of those accidents have had severe consequences, and there is potential for truly catastrophic consequences. Thus, the National Transportation Safety Board has recommended that FEMA develop emergency preparedness guidance for operators of railroad yards and the communities adjacent to those yards. The guidance focuses on planning for potential emergencies, pre-positioning equipment and other necessary resources, training personnel, and periodically testing plans and procedures to ensure their effectiveness and timely deployment.

Three issues prompted the Federal Emergency Management Agency (FEMA) to develop guidance for railyards and adjacent communities:

1. Despite carriers' extensive efforts to prevent accidents and attendant releases of hazardous materials, serious incidents can and do occur. Each year, approximately 1,000, or 40 percent, of all railroad accidents occur in railyards (*1*). Although comparatively few of these accidents involved release of hazardous materials (between 1984 and 1988, the annual number ranged from 10 to 22), serious property damage, injuries, and social and economic disruption can result. In a study conducted in response to one such accident, the National Transportation Safety Board (NTSB) concluded that increasing emergency preparedness is the most practical way to reduce harm from large-scale releases of hazardous materials in railyards. NTSB also recommended that FEMA develop emergency planning and response guidance for use by communities and operators of railyards that handle bulk shipments of hazardous materials, and incorporate that guidance into pertinent FEMA-sponsored training programs and manuals (*2*).
2. Large numbers of people are at risk from hazardous material emergencies in railyards. Although many railroads originally located their yards away from densely populated areas, urban and suburban development has encroached on them. Between 1984 and 1988, leaks of hazardous materials from railcars in railyards required 19 evacuations which affected 8,948 persons (*2*).
3. Guidance has been developed to improve the emergency preparedness of railroad mainlines (*3*), and fixed facilities like chemical plants (*4–9*), but no comparable guidance exists for railyards. The hazards posed by shipments of explosive, toxic, corrosive, or flammable materials present railyards with a set of emergency preparedness needs that differ from those faced by either (a) mainlines or (b) other fixed-site facilities. Like railyards, mainlines transport a variety of hazardous materials in an equally diverse variety of cars. However, once blocks of cars have been assembled, their locations within the train consist are fixed and the forces on them are more predictable than in railyards. Railyards are similar to mainlines in terms of the variety of hazardous materials handled, but different from both mainlines and other fixed facilities in terms of exposure duration. Normal railyard operations involve a wider range of cars containing an even wider range of hazardous materials than typically found at fixed-site facilities. Cars can be of different sizes, types, ages, designs, and conditions. In railyards, cars are also more likely to be moved over greater distances and at higher speeds than comparable vessels in fixed storage facilities.

Not only do in-yard movements increase the possibility of tank car damage, they also shift hazardous materials to different locations within the railyard. Yard personnel are responsible for detecting changes in car condition and location. Such monitoring is crucial because early detection can avert many emergencies and accurate location information is critical for responders likely to be faced with logistical problems greater than those found either at fixed-site facilities or along mainlines. Typical logistical problems include crossing several sets of tracks to reach the immediate hazard scene; promptly and correctly identifying the specific hazard; and combatting the release of toxic, explosive, corrosive, or flammable materials in a location not specifically designed for this purpose.

Special emergency procedures, equipment, and supplies, have been developed by railroads and communities to meet the needs of railyards in hazardous materials emergencies.

M. Mintz, K. Bertram, and C. Saricks, Argonne National Laboratory, 9700 South Cass Ave., Argonne, Ill. 60439. R. Rowland, Federal Emergency Management Agency, SL-NTH Hazmat, Federal Center Plaza, 500 C Street, S.W. Washington, D.C. 20472.

For the most part, these measures are used by railroads with heavy or diverse hazardous materials traffic and, thus, more advanced emergency preparedness programs. Summarized in the following and discussed further in the full report, some of these measures are relatively simple; others are more elaborate. They include

- Designating a yard tower or other structure as an emergency command center and equipping it with a telescope or high-powered binoculars, meteorological instruments, and tape for sealing doors and windows.
- Designating an isolation area (away from air intakes for buildings, tunnels, or other facilities) where damaged railcars can be moved.
- Positioning support locomotives at each end of the yard so workers relocating railcars can stay upwind of any potentially toxic plume.
- Constructing containment ditches or pits along isolation tracks, and installing oil retention booms and skimmers to prevent materials from migrating farther into the environment.
- Installing fixed overhead trays or small culverts so fire hoses, cables, and other equipment can be routed over or under tracks.
- Spot-checking hazardous material intermodal shipments for proper blocking and bracing.
- Installing automated or manual controls to prevent consists from leaving the yard if any railcars containing hazardous materials violate U.S. Department of Transportation (U.S. DOT) placement rules.
- Providing local response organizations with maps showing the locations of yard access points, rendezvous points inside or at the edge of the yard, and fire hydrants inside or adjacent to the yard.

FEMA contracted with Argonne National Laboratory to perform the field work needed to develop emergency preparedness guidance for railyards and adjacent communities. Field work consisted of a series of site visits and detailed interviews with a cross-section of nine railroads and nine adjacent communities to characterize current emergency preparedness practices. The railroad sample included four Class I, three regional (predominantly Class II), and two belt or terminal carriers (one of which served a large industrial concentration). The community sample included three large urban areas, three suburbs of large urban areas, and three small to mid-sized communities some distance from major metropolitan areas. Along with plan reviews and the authors' experience in radiological emergency planning (much of which is applicable to other hazardous materials emergencies), these formed the data base for the guidance.

RAILROAD AND COMMUNITY GUIDANCE

Emergency preparedness planing and response for hazardous material emergencies in railroad yards can be grouped into 11 functional areas, which are summarized in the following. Although targeted to situations and events likely to be encountered in railyards, guidance also includes certain general actions that are indispensable to effective planning and response or to incident mitigation. Although railroads and communities have some measure of accountability for each of the activities listed, some are primarily railroad (or community) responsibilities while others (e.g., planning) are joint responsibilities. The guidance combines the discussion of these activities to promote mutual understanding, and help identify opportunities for increasing organizational cooperation.

Roles and Responsibilities for Planning and Response

1. Identify laws and regulations that require and authorize the plans that could be activated in an emergency and the local, state, and federal agencies and officials empowered to act.
2. Identify planning responsibilities of government agencies, railroads, manufacturers, and shippers; and develop, review, and update coordinated plans and procedures specific to railyards.
3. Identify government and industry response organizations, and meet regularly with official liaisons.
4. Assign responsibilities to public and private responders, and designate (by title) the individuals responsible for coordinating and directing the response. Prepare organization charts showing the chain of command and other relationships among response units (including the railroad and the incident commander from the designated civil authority).
5. Arrange for supplemental resources, preferably by means of written agreements with clear activating conditions.
6. Identify qualified contractors for the safe and timely cleanup and disposal of debris and contaminated media, and arrange for their services. Inform them they will be under the direction of the incident commander (who will coordinate with responsible railroad officials) until the emergency is completely over.

Acquisition and Deployment of Emergency Facilities and Resources

1. Develop a hazard information system (preferably online) to quickly identify hazardous materials and determine their railyard location, quantity, hazard class, and properties.
2. Maintain and update contact lists for manufacturers of the hazardous materials most frequently handled at the railyard.
3. Designate off-site support facilities to direct railroad activities, to coordinate public and private response efforts, and to provide public information. Establish criteria for activating these facilities.
4. Establish an on-scene command post, equip it with additional communications links, and assign responsibility for 24-hr maintenance, security, and the staffing of communications links.
5. Designate primary and backup communications links to contact other railroads (if tracks are shared), shippers, and chemical experts. Designate at least one dedicated radio band for emergency communications and response coordination. Provide responders with mobile communications equipment tunable to local frequencies.
6. Inventory and classify by U.S. Environmental Protection Agency hazard category all emergency equipment and sup-

plies on-hand at the railyard or jurisdiction or available through supplemental support agencies, jurisdictions, or private organizations. Regularly update inventories, verifying equipment location and readiness. Coordinate with railroad or community staff to avoid duplication.

7. Regularly inspect and perform maintenance on stored equipment and facilities. Maintain records.

8. Establish procedures for the deployment of personal protective equipment, containment equipment, emergency monitoring devices, detoxification agents, and cleanup and disposal equipment.

9. Evaluate water supplies and the hookup needs of fire and rescue equipment. Add or upgrade on-site hydrants and provide safe connections to off-site hydrants. Install properly lined ditching systems and/or containment pits to avoid contaminating underground water.

Planning Analyses

1. Conduct hazards analyses, identifying the hazardous materials most frequently stored or handled at the railyard, likely emergency sequences and consequences, and overall risk.

2. Establish emergency classification levels with corresponding response actions. Coordinate with railroad and community emergency response officials to ensure compatibility.

Alert and Notification

1. Establish procedures and methods for 24-hr notification of local civil authorities and for verifying such notifications with the railyard. Use standardized messages and include chemical-specific information.

2. Establish procedures, methods, and priorities for 24-hr alert, notification, and mobilization of additional responders (including those from neighboring jurisdictions and facilities, and railroad, shipper, and industry response teams), second-shift personnel, and cognizant government agencies.

3. Establish procedures and means (e.g., sirens) for alerting the public that an emergency has occurred and for issuing emergency instructions.

4. Where faulty responses can have dire consequences, (e.g., all incidents involving Class A poisons, Class A and B explosives, or flammable liquid or gas), require that yard personnel promptly notify adjacent communities and request (at least) backup support.

Population Protective Actions

1. Establish guidelines and criteria for deciding if on-site actions, sheltering, or evacuation are needed.

2. Establish procedures for implementing sheltering and evacuation recommendations.

3. Designate one or more buildings in the railyard as shelters, indicate them on site maps and emergency plans, and stock them with appropriate supplies and instructions for their use as emergency shelters.

4. Establish procedures for reentering the railyard and/or evacuated adjacent areas. Designate (by title) the official responsible for recommending reentry, and set criteria for determining when it is safe.

5. Establish procedures for handling long-term physical and psychological effects on victims.

Responder Safety

1. Keep copies of key hazardous materials references (*10–12*) at the railyard and in response vehicles to help responders select appropriate protective gear and limit exposures. Send relevant information to the hospital with all contaminated or injured individuals.

2. Develop standard operating procedures specific to railyards yet parallel to generally applicable procedures for hazardous materials emergencies (e.g., procedures for monitoring release concentrations, donning and removing protective clothing, recording the presence of personnel in the hazard zone, relocating containers exposed to heat and flame, etc.).

3. Conduct regular training sessions on personal safety.

4. Establish a warning system for emergency evacuation of response teams in the hazard zone.

5. Structure response and repair operations for maximum personnel safety (e.g., obtain assessment data upwind and from a safe distance; have enough respirators in vehicles used for public notification; keep an explosimeter on hand if pressurized materials are handled).

6. Inform responders of the hazardous materials involved, exposure symptoms and hazard limits. Monitor exposures and relieve personnel at intervals appropriate to limits. Locate monitoring (and decontamination) near the checkout point.

Incident Assessment and Analysis

1. Improve incident detection by installing commercially available stationary devices to monitor toxic, corrosive, and flammable gases.

2. Provide the incident commander with clear and concise information, including rosters of available railroad personnel qualified to assist with mitigation and recovery, inventories of available equipment and supplies, data already obtained (from placards, shipping papers, standard references, the Chemical Transportation Emergency Center (CHEMTREC), etc.), and response actions already taken.

3. Improve incident assessment by automating and expanding hazard information systems with important firefighting information (e.g., site maps, floor plans, and the locations of stored supplies), maintaining comprehensive records of train consists, computerizing hazardous materials inquiries, and developing the capability to obtain hard copies from CHEMTREC or other data bases.

4. Obtain site-specific meteorological data to track airborne releases and support dispersion models.

5. Establish procedures for containing releases (e.g., with dikes and absorbent pads) or otherwise restricting the spread and intensity of emergency consequences, and for collecting environmental samples to monitor the success of those procedures.

6. Establish procedures for undertaking environmental assessment, biological monitoring, and contamination surveys, and for deploying field teams to monitor the size, concentration, and movement of hazardous materials releases.

7. Identify and initiate actions to restore the railyard and, if necessary, the surrounding environment. Monitor the success of those actions, and assign long-term responsibility for site control.

Emergency Worker Training

1. Familiarize fire and rescue personnel with railyard layout, access points, and possible points of unauthorized entry, the railroad's standard operating procedures for handling involved railcars, and railroad information and response resources and capabilities.

2. Instruct yard personnel and civil responders in the proper use of basic references (e.g., waybills, shipping papers, decision flowcharts, AAR and U.S. DOT guides, and CHEMTREC) for identifying involved materials, determining their physical properties and potential hazard, and indicating appropriate response measures. Maintain training records.

3. Take advantage of available courses and other training resources. Assemble a library of videotapes applicable to hazardous materials emergencies at railyards or borrow tapes through lending libraries.

4. Where gaps exist, develop programs and materials to supplement and enhance available resources. Emphasize the importance of efficiently locating information on specific chemicals, assessing container damage, and minimizing responder exposure, and the danger of railcars with empty or residue placards. Designate (by title) the individual responsible for emergency worker training.

5. Create opportunities for railyard personnel to train with local civil responders.

6. Conduct critiques as soon as possible after the emergency is over.

Emergency Preparedness Exercises

1. In conjunction with training activities, conduct an initial tabletop exercise to verify workers' understanding of their roles and responsibilities, and test their ability to perform assigned tasks.

2. Develop a regular program of internal, teamwork-oriented exercises (tabletop, functional, and full-scale) to systematically evaluate the plan, response skills, and coordination.

3. Develop a system to evaluate how well exercises meet prespecified objectives.

4. Establish guidelines for participating in safe joint exercises, and work with involved agencies to periodically conduct joint functional or full-scale exercises.

5. Use exercise results to identify shortcomings and suggest revisions to emergency preparedness plans, procedures, and training programs.

Public Education and Risk Communication

1. Participate in public meetings to develop plans for protective actions.

2. Improve public education. Provide public speakers and information that explain potential hazards and the planning and response measures that are in place for hazardous materials emergencies. Tell local media what to expect, how to get additional information, and which locations will be off-limits.

3. Plan for and standardize as much public information as possible. Develop pre-scripted messages in several languages, if appropriate, to convey standard information and assistance. Enter into formal emergency broadcast system agreements that include regular broadcast of test messages.

4. Develop plans and procedures to alert and communicate with special needs populations such as the vision- and hearing-impaired, the handicapped, and foreign-language speakers.

5. Develop a rumor-control program and train personnel. Designate (by title) an official spokesperson.

Post-Incident Documentation

1. Maintain detailed, chronological logs of events, conversations, and activities undertaken during the emergency, including reentry and recovery phases.

2. Evaluate response effectiveness. Identify necessary changes to plans and procedures, and additional needs for training and public information.

ACKNOWLEDGMENTS

Work sponsored by the Federal Emergency Management Agency through interagency agreement EMW-E-0769 with the U.S. Department of Energy.

REFERENCES

1. *1984–1988 Accident/Incident Reports Master File.* 49 CFR 225, RRS-22, Federal Railroad Administration, 1986–1989.
2. *Special Investigation Report: Railroad Yard SafetyHazardous Materials and Emergency Preparedness.* NTSB/SIR-85/02, National Transportation Safety Board, 1985.
3. *Hazardous Material Emergency Response Plan Guidance Document for Railroads.* Association of American Railroads, 1989.
4. *Guide for Development of State and Local Emergency Operations Plans.* CPG 1-8, Federal Emergency Management Agency, 1985.
5. *Hazardous Materials Emergency Planning Guide.* NRT-1, National Response Team of the National Oil and Hazardous Substances Contingency Plan, 1987.
6. *Developing a Hazardous Materials Exercise Program: A Handbook for State and Local Officials*, NRT-2, National Response Team of the National Oil and Hazardous Substances Contingency Plan, 1990.
7. *Technical Guidance for Hazards Analysis: Emergency Planning for Extremely Hazardous Substances.* U.S. Environmental Protection Agency, Federal Emergency Management Agency, and U.S. Department of Transportation, 1987.
8. *Community Awareness and Emergency Response Program Hand-*

book. Chemical Manufacturers Association, Washington, D.C., 1985.
9. *Handbook of Chemical Hazard Analysis Procedures*, Federal Emergency Management Agency, U.S. Department of Transportation; U.S. Environmental Protection Agency, 1989.
10. *Emergency Action Guides*. (P. C. Conlon and A. M. Mason, eds.), Association of American Railroads, Washington, D.C., 1984.
11. *Emergency Handling of Hazardous Materials in Surface Transportation*. Association of American Railroads, Washington, D.C., 1989.
12. *1990 Emergency Response Guidebook*. DOT P 5800.5, U.S. Department of Transportation, Research and Special Programs Administration, 1990.

Publication of this paper sponsored by Committee on Transportation of Hazardous Materials.

State and Local Issues in Transportation of Hazardous Materials: Toward a National Strategy

MARK ABKOWITZ, PAULA ALFORD, ASHOK BOGHANI, JON CASHWELL, ESSAM RADWAN, AND PAUL ROTHBERG

Findings of a recent conference whose objective was to identify effective state and local methods for managing hazardous materials transportation within an evolving national system are described in this paper. The conference was organized into five major themes: community preparedness and emergency response, evaluating and communicating risk, routing and siting considerations, data collection and information management, and inspection and enforcement. Although consensus was reached on several recent developments, several critical needs were identified, which form a future research and program policy agenda. A detailed discussion of recent accomplishments and proposed future initiatives by theme, leading to a general assessment of the effort required to maintain a level of adequacy necessary to manage the safe movement of hazardous materials, is presented.

The transportation of hazardous materials is inherent in any advanced and technologically complex society. A number of industrial processes of vital economic importance are dependent on the uninterrupted flow of hazardous materials shipments. However, when these shipments are made, there is significant potential danger to the population and the environment in the event of a release. The risks associated with the transportation of hazardous materials have drawn considerable attention at local, national and international levels, resulting in the development of a regulatory framework to enhance operational safety.

Many responsibilities associated with the safe transport of hazardous materials have been placed with state and local governments. Such tasks include community preparedness and emergency response, evaluating and communicating risk, routing and siting considerations, data collection and information management, and inspection and enforcement. The extent of assumption of these responsibilities varies across the country, and jurisdictional purview in some areas is subject to debate. Nevertheless, several exemplary activities have been undertaken by state and local governments that are compatible with the development of a national strategy, and which have been beneficial in managing the safe transport of dangerous goods.

To address these considerations, a national conference, sponsored by the Transportation Research Board (TRB) and many other organizations, was held in St. Louis in May 1990. The principal objective of this conference was to enhance the exchange of information concerning effective state and local methods for managing hazardous materials transportation within an evolving national system. Although state and local agencies were the primary consideration in this forum, industry, the federal government, and other affected parties attended and participated actively to provide a broader perspective of the complexity involved in the safe transport of hazardous materials.

The conference itself was organized into five major themes:

1. Community preparedness and emergency response,
2. Evaluating and communicating risk,
3. Routing and siting considerations,
4. Data collection and information management, and
5. Inspection and enforcement.

What follows is a summary description, by theme, of the major conclusions reached through the conference proceedings.

COMMUNITY PREPAREDNESS AND EMERGENCY RESPONSE

From the conference, it became apparent that a growing consensus is forming on the work needed to improve emergency preparedness across the nation, yet there is basic disagreement over the degree to which we are or are not adequately prepared.

The conference participants concluded that there is greater awareness of the need to get people involved and to maintain adequate emergency preparedness. Significant actions are being taken to help resolve some of the major roadblocks preventing overall emergency preparedness capability. They include the following:

1. Title III of the Superfund Amendments and Reauthorization Act (SARA) has been enacted and is being implemented by a number of states and localities;

M. Abkowitz, Vanderbilt Engineering Center for Transportation Operations and Research (VECTOR), Vanderbilt University, Box 103, Station B, Nashville, Tenn. P. Alford, Nuclear Waste Technical Review Board, 1110 Wilson Boulevard, Arlington, Va. 22209. A. Boghani, Arthur D. Little, Inc. 35/220 Acorn Park, Cambridge, Mass. 02140. J. Cashwell, Sandia National Laboratories, P.O. Box 5800, Albuquerque, N.Mex. 87185. E. Radwan, Department of Civil and Environmental Engineering, University of Central Florida, Orlando, Fla. P. Rothberg, Congressional Research Service, The Library of Congress, Washington, D.C. 20540.

2. Greater efforts are being made by the Federal Emergency Management Agency (FEMA) to focus on preparing communities for all types of emergencies;
3. A five federal agency cooperative has encouraged Congress to allocate funds for more flexible purposes and that FEMA's role be strengthened and clarified;
4. National competency standards for responders have been prepared;
5. The U.S. Department of Transportation (U.S. DOT) is spending more time on hazardous materials transportation management issues than ever before;
6. The U.S. Department of Energy (DOE), with respect to radioactive waste transportation, is making a concerted effort to develop open, two-way communication with affected parties, and has outlined a number of specific initiatives; U.S. DOE has recognized that the greatest obstacle the radioactive waste program faces is public perception about the danger of radioactive waste;
7. States have increased their enforcement efforts as a result of SARA Title III, resulting in 30 states having their own fee system. Almost all states have adopted federal regulations on hazardous materials.

Despite this progress, states still believe that existing regulations are too complicated and restrictive; the federal government provides too few resources; federal training must be more comprehensive and coordinated; and there is a need for preemption of state and local activities. Fortunately, Congress is showing a greater awareness of problems that are technical and administrative as opposed to those that are political in nature, including the need for providing adequate training and an equitable method for distributing financial assistance.

An additional conference finding is that there is greater agreement among parties involved as to what constitutes adequate emergency preparedness. Encouraging examples of coordinated planning and response were described as part of the TRANSCAER program, developed by the Chemical Manufacturers Association (CMA). The key ingredient appears to be that industry works closely with local officials and then succeeds in having the locality make planning and response mechanisms their own. CMA is also preparing stringent disposal codes under its Responsible Care program, and the American Petroleum Institute has also adopted a set of operating procedures.

The two most popular words used during the conference to characterize successful emergency preparedness were *cooperation* and *communication*. The point was repeatedly made that if these two ingredients are present, then response will be successful. It may not be pretty or perfect, but it will suffice.

To have adequate cooperation and communication, however, the people involved must pursue information; it does not come to them without effort. Information has also progressed beyond the basics. There is growing knowledge as to the resources and system needed to respond to an incident, including:

1. Development of a good plan,
2. Ultimate authority in one place during an incident,
3. Proper basic equipment,
4. Proper technical communication equipment,
5. Quick access to experts, but final control over their differing views,
6. Ability to use media effectively to help,
7. A basic level of knowledge at dispatch, police, fire fighter, and local elected official levels.
8. A satisfactory decision-making process, and
9. Knowledge of what to look for and how to identify products.

A final finding emanating from the conference is that adequate preparedness on a national basis is still a long way off, primarily because many of those involved in this effort are volunteers. Volunteerism, for all it merits, presents problems, particularly in a discipline such as hazardous materials emergency preparedness, in which advanced communication, information gathering, and response capabilities are needed to ensure public health and environmental safety.

U.S. DOT has worked hard to expand its training network, but getting those who need the training to spend time away from their jobs is a problem. Although more information is available than ever before, additional guidance is needed for volunteers. Time may also be a problem for advanced levels of training, however, as these courses can exceed 200 hours of commitment.

Beyond these general conclusions, several other noteworthy observations were made:

1. More work is needed by state government, local authorities and industry in understanding what cooperation among sectors means.
2. More work is needed nationwide at the sub-state level to ensure that integrated broad base planning exists such as is required under SARA Title III.
3. Liability problems continue for industries and local responders arriving on the scene.
4. Most communities will not budget money for hazardous materials transportation preparedness; consequently it takes a long time for plans to develop. A $400 budget commitment per year by a locality is typical.
5. One interesting revelation is that those involved have learned that a farm community of 4,000 residents faces the same risk considerations as a larger municipality.
6. A special area of concern was raised as to how one assesses the capabilities of carriers prior to transport; greater emphasis will have to be placed on this task by industry in the future.
7. Conference participants agreed that since current legislation introduced to monitor hazardous materials shipments may not provide an adequate solution to the real or important problems, further study is needed.
8. Confusion remains as to what materials are considered toxic or nontoxic; greater information on the nature of chemicals needs to be provided to those involved in order to allow for effective treatment.

A fitting summary, perhaps, to this area are two revealing quotes which emerged from the conference proceedings and shed appropriate light on the subject matter. They are, "a little hazardous materials knowledge is a bad thing," and "we must be prepared with the best we have to handle the worst that can occur."

EVALUATING AND COMMUNICATING RISK

Risk evaluation is part of a necessary process for making rational decisions on how to move hazardous materials. Risk communication refers to a method of conveying and gaining public acceptance of the decisions which have been made. In the following discussion summarizing conference findings, these subjects are treated separately.

Risk Evaluation

Risk evaluation generally involves conducting a risk assessment. When risk assessment is performed, a number or a set of numbers expressing risk severity are typically generated. This process is often repeated for several alternatives to identify the best option when all issues are considered.

There is no question that making decisions on routing is the most frequent use of risk assessment. This was evident by the number of papers presented at the conference, including issues concerning rail routing, software applications that perform computerized routing, and routing issues involved at the state and regional level.

Several trends were identified in risk assessment, whether used for routing or some other application. First, people tend to prefer the use of local data for performing risk assessment rather than national data, when it is readily available. Examples of this trend were demonstrated by presentations on recent risk assessments performed in Pennsylvania, California, and Arizona using site-specific data. Secondly, the analysts are devoting more effort to factors other than cost and risk in developing risk assessments; in particular, risk aversion, risk equity, emergency response, and the proximity of sensitive facilities are emerging as other factors to consider. Finally, the trend to develop models on the basis of relative risk indexes instead of absolute risk continues.

A consensus is also forming that development of risk assessment methodology has been overemphasized, in comparison with practical implementation issues. Many believe that simpler models are better, serving as screening methods to support local decision making. It may be time to shift our focus to other areas instead of developing new ways to quantify risk, such as:

1. What is acceptable risk in a national framework? Are the comparisons to being struck by lightning or killed in a car accident reasonable or should some other benchmark be found?
2. There is a need to review and evaluate all of the risk models that are available, and assist decision makers in selecting a standardized approach to risk assessment.
3. Effort must be expended on understanding human factors and their effect on risk (e.g., effects of training on safety, acceptability of technological aids by drivers, etc.).

Ultimately, of course, even if transportation professionals become convinced that the risk assessment is accurate and the level of risk is acceptable, the public needs to become equally convinced. Hence, we must consider communication.

Communication

At the moment, risk communication poses a formidable challenge. There is a basic mistrust in the public mind of both big business and government that must be overcome. There is no question that additional resources must be devoted to this topic so that rational decisions are made quickly, and the balance between risk and the need to move hazardous materials cost-effectively is preserved.

Of the several presentations made in this area, a number of noteworthy quotes emerged:

- "Educating the public comes after educating yourself."
- "The best way to gain trust and credibility is to be forthright—tell people what the risk is and what you are doing to bring it down."
- "Get people involved up front—not when the draft report is prepared."
- "Make sure that the key people in the community are informed prior to giving a story to the media."
- "People tend to focus on consequences even though they know that the chances are small."
- "Lack of control over decision-making is what bothers people most."
- "Risk equity and fairness are very important."
- "Risk communication is still an art, not a science."

There is no question that a lot of good work has been conducted, yet much more needs to be done. Ideally, one day, the level of communication will be so good that there will be no discernable difference between estimated or measured risk and the risk perceived by the public.

ROUTING AND SITING CONSIDERATIONS

Routing and siting issues in the transportation of hazardous materials were the principal topic of discussion in the following areas:

1. State and regional routing concerns,
2. Community awareness and participation in routing decisions,
3. Rail routing of hazardous materials,
4. Routing regulation and enforcement, and
5. The state of the art in highway routing models.

Siting of facilities that handle hazardous materials was addressed as a secondary issue relative to the subject of routing, in part because of the conference theme, which stressed transport, and perhaps, in part, because of a greater concern expressed by governments and the public regarding transportation issues. Furthermore, siting of fixed facilities has long involved the National Environmental Policy Act process, with participation from area governments, affected interest groups, and the public.

Transportation, on the other hand, is increasingly becoming a high-profile, public-awareness issue. Public, local, state, national, and industry concerns regarding transport activities have resulted in varying regulations and operational constraints being placed on the movement of these materials. The reason for this concern, however, is not entirely clear. Indeed, little evidence appears to exist that the threat to the public of hazardous materials transportation movement is higher than for many common activities.

It was apparent from the conference dialogue that U.S. DOT clearly will be gaining increasing authority in overseeing hazardous materials transportation issues, including issuance of a new routing workbook and associated software to assist state and local agencies in determination of routing alternatives. The U.S. DOT maintained an active presence at the conference, permitting access and interchange with interested participants.

Noteworthy presentations included a timely discussion on achieving public acceptance of routing decisions. The difficulty in achieving consensus on routing recommendations was emphasized, because of the emotion-evoking nature of the cargo as well as the involvement of a wide spectrum from the public, interest groups, and policy makers. The misunderstanding regarding true "measures of risk" to the public was underscored, as was the confusion between routing and risk concepts among the various interest groups.

Panel discussions on community awareness and participation in routing decisions, regulation, and enforcement underscored the benefits of understanding and dealing with real world problems and approaches, as well as the need to reflect accurately these experiences in future activities. A conference session on rail routing emphasized the need to develop mode-specific analysis approaches because of the inherent operational and institutional differences between rail and truck transport.

Finally, an excellent overview of the tools and techniques available to the hazardous materials transport analyst was presented, focusing not only on the individual methods available, but also on the similarities and differences in the approaches available. Several of these methods were either demonstrated or presented during the conference.

A major concern that surfaced at the conference is the complex relationship between routing and risk analysis. Commonly used risk surrogates such as population density (as a measure of potential population exposure) are often factored into route selection models. Risk communication, perceived risks, and absolute risks as topics of concern also overlapped into the routing analysis area.

Because the processes used to analyze routing alternatives and risk assessment methodologies are fundamentally different, the technical approaches to model development appeared to emphasize the inclusion of vast amounts of data without a strong justification. How to weigh the various factors relative to one another, questions regarding the individual assumptions used, and uncertainty or sensitivity analysis left a number of unresolved issues.

From these presentations it appears that there is a continuing need to answer a number of basic questions:

1. What is the federal role? Where should routing decisions be made and routing criteria established?
2. How does industry participate in this process?
3. Risk versus routing, which leads the other?
4. Are route analysis methods and quality of the data scientifically credible? Are the outputs understandable?
5. Are computer routing models a tool or a crutch?
6. Who will fund the development of more comprehensive methods?

To answer these questions in a timely fashion, it was clear that transportation professionals must become more pragmatic in their approach, recognizing that many of these needs require responsive action.

DATA COLLECTION AND INFORMATION MANAGEMENT

During the conference, statistics were presented relative to the magnitude of hazardous materials transportation activity. For example, there are over 2,300 different substances being handled daily, and that in 1982 alone, more than 1.5 billion tons of hazardous materials were transported by rail, highway, water, and air.

As the transportation of hazardous materials has emerged as a major concern for federal, state, and local agencies, it has also become imperative that data used to draw general conclusions on safety issues at the national, regional, and local level be credible. To be able to conduct responsible risk or vulnerability analyses at any level, one must have a comprehensive information system as a basis.

Conference discussion included both federal and state efforts. At the federal level, the Hazardous Materials Incident Reporting System (HMIRS) was presented as a unique source of information on hazardous materials transport incidents in the United States. Follow-up reports by telephone and in writing collectively provide information on incident types and severity, danger to the public and environment, impact on operation of major transportation arteries, contamination to certain areas, and possible evacuation. This system is made available to federal, state, and local agencies by means of special computer accounts. In Ontario, Canada, the Risk Management Branch of the Transport Dangerous Goods Directorate reported on their data collection and analysis system for commodity flow and incidents. Three types of data bases are maintained: (*a*) an accident data base, (*b*) a commodity flow information system, and (*c*) a cost file. Mandatory reporting requirements are imposed on all provinces in Canada.

A presentation on the Radioactive Materials Incident Reporting data base, managed by Sandia National Laboratory, exemplified material-specific information systems that are available. It includes information on three accident types, namely transportation accidents, handling accidents, and in-transit incidents. Data are secured from federal agencies, states, and media reports.

At the state level, Arizona, Illinois, and Pennsylvania reported on their experience with incident data bases. In Arizona, a statewide post-incident hazardous materials reporting system is being developed using an incident report form similar to one developed by California. This form has been distributed to over 300 fire departments, sheriff's offices, local emergency planning committees, emergency management agencies, and state hazardous materials response agencies to solicit their comments and, more importantly, to seek their commitment of participation. In this proposed program, the Arizona Division of Emergency Services will supply incident report forms and maintain a computerized data base system for incident reports. Statewide participation in Arizona will continue to be irregular under a voluntary submittal program; however, new legislation mandating reporting is being explored.

In Illinois, a Hazardous Materials Advisory Board has been established, composed of the directors of twelve state agencies, representatives from the major statewide response organizations, and four individuals appointed by the governor. Participation in the data collection process is voluntary, and the Board has recommended that the Illinois Department of Transportation be given the responsibility of managing data collection and analysis. The program has been viewed as a success in Illinois simply because more information is now available about the severity and frequency of hazardous materials incidents.

A study sponsored by the Pennsylvania Department of Transportation has investigated three data bases for risk assessment: the HMIRS, the Office of Motor Carrier Safety, and State of Pennsylvania accident data. The comparison concluded that no correlation among the three systems exists, which is somewhat surprising since, in principle, many of the same accidents in Pennsylvania should be tracked by all three systems. Since the analysis being conducted applied to the state level, Pennsylvania state-specific data was consequently recommended. Subsequently, it was discovered that the state system was not comprehensive and suitable for segment level risk analysis, forcing a more aggregate study approach.

In reviewing the presentations involving hazardous materials data bases accessed from both federal and state sources, it is apparent that the top-down approach is not sufficient for conducting comprehensive risk analysis. Instead, a bottom-up approach is essential in generating credible data. What this means is that each state likely will have to create a comprehensive hazardous materials data base that includes both flows, incidents, and consequences related to hazardous materials shipments.

To accomplish this task, the use of geographical information systems (GIS) was identified as a promising technology, enabling different agencies to store data and conduct "what if" type analyses efficiently. The graphical displays generated by GIS for hazardous materials routing or to identify vulnerable areas in a region would assist planners and top administrators in making intelligent decisions.

INSPECTION/ENFORCEMENT

Issues relating to hazardous materials transportation inspection and enforcement were addressed in panel format. Discussion focused on measuring the importance of inspection/enforcement to state and local officials, and identifying future needs related to the inspection/enforcement function. Among the questions raised were:

1. What strategies promote effective and efficient hazardous materials transportation inspection/enforcement programs?
2. How does inspection/enforcement of hazardous materials transportation interact with broader state and local hazardous material planning and emergency response activities?
3. How can state and local officials help the hazardous materials transportation inspection/enforcement community?
4. How can the federal government help state and local governments improve their hazardous materials inspection/enforcement capabilities?
5. What should be the future of the Cooperative Hazardous Material Enforcement Development Program (COHMED) and the federal/state/local enforcement partnership embodied in the Motor Carriers Safety Assistance Program (MCSAP)?
6. Is self-inspection an effective option?

Key themes expressed by various panel members can be summarized in three words: cooperation, communication, and training. Cooperation is needed to ensure that there are active, ongoing positive relationships among the state and local emergency planning communities and those enforcing the hazardous material transportation regulations. Although the relationship between these two groups has improved in some jurisdictions because of the requirements of Title III of SARA, there are substantial opportunities to continue to improve cooperation in many jurisdictions. One way to promote cooperation is to name representatives of the enforcement community to the State Emergency Response Commissions and Local Emergency Planning Committees.

A variety of strategies to reduce interagency conflict, especially those between the fire services and enforcement communities, may be especially helpful in improving cooperation. Another aspect of cooperation that was identified is the need for political support for effective enforcement of the hazardous materials transportation regulations. The program participants stated that political "interference" can adversely affect efforts to promote compliance with the hazardous materials transportation regulations.

Improved communications and information sharing also would aid in the coordination process. Emergency response plans developed by various state and local governmental entities need to pay more attention to the enforcement component of an emergency situation.

Much of the attention devoted to future need focused on training of hazardous materials officers and the effectiveness of their efforts. The importance of real world experience as a teaching method was underscored. Training and the effectiveness of many hazardous materials inspection/enforcement officers have been enhanced significantly as a direct result of MCSAP. U.S. DOT is contributing to state activities by substantially increasing its training for state inspectors. The information dissemination efforts of U.S. DOT have also helped improve inspection/enforcement capabilities.

Numerous options to improve the training and effectiveness of state hazardous materials inspection/enforcement activities were presented as a result of the issues raised.
These included

1. Providing at least $1 million of MCSAP funding for training a specialized core of hazardous materials inspectors. It was noted that several states have successfully instituted specialized units of hazardous materials;
2. Increasing the involvement of local government enforcement officers in hazardous materials transportation. This would need to be accompanied by increased training to ensure quality and uniformity with accepted practices approved by the Commercial Vehicle Safety Alliance. This objective also could be furthered by increased local agency involvement in COHMED and U.S. DOT training activities;
3. Defining better the roles of state and local governments in hazardous materials transportation inspection/enforcement, and improve communication among all levels of government; and
4. Requiring certain levels or standards of training for hazardous material inspectors.

CONCLUDING REMARKS

The St. Louis conference represented a departure from hazardous materials transport forums held in the 1980s in that the focus shifted from one of issue identification to the establishment of an action agenda on the basis of previously defined issues. Toward that end, many findings emerged to constitute a research and program policy agenda for the next few years.

Emergency response is becoming a dominant area of concern, particularly for the need for better and more interagency cooperation, communication, and training. Additional resources, simplified rules, and greater political support characterize the needs of the response community at this time, including the enforcement component of emergency situations. Methods for evaluating emergency response capability are also desperately needed at this time, to enable the allocation of available resources according to priority.

With risk assessment maturing as a field, it is apparent that many factors require explicit consideration as part of this process, including risk perception, risk equity, and determination of a reasonable definition for what constitutes adequate safety. With the proliferation of various risk estimation techniques and the trend towards site-specific applications, establishment of standard methods for risk assessment are clearly needed. Equally as important is the need to emphasize risk communication as a vital part of the risk assessment process and to develop procedures for effective communication practice.

According to conference participants, the time has come for the issue of routing to be tackled head-on. Criteria must be established for selecting preferred routes and the interrelationship between risk assessment and routing analysis methodology must be clearly defined. One of the key elements in supporting this process is the availability of credible data. Discrepancies in incident reporting systems and the paucity of well-designed and carefully implemented flow studies makes it paramount that there be quality improvements in the techniques applied to data collection. Promising approaches in this direction are the use of a bottom-up approach (rather than top-down) to gather site-specific data and the adaptation of GIS as an information technology for storing and managing data for analysis purposes.

EPILOGUE

Several months following the St. Louis conference, the Hazardous Materials Transportation Uniform Safety Act of 1990 (HMTUSA) was signed into law. Many of the provisions contained in this reauthorization address issues identified in this paper. The St. Louis conference may well have provided a forum for advancing the thinking that went into the final legislation. Hopefully, as the initiatives contained within HMTUSA are implemented over the next few years, we will move closer towards an effective national strategy for managing the safe transport of hazardous materials.

ACKNOWLEDGMENTS

The authors would like to recognize the many individuals and organizations who banded together to structure a comprehensive technical conference program in St. Louis. Special thanks are extended to the Transportation Research Board, U.S. Department of Transportation, and American Society of Civil Engineers, for their logistical, technical and financial support, and to members of the Conference Organizing Committee for their time, energy, expertise, and perseverance.

The views presented in this paper are solely those of the authors and not of their employers or sponsoring agencies.

Publication of this paper was sponsored by Committee on Hazardous Materials.

Detailed Inspection of U.S. Army Railroad Trackage and Application to Civilian Short-Line Railroads

DAVID G. BROWN, DONALD R. UZARSKI, AND RICHARD W. HARRIS

The U.S. Army Construction Engineering Research Laboratory has developed a railroad track maintenance management decision support system called RAILER. The detailed track inspection procedures are designed to implement the recently issued Army Track Standards in a manner consistent with the larger goals of RAILER, thus promoting both track safety and track maintenance management. The inspection procedures are divided into six track component areas, and field inspection forms have been developed that guide the inspector through the inspection of each component area. The inspection procedures include measures for dealing with track components that are hidden, such as by vegetation or road crossings. In addition to the Army Track Standards, the inspection procedures can also support other track standards such as those propagated by the FRA or designed by a private operator. This property serves to facilitate a transfer to the civilian sector. The inspection procedures also take advantage of the RAILER computer software to ease the overall burden of the inspector.

RAILER is a decision support system for track maintenance management developed at the U.S. Army Construction Engineering Research Laboratory (USA-CERL) (*1*, *2*). It is currently being implemented at selected Army installations. Although primarily designed for Army use, RAILER was constructed to also facilitate technology transfer to the civilian sector for use by the commercial railroad community, especially short lines and industrial networks.

As a decision support tool, RAILER can be used, in part, to develop annual and long-range work plans, develop budgets, determine condition levels, and estimate maintenance and repair costs. RAILER uses personal computer-based software developed at USA-CERL to accomplish these tasks. The data base includes several information types, the most important of which are inventory and inspection. The inventory data elements are discussed in a paper by Uzarski et al. (*3*). The RAILER detailed inspection procedures are discussed here; a complete description of these procedures is presented in a USA-CERL technical report (*4*).

BACKGROUND

Commercial railroads are governed by the safety inspection requirements of the FRA (*5*). Individual railroad companies may also have their own inspection procedures for locating defects for maintenance planning. However, U.S. Army track networks do not fall under the auspices of the FRA, nor do Army track inspectors. Because of their varied duties and responsibilities, these Army track inspectors also do not have the same intimate knowledge of their networks as do track section foremen, track inspectors, and road masters in the commercial sector. Until recently, the Army's approach to track safety and track maintenance management was not very structured. Army track was divided into just two components for maintenance management—ties and trackage—and track inspection procedures were only generally described (*6*). Also, inspection intervals tended to be infrequent.

To facilitate efficient maintenance management of Army track and safe railroad operations, the Army has developed RAILER and issued detailed track maintenance standards (*7*). The standards serve the dual function of ensuring safety and identifying maintenance needs. The safety aspects are covered through the inspection frequency and the imposing of operating restrictions associated with certain defects. These operating restrictions are 10 mph, 5 mph, and "No Operations." Maintenance needs are determined through specific defect identification. Accordingly, the track standards provide a fundamental basis for track inspection and evaluation.

Many of the decision support tasks that RAILER is designed to perform require an assessment of track conditions, current and future. These conditions are determined by inspection with respect to the new Army Track Standards. While these standards are quite precise, they do not delineate specific inspection procedures. Such procedures were developed for RAILER. The inspection procedures outlined in this paper expand on and modify the previously documented interim detailed inspection procedures (*1*, *2*).

INSPECTION PROCEDURE CHARACTERISTICS

The RAILER detailed inspection procedures were developed primarily to fulfill two interrelated tasks. The first is to promote safe Army railroad operations by incorporating the technical aspects of the U.S. Army Track Standards into practical procedures. Second, the procedures provide a means for capturing the defect information in a format that facilitates use within the RAILER system for track maintenance management. The inspection procedures have the following characteristics:

D. G. Brown, 3209 Ridgewood Drive, Champaign, Ill. 61821. D. R. Uzarski and R. W. Harris, U.S. Army Construction Engineering Research Laboratory, P.O. Box 4005, Champaign, Ill. 61824.

- The inspection procedures are divided into component areas consistent with the Army Track Standards and the RAILER inventory data elements (*8*).
- Thorough detailed field inspection forms are used to guide the inspector through the inspection of each component area.
- Procedures are included for dealing with track components that are hidden, such as by vegetation or road crossings.
- Although the inspection procedures are designed to capture all discrepancies with the Army Track Standards, the procedures are at the same time flexible and thorough enough to support other track standards (such as those propagated by the FRA).
- The inspection procedures take advantage of the RAILER computer software to ease the burden of the inspector.

These interrelated characteristics are discussed more fully in the following subsections.

Inspection Component Areas

For convenience, the inspection procedures are divided into six track component areas:

1. Tie inspection;
2. Vegetation inspection;
3. Rail and joint inspection;
4. Other track components inspection;
5. Turnout inspection; and
6. Track geometry inspection.

The components included in "Other track components" are the bridge approach, ballast/subgrade, car bumper, car stop, culvert, ditch, derail, drain, embankment, grade crossing, gage rod, hold down device, insulated component, rail anchor, rail crossing, signals, signs, shim, spike, storm sewer, and tie plate.

The inspection procedures primarily consist of specific visual observations and manual measurements of the track structure, which may be augmented by automated data collection for track geometry and for rail and joint defects. A complete regular manual inspection would include the first five component areas; manual track geometry inspection is usually conducted only when there are specific indications of potential problems. (Examples of these indications include visual observations and reports of rough riding from the engine crew.)

The segmentation of the inspection process by component areas permits significant flexibility. For example, a track may be inspected for only one or two components, or all components, depending on the purpose of the inspection. This flexibility also allows the order in which component areas and track segments are inspected to be tailored for the particular network layout. Such an inspection plan is illustrated in Figure 1. For example, with a single isolated loading track, it may be advantageous to inspect some components in one direction and other components while walking back. However, with two parallel loading tracks, it may be better to inspect some or all components of one track in one direction and the same components of the other track while walking back.

Field Inspection Forms

The inspection process is organized around five field inspection forms. One of these forms deals with three component areas: ties, vegetation, and rail and joints. A completed example of this form is presented in Figure 2.

These forms are designed to guide the inspector through a structured inspection process. This is especially well illustrated by the turnout inspection form (see Figure 3). Mastering the inspection procedure associated with using this form requires a minimal amount of training, despite the large amount of information that is collected. In this case, the four blocks on the form lead the inspector through the inspection; the inspector simply has to fill in the various blanks and circle the appropriate responses.

The other inspection forms are presented in an abbreviated fashion in Figures 4 through 6. The form depicted in Figure 4 can be used to continue the visual rail and joint inspection (see Figure 2) or for automated rail inspection. Because many rail defects are not visible (and hence can only be detected with specialized equipment), the continuation form depicted in Figure 4 lists more rail and joint defects than the form depicted in Figure 2. When used with automated rail inspection, the continuation form serves as a data transfer medium between the commercially prepared report (list of defects) and RAILER.

The track geometry inspection form (see Figure 5) is generally only used for manual inspection. Automatically collected track geometry data can be transferred directly from the geometry test equipment onto floppy disks for processing within the RAILER system.

Explanation of Field Inspection Forms

Explanations for some completed example field inspection forms (Figures 2–6) follow.

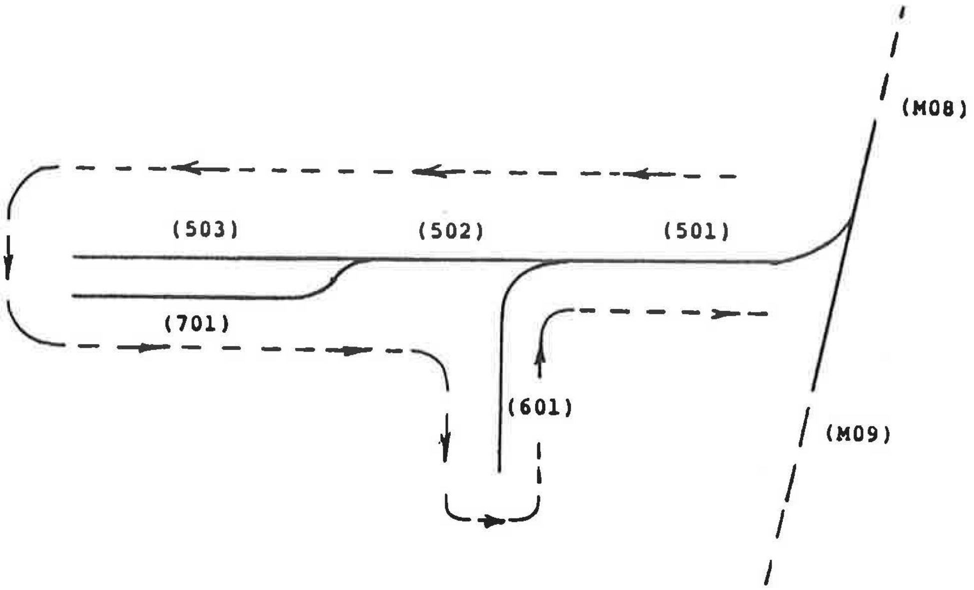
Tie Inspection (Figure 2)

- In the column for Inspection Impaired by Vegetation or Other Material, the inspector has entered four lengths of track where tie inspection was impaired. The lengths were 10, 30, 70, and 25 ft, respectively. Addition (+) signs are used to separate the lengths. The lengths are then totaled below (135 ft).
- The various tie defects are delineated in the columns. Hash marks are used to note defects and then totaled.

Vegetation Inspection (Figure 2)

Vegetation growth is noted in feet of affected track. Results of the vegetation inspection were as follows:

- There were four occurrences of low severity (Growing in Ballast, Interferes with Walking, etc.) vegetation growth. The occurrences were 10, 50, 20, and 200 ft in length, for a total of 280 ft.
- A 50-ft length of vegetation growth prevented track inspection.
- No vegetation growth serious enough to interfere with train movements was found.



Inspection Plan for Tracks 5, 6, and 7

Segment	Component Areas
501	Ties and Other Track Components
502	Ties and Other Track Components
503	All Components
701	All Components
502	Vegetation and Rail and Joints
601	Ties and Other Track Components
601	Vegetation and Rail and Joints
501	Vegetation and Rail and Joints

FIGURE 1 Example of inspection plan.

Rail and Joint Inspection (Figure 2)

Rail and joint inspection found the following defects:

- All bolts were loose (ABL) in a joint in the left rail at Station 1+00.
- The end batter (ENB) at joints was greater than ¼ in. in both rails starting at Station 1+00 and continuing over 10 joints.
- There was a broken or cracked joint bar (BCB) in the right rail at Station 2+20.
- Some joints had improper bolt pattern (IBP). Starting at Station 2+50 and continuing for 200 ft, about 50 percent of the joints had the improper pattern.
- Several lengths of inspection impairment were noted. Inspection was impaired for one quarter (one side of one rail) for an 8-ft length. For two-, three-, and four-quarters coverage, the lengths of impairment were 6, 8, and 4 ft, respectively. The line totals are then multiplied by the quarters of coverage to get the quarter lengths (Q.L.). The quarter lengths are then summed and divided by 4, which gives the equivalent length of complete inspection impairment.

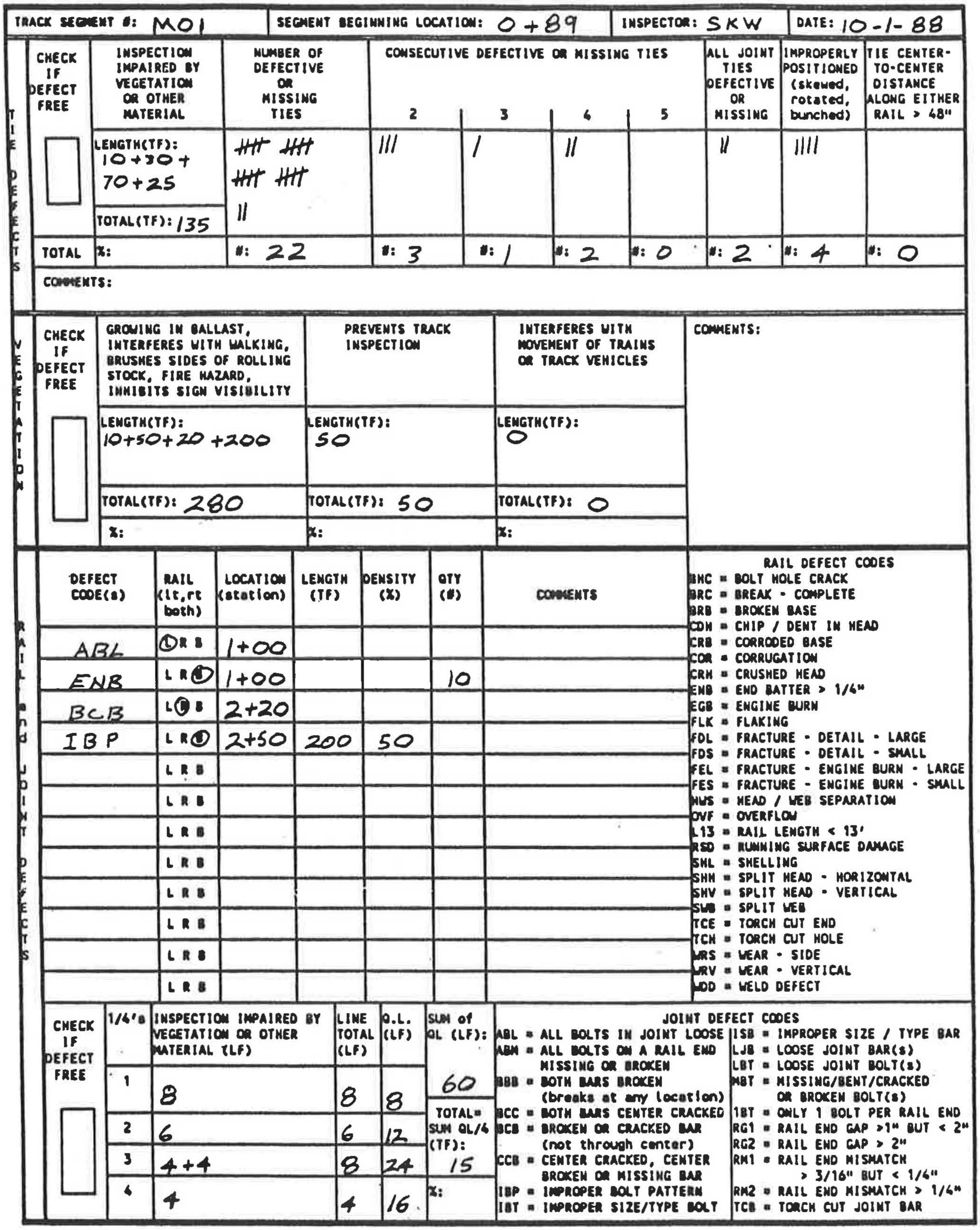
Track Geometry Inspection (Figure 5)

Results of the track geometry inspection were as follows:

- In Segment 101, Station 5+50, the gage is 57.8 in.
- In Segment 101, Station 7+00, the crosslevel is +1.5 in. (using the left rail as reference), the alignment is 0.5 in. in both the left and right rails, the profile of the left rail is 1.1 in., and the profile of the right rail is 0.5 in.
- In Segment 101, Station 7+05, the crosslevel is +0.5 in. (using the left rail as reference).
- In Segment 102, Station 9+00, the alignment of the left rail is 1.1 in., and the profile of the left rail is 1.5 in.
- In Segment 102, Station 10+50 (in Curve 1C1), the gage is 56.7 in., the crosslevel is +2.0 in. (using the left rail as the reference), the left alignment is 4.0 in., and the right alignment is 4.0 in.

Other Track Components Inspection (Figure 6)

Other track components inspection found the following defects and measurements:



TRACK SEGMENT #: MO1 | **SEGMENT BEGINNING LOCATION:** 0+89 | **INSPECTOR:** SKW | **DATE:** 10-1-88

TIE DEFECTS

CHECK IF DEFECT FREE	INSPECTION IMPAIRED BY VEGETATION OR OTHER MATERIAL	NUMBER OF DEFECTIVE OR MISSING TIES	CONSECUTIVE DEFECTIVE OR MISSING TIES 2	3	4	5	ALL JOINT TIES DEFECTIVE OR MISSING	IMPROPERLY POSITIONED (skewed, rotated, bunched)	TIE CENTER-TO-CENTER DISTANCE ALONG EITHER RAIL > 48"
☐	LENGTH(TF): 10+30+ 70+25	~~||||~~ ~~||||~~ ~~||||~~ ~~||||~~ ||	|||	|	||		||	||||	
	TOTAL(TF): 135								
TOTAL	%:	#: 22	#: 3	#: 1	#: 2	#: 0	#: 2	#: 4	#: 0

COMMENTS:

VEGETATION

CHECK IF DEFECT FREE	GROWING IN BALLAST, INTERFERES WITH WALKING, BRUSHES SIDES OF ROLLING STOCK, FIRE HAZARD, INHIBITS SIGN VISIBILITY	PREVENTS TRACK INSPECTION	INTERFERES WITH MOVEMENT OF TRAINS OR TRACK VEHICLES	COMMENTS:
☐	LENGTH(TF): 10+50+20 +200	LENGTH(TF): 50	LENGTH(TF): 0	
	TOTAL(TF): 280	TOTAL(TF): 50	TOTAL(TF): 0	
	%:	%:	%:	

RAIL and JOINT DEFECTS

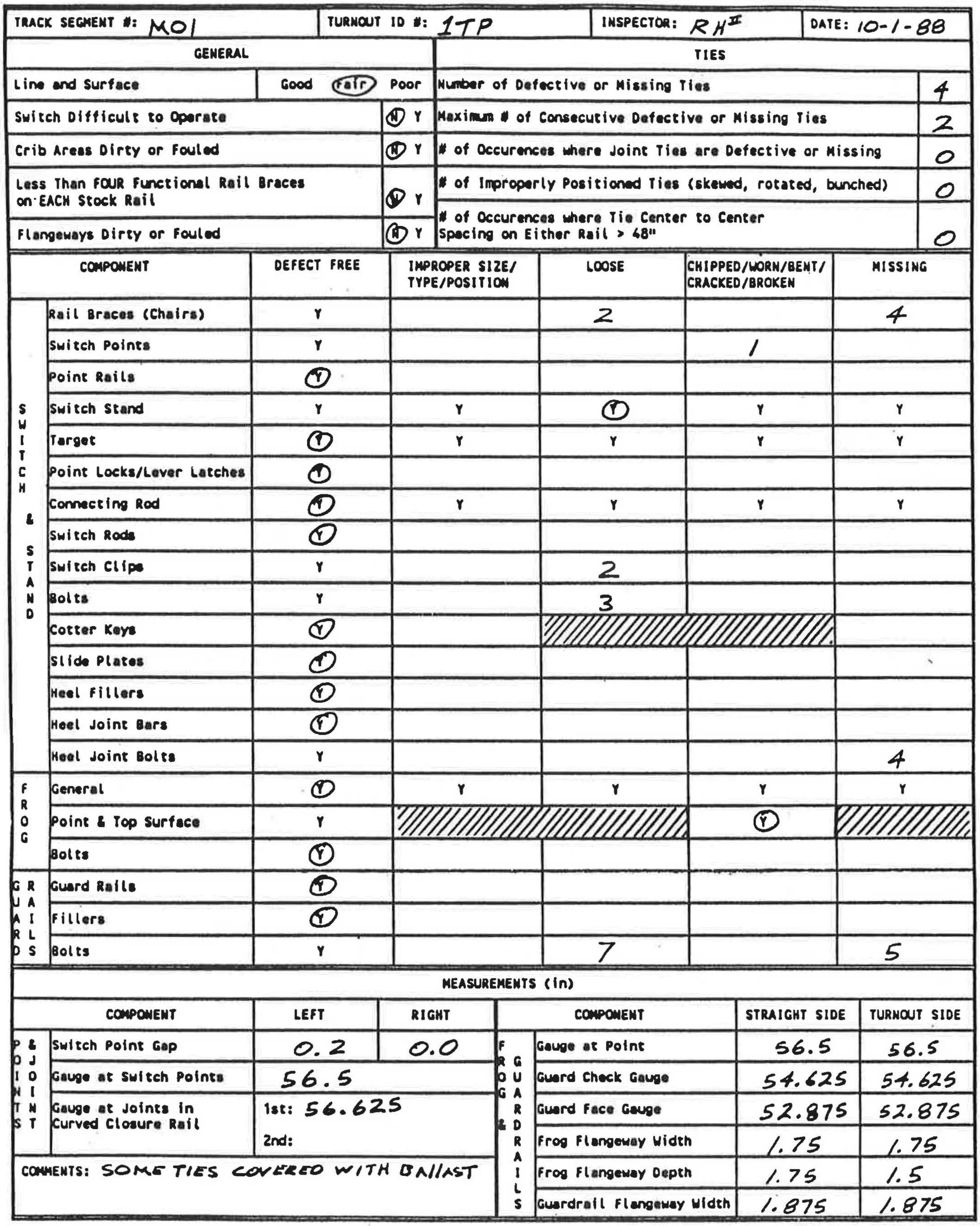
DEFECT CODE(s)	RAIL (lt,rt both)	LOCATION (station)	LENGTH (TF)	DENSITY (%)	QTY (#)	COMMENTS
ABL	[✓ L] R B	1+00				
ENB	L R [✓ B]	1+00			10	
BCB	L [✓ R] B	2+20				
IBP	L R [✓ B]	2+50	200	50		
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					

RAIL DEFECT CODES
BHC = BOLT HOLE CRACK
BRC = BREAK - COMPLETE
BRB = BROKEN BASE
CDH = CHIP / DENT IN HEAD
CRB = CORRODED BASE
COR = CORRUGATION
CRH = CRUSHED HEAD
ENB = END BATTER > 1/4"
EGB = ENGINE BURN
FLK = FLAKING
FDL = FRACTURE - DETAIL - LARGE
FDS = FRACTURE - DETAIL - SMALL
FEL = FRACTURE - ENGINE BURN - LARGE
FES = FRACTURE - ENGINE BURN - SMALL
HWS = HEAD / WEB SEPARATION
OVF = OVERFLOW
L13 = RAIL LENGTH < 13'
RSD = RUNNING SURFACE DAMAGE
SHL = SHELLING
SHH = SPLIT HEAD - HORIZONTAL
SHV = SPLIT HEAD - VERTICAL
SWB = SPLIT WEB
TCE = TORCH CUT END
TCH = TORCH CUT HOLE
WRS = WEAR - SIDE
WRV = WEAR - VERTICAL
WDD = WELD DEFECT

CHECK IF DEFECT FREE	1/4's	INSPECTION IMPAIRED BY VEGETATION OR OTHER MATERIAL (LF)	LINE TOTAL (LF)	Q.L. (LF)	SUM of QL (LF):
☐	1	8	8	8	60
	2	6	6	12	TOTAL= SUM QL/4 (TF): 15
	3	4+4	8	24	
	4	4	4	16	%:

JOINT DEFECT CODES
ABL = ALL BOLTS IN JOINT LOOSE
ABM = ALL BOLTS ON A RAIL END MISSING OR BROKEN
BBB = BOTH BARS BROKEN (breaks at any location)
BCC = BOTH BARS CENTER CRACKED
BCB = BROKEN OR CRACKED BAR (not through center)
CCB = CENTER CRACKED, CENTER BROKEN OR MISSING BAR
IBP = IMPROPER BOLT PATTERN
IBT = IMPROPER SIZE/TYPE BOLT
ISB = IMPROPER SIZE / TYPE BAR
LJB = LOOSE JOINT BAR(s)
LBT = LOOSE JOINT BOLT(s)
MBT = MISSING/BENT/CRACKED OR BROKEN BOLT(s)
1BT = ONLY 1 BOLT PER RAIL END
RG1 = RAIL END GAP >1" BUT < 2"
RG2 = RAIL END GAP > 2"
RM1 = RAIL END MISMATCH > 3/16" BUT < 1/4"
RM2 = RAIL END MISMATCH > 1/4"
TCB = TORCH CUT JOINT BAR

FIGURE 2 Completed inspection form for ties, vegetation, and rail and joints.



TRACK SEGMENT #: MO1 | TURNOUT ID #: 1TP | INSPECTOR: RH^{II} | DATE: 10-1-88

GENERAL	
Line and Surface	Good [✓ Fair] Poor
Switch Difficult to Operate	[✓ N] Y
Crib Areas Dirty or Fouled	[✓ N] Y
Less Than FOUR Functional Rail Braces on EACH Stock Rail	[✓ N] Y
Flangeways Dirty or Fouled	[✓ N] Y

TIES	
Number of Defective or Missing Ties	4
Maximum # of Consecutive Defective or Missing Ties	2
# of Occurences where Joint Ties are Defective or Missing	0
# of Improperly Positioned Ties (skewed, rotated, bunched)	0
# of Occurences where Tie Center to Center Spacing on Either Rail > 48"	0

	COMPONENT	DEFECT FREE	IMPROPER SIZE/ TYPE/POSITION	LOOSE	CHIPPED/WORN/BENT/ CRACKED/BROKEN	MISSING
SWITCH & STAND	Rail Braces (Chairs)	Y		2		4
	Switch Points	Y			1	
	Point Rails	[✓ Y]				
	Switch Stand	Y	Y	[✓ Y]	Y	Y
	Target	[✓ Y]	Y	Y	Y	Y
	Point Locks/Lever Latches	[✓ Y]				
	Connecting Rod	[✓ Y]	Y	Y	Y	Y
	Switch Rods	[✓ Y]				
	Switch Clips	Y		2		
	Bolts	Y		3		
	Cotter Keys	[✓ Y]		▨	▨	
	Slide Plates	[✓ Y]				
	Heel Fillers	[✓ Y]				
	Heel Joint Bars	[✓ Y]				
	Heel Joint Bolts	Y				4
FROG	General	[✓ Y]	Y	Y	Y	Y
	Point & Top Surface	Y	▨	▨	[✓ Y]	▨
	Bolts	[✓ Y]				
GUARD RAILS	Guard Rails	[✓ Y]				
	Fillers	[✓ Y]				
	Bolts	Y		7		5

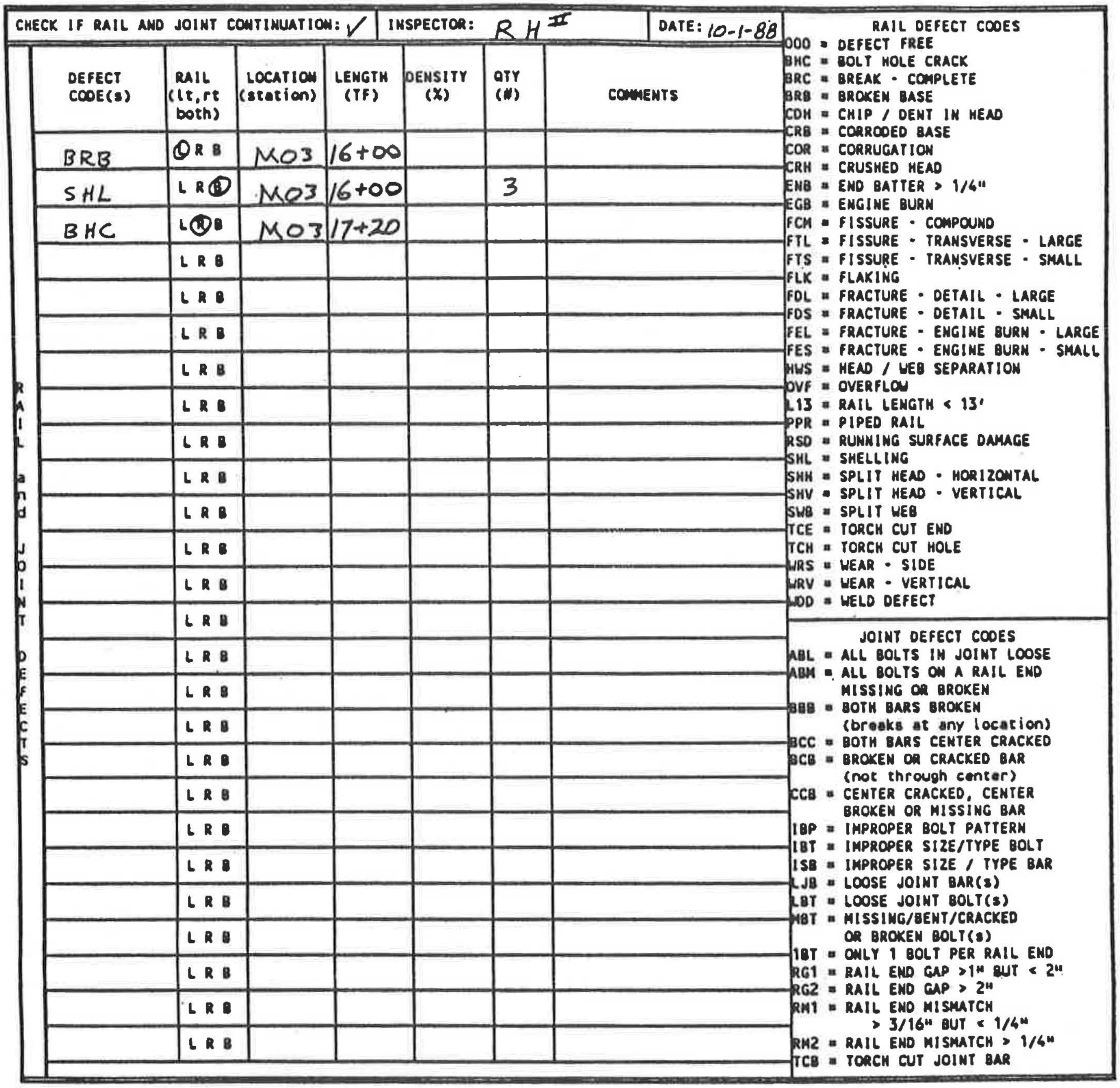
MEASUREMENTS (in)

	COMPONENT	LEFT	RIGHT
POINTS & JOINTS	Switch Point Gap	0.2	0.0
	Gauge at Switch Points	56.5	
	Gauge at Joints in Curved Closure Rail	1st: 56.625 2nd:	

	COMPONENT	STRAIGHT SIDE	TURNOUT SIDE
FROG & GUARDRAILS	Gauge at Point	56.5	56.5
	Guard Check Gauge	54.625	54.625
	Guard Face Gauge	52.875	52.875
	Frog Flangeway Width	1.75	1.75
	Frog Flangeway Depth	1.75	1.5
	Guardrail Flangeway Width	1.875	1.875

COMMENTS: SOME TIES COVERED WITH BAllAST

FIGURE 3 Completed turnout inspection form.



CHECK IF RAIL AND JOINT CONTINUATION: ✓ INSPECTOR: RH II DATE: 10-1-88

RAIL and JOINT DEFECTS

DEFECT CODE(s)	RAIL (lt,rt both)	LOCATION (station)	LENGTH (TF)	DENSITY (%)	QTY (#)	COMMENTS
BRB	[✓ L] R B	M03	16+00			
SHL	L R [✓ B]	M03	16+00		3	
BHC	L [✓ R] B	M03	17+20			
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					
	L R B					

RAIL DEFECT CODES

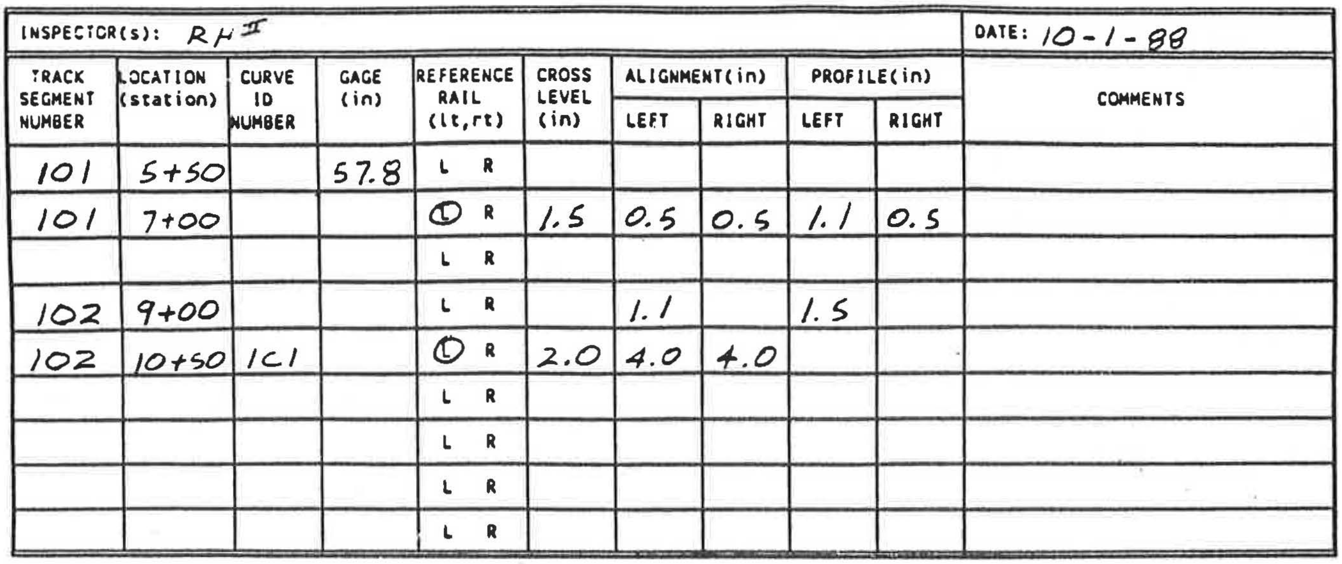
000 = DEFECT FREE
BHC = BOLT HOLE CRACK
BRC = BREAK - COMPLETE
BRB = BROKEN BASE
CDH = CHIP / DENT IN HEAD
CRB = CORRODED BASE
COR = CORRUGATION
CRH = CRUSHED HEAD
ENB = END BATTER > 1/4"
EGB = ENGINE BURN
FCM = FISSURE - COMPOUND
FTL = FISSURE - TRANSVERSE - LARGE
FTS = FISSURE - TRANSVERSE - SMALL
FLK = FLAKING
FDL = FRACTURE - DETAIL - LARGE
FDS = FRACTURE - DETAIL - SMALL
FEL = FRACTURE - ENGINE BURN - LARGE
FES = FRACTURE - ENGINE BURN - SMALL
HWS = HEAD / WEB SEPARATION
OVF = OVERFLOW
L13 = RAIL LENGTH < 13'
PPR = PIPED RAIL
RSD = RUNNING SURFACE DAMAGE
SHL = SHELLING
SHH = SPLIT HEAD - HORIZONTAL
SHV = SPLIT HEAD - VERTICAL
SWB = SPLIT WEB
TCE = TORCH CUT END
TCH = TORCH CUT HOLE
WRS = WEAR - SIDE
WRV = WEAR - VERTICAL
WDD = WELD DEFECT

JOINT DEFECT CODES

ABL = ALL BOLTS IN JOINT LOOSE
ABM = ALL BOLTS ON A RAIL END MISSING OR BROKEN
BBB = BOTH BARS BROKEN (breaks at any location)
BCC = BOTH BARS CENTER CRACKED
BCB = BROKEN OR CRACKED BAR (not through center)
CCB = CENTER CRACKED, CENTER BROKEN OR MISSING BAR
IBP = IMPROPER BOLT PATTERN
IBT = IMPROPER SIZE/TYPE BOLT
ISB = IMPROPER SIZE / TYPE BAR
LJB = LOOSE JOINT BAR(s)
LBT = LOOSE JOINT BOLT(s)
MBT = MISSING/BENT/CRACKED OR BROKEN BOLT(s)
1BT = ONLY 1 BOLT PER RAIL END
RG1 = RAIL END GAP >1" BUT < 2"
RG2 = RAIL END GAP > 2"
RM1 = RAIL END MISMATCH > 3/16" BUT < 1/4"
RM2 = RAIL END MISMATCH > 1/4"
TCB = TORCH CUT JOINT BAR

FIGURE 4 Completed rail and joint inspection continuation form.

- The ballast (component code: BS) is dirty (defect code: BAD) starting at Station 0+00 and continuing for 100 ft. This is not an immediate hazard.
- A culvert (CU) is clogged so that flow is obstructed (OBF). The culvert is a discrete item located at Station 0+50. This is not an immediate hazard.
- Three gage rods (GR) are loose (LOS). The first loose gage rod is located at Station 0+90. This is not an immediate hazard.
- Some spikes (SP) are improperly positioned (IMP) because of an improper spike pattern. Starting at Station 1+40 and continuing for 200 ft, about 50 percent of the spikes are improperly positioned. This is not an immediate hazard.
- A spike (SP) is missing (MIS) at Station 1+50. This is not an immediate hazard.
- An embankment (EM) is experiencing erosion (ERO) starting at Station 2+10 and continuing for 20 ft. This is not an immediate hazard.
- A culvert (CU) has suffered structural deterioration (STD). The culvert is located at Station 2+50. This defect is marked as an immediate hazard, and the comment indicates that the track has "settled badly," which could lead to unsafe car movement (e.g., rocking) if the track is used.

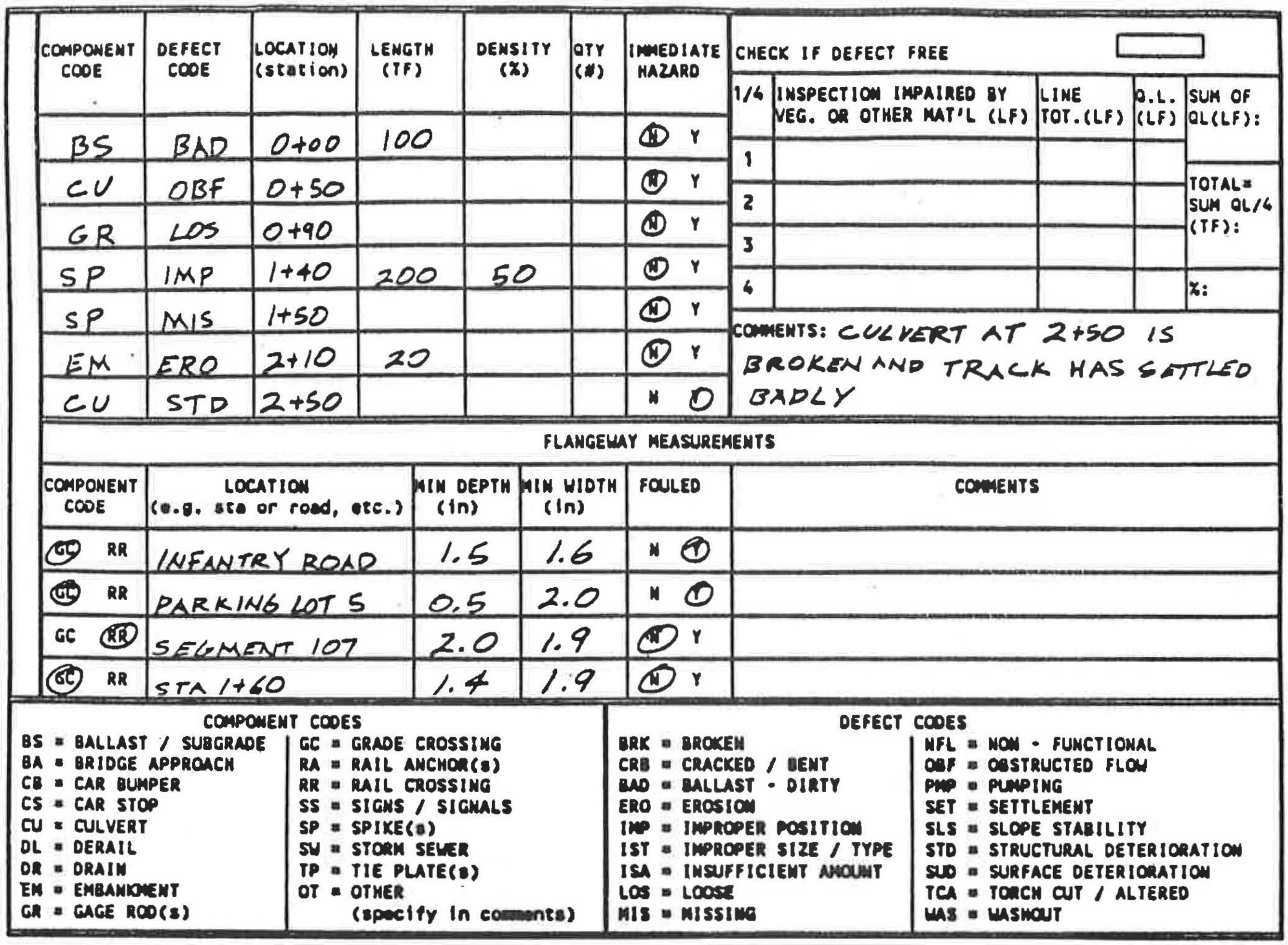


INSPECTOR(s): RH II

DATE: 10-1-88

TRACK SEGMENT NUMBER	LOCATION (station)	CURVE ID NUMBER	GAGE (in)	REFERENCE RAIL (lt,rt)	CROSS LEVEL (in)	ALIGNMENT(in)		PROFILE(in)		COMMENTS
						LEFT	RIGHT	LEFT	RIGHT	
101	5+50		57.8	L R						
101	7+00			[✓ L] R	1.5	0.5	0.5	1.1	0.5	
				L R						
102	9+00			L R		1.1		1.5		
102	10+50	1C1		[✓ L] R	2.0	4.0	4.0			
				L R						
				L R						
				L R						
				L R						

FIGURE 5 Completed track geometry inspection form.



COMPONENT CODE	DEFECT CODE	LOCATION (station)	LENGTH (TF)	DENSITY (%)	QTY (#)	IMMEDIATE HAZARD
BS	BAD	0+00	100			[✓ N] Y
CU	OBF	0+50				[✓ N] Y
GR	LOS	0+90				[✓ N] Y
SP	IMP	1+40	200	50		[✓ N] Y
SP	MIS	1+50				[✓ N] Y
EM	ERO	2+10	20			[✓ N] Y
CU	STD	2+50				N [✓ Y]

CHECK IF DEFECT FREE ☐

1/4	INSPECTION IMPAIRED BY VEG. OR OTHER MAT'L (LF)	LINE TOT.(LF)	Q.L. (LF)	SUM OF QL(LF):
1				
2				TOTAL= SUM QL/4 (TF):
3				
4				%:

COMMENTS: CULVERT AT 2+50 IS BROKEN AND TRACK HAS SETTLED BADLY

FLANGEWAY MEASUREMENTS

COMPONENT CODE	LOCATION (e.g. sta or road, etc.)	MIN DEPTH (in)	MIN WIDTH (in)	FOULED	COMMENTS
[✓ GC] RR	INFANTRY ROAD	1.5	1.6	N [✓ Y]	
[✓ GC] RR	PARKING LOT 5	0.5	2.0	N [✓ Y]	
GC [✓ RR]	SEGMENT 107	2.0	1.9	[✓ N] Y	
[✓ GC] RR	STA 1+60	1.4	1.9	[✓ N] Y	

COMPONENT CODES

BS = BALLAST / SUBGRADE
BA = BRIDGE APPROACH
CB = CAR BUMPER
CS = CAR STOP
CU = CULVERT
DL = DERAIL
DR = DRAIN
EM = EMBANKMENT
GR = GAGE ROD(s)
GC = GRADE CROSSING
RA = RAIL ANCHOR(s)
RR = RAIL CROSSING
SS = SIGNS / SIGNALS
SP = SPIKE(s)
SW = STORM SEWER
TP = TIE PLATE(s)
OT = OTHER (specify in comments)

DEFECT CODES

BRK = BROKEN
CRB = CRACKED / BENT
BAD = BALLAST - DIRTY
ERO = EROSION
IMP = IMPROPER POSITION
IST = IMPROPER SIZE / TYPE
ISA = INSUFFICIENT AMOUNT
LOS = LOOSE
MIS = MISSING
NFL = NON - FUNCTIONAL
OBF = OBSTRUCTED FLOW
PMP = PUMPING
SET = SETTLEMENT
SLS = SLOPE STABILITY
STD = STRUCTURAL DETERIORATION
SUD = SURFACE DETERIORATION
TCA = TORCH CUT / ALTERED
WAS = WASHOUT

FIGURE 6 Completed other track components inspection form.

- A grade crossing (component code: GC) that crosses Infantry Road has an effective minimum flangeway depth and width of 1.5 in. and 1.6 in., respectively. The flangeways are fouled.
- A grade crossing (GC) that crosses Parking Lot 5 has an effective minimum flangeway depth and width of 0.5 in. and 2.0 in., respectively. The flangeways are fouled.
- A rail crossing (RR) that crosses Segment 107 has an effective minimum flangeway depth and width of 2.0 in. and 1.9 in., respectively. The flangeways are not fouled.
- A grade crossing (GC) located at Track Station 4+60 has an effective minimum flangeway depth and width of 1.4 in. and 1.9 in., respectively. The flangeways are not fouled.

Impaired Track Inspection

Sometimes grade crossings or material, such as excessive ballast and vegetation, will interfere with track inspection. This can be a particular problem where seldom used tracks may be hidden by vegetation or other material and where significant track lengths may be paved (such as around warehouses and marshalling areas). If not properly accounted for, significant amounts of inspection-impaired track could cause profound overestimation of general track quality and consequent underestimation of necessary repair materials. This occurs when it is implicitly and erroneously assumed that defects not seen (and hence not recorded) do not exist. Furthermore, even a few linear feet of foreign material may hide serious defects affecting the safety of railroad operations.

Inspection-impaired track is accounted for separately within the RAILER detailed track inspection procedures for each of three component areas: ties, rail and joints, and other track components. These are separated for two reasons. First, foreign material that obscures one component might not impair the inspection of another component. For example, rail and joints can often be easily inspected when the ties are covered by ballast or soil. Second, the nature and extent of obscuring foreign material may change between the inspection of two component areas. For example, during the time between a tie inspection and an "other track components" inspection (which may be more than a month), gravel may have been accidentally spilled on the track, obscuring tie plates and spikes ("other track components").

Ties are considered inspection impaired if less than half of the top surface is visible. The other two component areas use the concept of quarters for inspection impairment. For example, if the base on one side of only one rail is covered, then rail and joint inspection is one-quarter impaired. At the other extreme, four-quarters inspection impairment occurs when the base on both sides of both rails is covered. Quarters of inspection impairment are also used with "other track components"; the only difference is that the inspection impairment criterion is whether or not the spike heads are visible (instead of the rail base).

For each of the three component areas, obscuring foreign material is accounted for in terms of (equivalent) linear track feet and percentage of track length. These are calculated within the RAILER computer software based on data collected in the field during track inspection and can also be calculated manually if RAILER is not computer implemented. The field entries associated with inspection-impaired track are illustrated in Figure 2.

In addition to undesirable foreign material, grade crossings (paved areas) also obscure track inspection. Grade crossing length is a RAILER inventory data element. This data element is used within the RAILER software to account for the effect of grade crossings on track inspection. For this reason, the inspection impairment associated with grade crossings can be ignored during track inspection field procedures if RAILER is computer implemented. Otherwise, the effect of grade crossings is accounted for in the field in conjunction with undesirable foreign material.

This process quantifies, for each of the three component areas, the amount of track that cannot be properly inspected. Procedures for using this information to estimate the hidden defects are still under development.

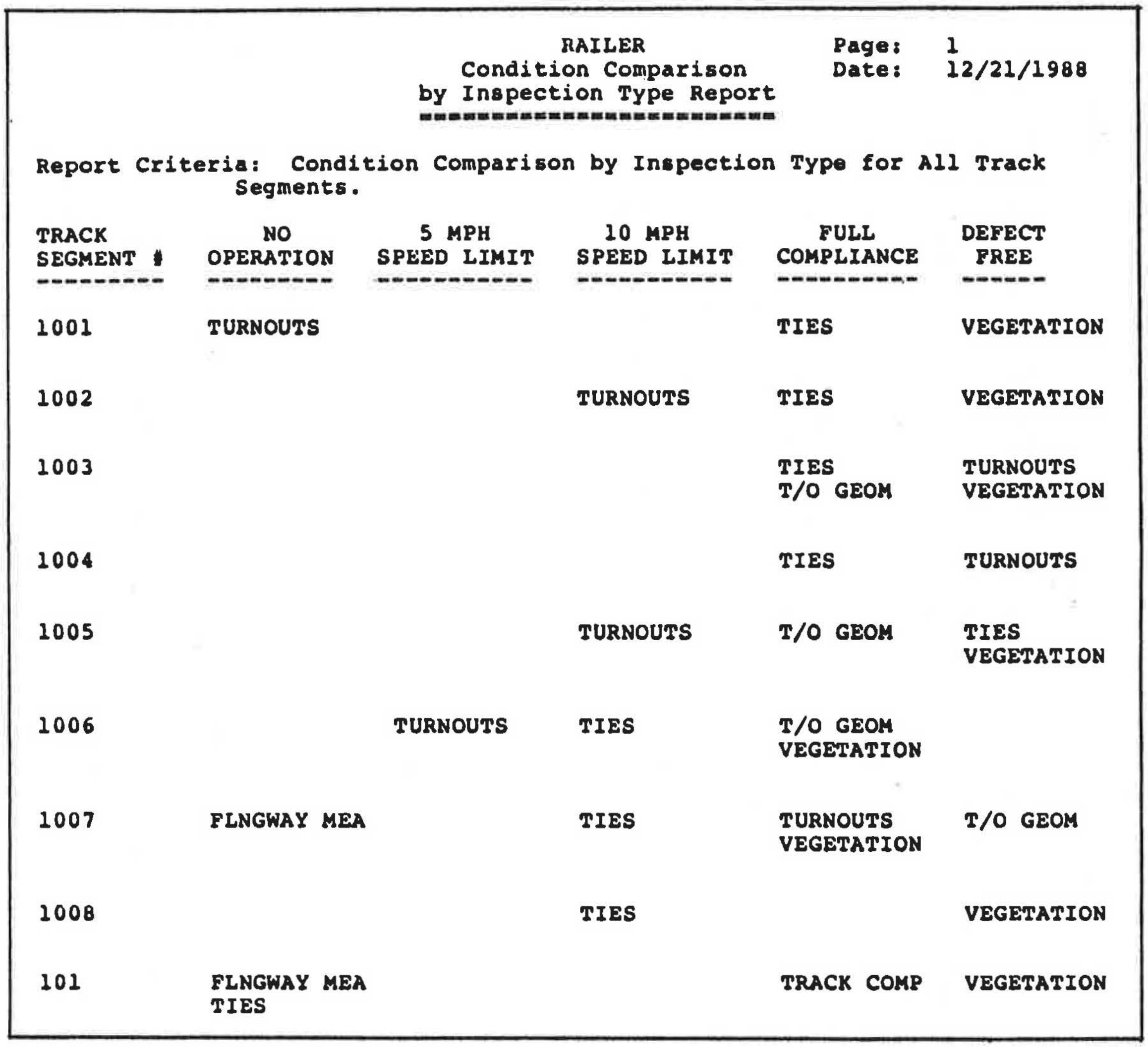
Relationship to Track Standards

Track maintenance or safety standards describe desired or acceptable track conditions. In addition, track standards may indicate the relative severity of various deviations from these acceptable track conditions (as the Army standards do).

The first immediate goal of the detailed inspection procedures described here is implementing the Army Track Standards in a manner consistent with the RAILER program. However, RAILER is also designed to accommodate other track standards. For example, a version of RAILER is being developed for the U.S. Army in Europe that will incorporate German Track Standards. Also, it is envisioned that RAILER will be eventually transferred to the civilian/private sector for use by short lines, industrial networks, and possibly some branch line operations. These operators may wish to incorporate FRA or their own track standards.

In order to accommodate this flexibility, the inspection procedures are designed (as much as possible) to collect raw data, which are later compared within the computer with the appropriate standards (or possibly multiple standards). For example, instances of three consecutive defective ties are noted as raw data during tie inspection (see Figure 2). This defect implies a 10-mph operating restriction in the Army Track Standards. However, in some industrial situations, such as in a steel mill operation where eight-axle ladle cars regularly carry molten iron, management could elect to impose a more restrictive 5-mph limit, or perhaps prohibit all train movements, whenever three consecutive defective ties are encountered.

The analysis of the inspection data relative to a given set of track standards is provided in three RAILER "Comparison Reports" that vary in their level of detail. These are a Condition Summary, a Condition Comparison by Inspection Type (component area), and a Detailed Comparison. An example of the Condition Comparison by Inspection Type report is presented in Figure 7. The comparison results can be tied to a locally developed maintenance policy so that a Maintenance and Repair (M&R) report can be generated for work planning. This report can be generated in two levels of detail, an M&R Summary and a Detailed M&R. An example of the summary level is presented in Figure 8.



```
                                     RAILER             Page:   1
                              Condition Comparison      Date:   12/21/1988
                           by Inspection Type Report
                           =========================

Report Criteria:  Condition Comparison by Inspection Type for All Track
              Segments.

TRACK           NO         5 MPH       10 MPH          FULL      DEFECT
SEGMENT #   OPERATION   SPEED LIMIT   SPEED LIMIT   COMPLIANCE    FREE
---------   ---------   -----------   -----------   ----------   ------

1001        TURNOUTS                                TIES         VEGETATION


1002                                  TURNOUTS      TIES         VEGETATION


1003                                                TIES         TURNOUTS
                                                    T/O GEOM     VEGETATION


1004                                                TIES         TURNOUTS


1005                                  TURNOUTS      T/O GEOM     TIES
                                                                 VEGETATION


1006                    TURNOUTS      TIES          T/O GEOM
                                                    VEGETATION


1007        FLNGWAY MEA               TIES          TURNOUTS     T/O GEOM
                                                    VEGETATION


1008                                  TIES                       VEGETATION


101         FLNGWAY MEA                             TRACK COMP   VEGETATION
            TIES
```

FIGURE 7 Condition Comparison by Inspection Type report.

Use of a Computer to Simplify Inspection Procedures

Inspecting for all the defects specified in the Army Track Standards is a significant task. Therefore, an important consideration in developing these inspection procedures was easing, as much as possible, the burden of the inspector. This was accomplished in several ways, including, as discussed previously, in the design of the inspection forms.

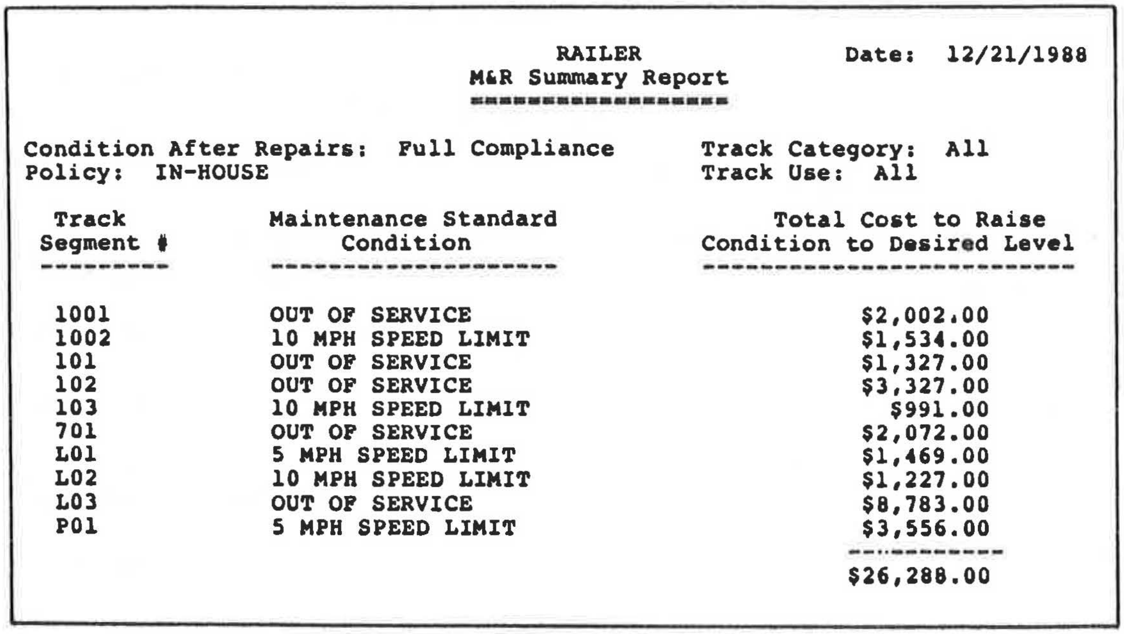
The RAILER computer software provides another means to this end. The focus on collecting raw data (as discussed previously) is an important example. This is especially true of measurements such as those obtained during turnout inspection (see lower portion of form presented in Figure 3). The inspector does not need to know the acceptable value ranges and the cut-off points for different operating restrictions (severity levels). The inspector only needs to properly make the measurement(s) and enter the values on the form. These values are later compared with the standards, either in the computer or by hand if RAILER is not computer implemented.

The computer software is also designed to prevent the entry of some obviously inconsistent defect combinations such as rail anchors that are pumping (see in Figure 6 Component Code RA and Defect Code PMP). This increases the reliability of the inspection process.

SHORT-LINE APPLICABILITY

Potential technical transfer to the civilian sector is an important consideration in research conducted by the federal government. Early in the development of RAILER, it was observed that many characteristics associated with Army track maintenance management are also true for commercial short lines and industrial networks. These common characteristics include general track quality, service levels and types of operations, and the availability of local expertise.

Therefore, potential use by short lines was a strong consideration throughout the development of RAILER. This was partially accomplished by introducing into RAILER the necessary flexibility to accommodate those areas in which the Army's needs are not completely consistent with those of potential civilian users. An example of this flexibility is the ability to develop within RAILER customized track standards



```
                                    RAILER              Date:  12/21/1988
                               M&R Summary Report
                               ==================

Condition After Repairs:  Full Compliance       Track Category:  All
Policy:  IN-HOUSE                               Track Use:  All

  Track          Maintenance Standard             Total Cost to Raise
 Segment #           Condition                 Condition to Desired Level
 ---------       ---------------------         ---------------------------

  1001           OUT OF SERVICE                            $2,002.00
  1002           10 MPH SPEED LIMIT                        $1,534.00
  101            OUT OF SERVICE                            $1,327.00
  102            OUT OF SERVICE                            $3,327.00
  103            10 MPH SPEED LIMIT                          $991.00
  701            OUT OF SERVICE                            $2,072.00
  L01            5 MPH SPEED LIMIT                         $1,469.00
  L02            10 MPH SPEED LIMIT                        $1,227.00
  L03            OUT OF SERVICE                            $8,783.00
  P01            5 MPH SPEED LIMIT                         $3,556.00
                                                          ----------
                                                          $26,288.00
```

FIGURE 8 Maintenance and Repair Summary report.

as discussed previously. The RAILER detailed inspection procedures provide the same benefits for short-line users, as they do for Army users.

FIELD TESTING

The detailed inspection procedures described here have been under development for over 3 years. They have evolved into their present form with the concurrent development of the Army Track Standards. Both involved considerable revision during their history. The development was an iteration process; needed information was ascertained, procedures were then developed to collect the information, these procedures were field tested, and revisions were made. The overall goal was to be able to easily collect the necessary information with trained installation track inspectors.

Many weeks were spent in the field testing the procedures. Teams were sent to the Tooele Army Depot, Utah; Ft Devens, Massachusetts; Ft Stewart, Georgia; and Hunter Army Airfield, Georgia. Additionally, the Urbana, Illinois, yard of the Consolidated Rail Corporation (Conrail) served as a local site. Generally, data collection procedures were first developed in the laboratory and tested locally. Then, field trips to the installations were scheduled to uncover procedural shortcomings. The various locations were chosen to provide the great variety of operating, climatic, and maintenance differences that were needed to properly test and evaluate the data collection procedures. Also, the field work permitted the researchers to test the practical requirements of the Army Track Standards. Feedback to the developers of the standards resulted in some changes. Those, in turn, resulted in inspection changes and data collection modifications.

The field work has shown that inspection productivity rates are strongly dependent on the condition of the track (i.e., the more defects there are, the longer the inspection takes). The inspections may only progress at a slow walking pace. This is because many of the defects are quite finite and require acute attention to be observed. Also, for the same reason, it was found that it can be nearly impossible for a single inspector to inspect all of the components concurrently. In fact, it may take up to three passes of the track by one inspector to note all of the defects for all of the components. The track can be inspected by one person, but a team of two significantly improves the efficiency; it can be nearly impossible for one person to perform certain manual track geometry inspection tasks.

Based on the range of conditions found at the various installations, one inspector could completely inspect, on foot, approximately 0.3 mi/hr. Turnouts take approximately 15 min each to inspect (time actually spent at the turnout). These are average rates and include allowance for nonproductive walking time (time lost walking back from the end of a terminating track at the completion of an inspection). They do not include travel time to and from the network portion being inspected.

A two-person inspection team was found to be able to inspect at a rate of approximately 0.8 mi/hr. Turnout inspection can be reduced to approximately 8 min.

None of the above productivity rates includes time for manual track geometry measurements.

Track inspection from a moving track vehicle, even at slow speeds (<5 mph), resulted in a number of missed defects.

CONCLUSIONS AND RECOMMENDATIONS

The detailed inspection procedures described in this report were developed for use within the RAILER system. The inspection data collection forms were developed to facilitate relative ease in data collection and recording, as well as eventual loading into installation RAILER data bases for processing and analysis. Testing has shown that this has been accomplished.

These same detailed inspection procedures were designed to satisfy the requirements of the Army Track Standards. The methods and procedures described in this report can be used to satisfy the inspection requirements of those track standards.

Also, these inspections are currently intended to satisfy several maintenance management requirements at both the network and project levels (*1*, *2*). At the network level, these include identifying safety problems, assessing conditions, developing long-range work plans, budgeting, and prioritizing work for the entire network. Project-level management focuses on specific track segments and includes quantifying work needs associated with preparing job orders and contracts, determining the cause of the track problems, and selecting the most feasible M&R alternative.

The detailed track inspection procedures are explicitly designed to provide the information required for project-level management, in which detail becomes very important. However, much of that detailed information is not needed for network-level management tasks. Network-level management tasks are performed at least annually, whereas project-level tasks are performed only when and where needed. Thus, most management tasks are at the network level.

The authors believe that management needs should dictate data requirements, not vice versa. Specific information should be collected only when needed to satisfy management needs. Accordingly, simplified track inspection procedures are being formulated as part of the Track Structure Condition Index (TSCI) development currently under way at USA-CERL. The TSCI will measure the "health" of both individual track segments and the overall network. This measure will be the prime tool for network-level management tasks. The new simplified inspection procedures will capture just enough information to perform those tasks, yet at the same time be sensitive enough to identify critical defects requiring immediate attention for safety reasons. The spirit and intent of the Army Track Standards will still be met. A tangible benefit consisting of a significant reduction in inspector hours would result. The detailed inspection procedures described in this report would be reserved for project-level management tasks.

ACKNOWLEDGMENTS

The authors would like to acknowledge members of the U.S. Army Pavement and Railroad Maintenance Committee, chaired by the RAILER system project sponsor, Robert Williams, from the U.S. Army Engineering and Housing Support Center, for their significant contributions to the development of the RAILER detailed inspection procedures. The cooperation of Conrail for the ongoing use of their Urbana, Illinois, yard is greatly appreciated.

Special appreciation goes to the group at USA-CERL who worked on these procedures. Thanks go especially to Don Plotkin, who contributed much to the early development of these procedures and was a codeveloper of the Army Track Standards. Thanks also go to Debra Piland, Mike Britton, and Joshua Crowder for coordinating the relationship between the inspection procedures and the RAILER computer software. The efforts of David Coleman from the U.S. Army Waterways Experiment Station in codeveloping the Army Track Standards are also acknowledged.

REFERENCES

1. D. R. Uzarski, D. E. Plotkin, and D. G. Brown. *The RAILER System for Maintenance Management of U.S. Army Railroad Networks: RAILER I Description and Use.* Technical Report USA-CERL M-88/18. U.S. Army Construction Engineering Research Laboratory, Champaign, Ill., 1988.
2. D. R. Uzarski and D. E. Plotkin. Interim Method of Maintenance Management for U.S. Army Railroad Track Networks. In *Transportation Research Record 1177*, TRB, National Research Council, Washington, D.C., 1988, pp. 84–94.
3. D. R. Uzarski, D. E. Plotkin, and S. K. Wagers. Component Identification and Inventory Procedures of U.S. Army Railroad Trackage. In *Transportation Research Record 1131*, TRB, National Research Council, Washington, D.C., 1987, pp. 89–98.
4. D. R. Uzarski, D. G. Brown, R. W. Harris, and D. E. Plotkin. *Maintenance Management of U.S. Army Railroad Networks—The RAILER System: Detailed Track Inspection Manual.* Draft Technical Report. U.S. Army Construction Engineering Research Laboratory, Champaign, Ill., 1988.
5. *Track Safety Standards.* Office of Safety, FRA, U.S. Department of Transportation, Nov. 1982.
6. RPMA *Component Inspector's Handbook.* U.S. Army Facilities Engineering Support Agency, May 1979.
7. *Railroad Track Standards.* TM 5-628. U.S. Army Headquarters, Assistant Chief of Engineers, Oct. 1988.
8. D. R. Uzarski, D. E. Plotkin, and D. G. Brown. *Maintenance Management of U.S. Army Railroad Networks—The RAILER System: Component Identification and Inventory Procedures.* Technical Report M-88/13. U.S. Army Construction Engineering Research Laboratory, Champaign, Ill., 1988.

The views of the authors do not necessarily reflect the position of the Department of the Army or the Department of Defense.

Publication of this paper sponsored by Committee on Railway Maintenance.

Optimal Pricing Policies for Temporary Storage at Ports

BERNARDO DE CASTILHO AND CARLOS F. DAGANZO

Pricing schemes for temporary storage facilities (sheds) at ports are examined in this paper. It is recognized that shippers respond to pricing changes by choosing storage times that maximize their profit. Two types of strategies are considered. Nondiscriminatory strategies set the shed storage charges as a function of shipment volume and time in storage alone (the same for all shippers); they do not require much knowledge about the shippers' behavior and can be found easily. Discriminatory strategies have the potential for improved efficiency but require more information. In some instances, identified in this report, nondiscriminatory strategies can be just as efficient as their discriminatory counterparts. If the demand is steady and there is no alternative storage site, we find that shed prices should increase linearly with time, at a rate that will prevent overflows without causing undue hardship to users. If the demand is heavy, then the shed should be close to capacity most of the time. There is no need for discrimination. Stochastic fluctuations in demand complicate matters slightly because they may make it worthwhile to increase shed prices at an increasing rate with time and to discriminate across shippers. If overflow can be sent to a remotely located warehouse, there is more flexibility and the pricing strategies are almost as simple. Two problems are examined in this paper: finding the optimal shed prices for a given warehouse price and finding both sets of prices jointly. A computer spreadsheet can be used to find the best pricing schemes.

The operation of temporary storage facilities can be improved with the adoption of rational pricing schemes. This introductory section examines current pricing practices for port sheds and the body of the paper presents more refined policies that take into account the user's response to pricing changes.

Transit sheds are buildings located within ports—usually alongside cargo berths—used for receiving, storing, and handling various types of in-transit cargo. They provide safe and convenient storage while freight waits for such administrative formalities as customs clearance and the processing of shipping documents. Transit sheds also act as buffer zones between fast ship-shore flow and the slower shore-inland goods movement.

Within the sheds, import cargo is broken down into small consignments for easy access when the overland shippers come individually to claim it. Conversely, export loads for a specific ship are consolidated in the shed as they arrive, ensuring that they can be retrieved in the order prescribed by the ship-stowage plan.

Warehouses perform a somewhat different function. Remotely located warehouses are subject to much less severe capacity constraints than the sheds but require additional cargo handling; this makes them attractive for longer term storage only.

Shed management directly affects overall port performance. When sheds are congested, they cannot perform their function as buffers for the flow of goods, and this hampers the efficient loading of vessels and increases their turnaround times. Shortages in storage space may also increase costs as a result of additional cargo handling, insurance premiums paid for deteriorated or damaged goods, and shippers' failure to meet delivery dates. Finally, shed congestion may force shippers to use warehouses to store relatively fast-moving cargo, increasing traffic between port, warehouses, and land transportation terminals.

Clearly, adequate pricing policies must avoid congestion by controlling the average cargo stay in the sheds. The importance of this principle is recognized in practice. According to a 1987 United Nations Conference on Trade and Development (UNCTAD) report,

> In an Asian port, the demurrage rates for transit sheds were quadrupled to make it unprofitable for consignees to use the transit sheds for warehousing. The result was that congestion was considerably reduced. (*1*)

Modern container terminals, prevalent in industrialized countries, also need temporary storage areas within the terminal to serve as buffer zones between containerships and trucks or trains. The need to avoid abusive use of these areas is also clear and can be illustrated in practice. For example, at the TransBay Terminal in Oakland, California, a fee is imposed on containers that arrive more than ten days before their scheduled departure date (*2*).

Of course, if shippers are encouraged to reduce their transit time so much that the storage facility is underutilized, the result—wasted capacity and shipper inconvenience—is also undesirable. How efficient pricing schemes can be developed for a variety of situations is demonstrated in this report.

In an UNCTAD study, which analyzed more than 50 ports (*3*), it was determined that most current pricing policies for transit sheds exhibit the following features:

1. A fixed time period of free storage, which starts when the goods are deposited in the shed.
2. Storage fees that are proportional to either the storage area occupied, the cargo weight, or the cargo volume, depending on the commodity. (The discussion here will be phrased in terms of volume, but no generality is lost if most of the commodities are priced on the same basis.) The storage fee per unit volume will be called price from now on.
3. Price per unit volume increases with the excess transit time after the free period. Tariffs—defined here as the stor-

---

Institute of Transportation Studies, University of California, Berkeley, Calif. 94707.

age charge per unit volume and unit time—are either constant (in about 20 percent of the cases) or increase with time. Storage times are normally measured in days.

Imakita (*4*) describes a simple model in which storage time varies across shippers but is insensitive to price and in which a remote warehouse accommodates the shippers that find the shed too expensive.

Because storage times change across shippers, a shed tariff increase does not affect all the shippers equally. If some decide to switch from the shed to the warehouse, the volume stored in the shed will change. The relationship between pricing policy and various measures of performance (shed accumulation, shed revenue, warehouse flow, etc.) is now introduced as a prelude to the elastic demand models object of this paper. The following variables are used:

q = port's cargo flow (in volume units per unit time);
q_s = flow through the shed;
q_w = flow through the warehouse ($q = q_s + q_w$);
C = static shed capacity; that is, the maximum cargo volume that can be stored in the shed at any given time (warehouses are assumed to have infinite capacity);
$F_T(t)$ = proportion of the port's cargo flow that is stored for no more than t time units, assumed to be independent of pricing and storage locale [this function can be viewed as a cumulative probability distribution function for the time in storage T of a randomly chosen flow unit; the corresponding probability density function is denoted $f_T(t)$];
$p_w(t)$ and $p_s(t)$ = warehouse and shed prices (in dollars per unit volume) as functions of time in storage; and
t^0 = indifference time in storage: $p_w(t^0) = p_s(t^0)$.

If shed prices are less than warehouse prices for short stays but escalate faster with time (logically, the shed's marginal tariff should be higher) then the indifference time, if it exists, will be unique. Cost-conscious shippers will choose the shed if $T < t^0$, and the warehouse if $T > t^0$ (see Figure 1).

The flow through the shed is then

$$q_s = q\, F_T(t^0) \tag{1}$$

and the revenue is $p_s(t^0)\, q\, F_T(t^0)$. If for a given t^0 the shed capacity is never exceeded, the average volume in storage can be viewed as the average queue length in a multiserver queueing system with an infinite number of parallel channels. The average volume V_{avg} in storage is therefore

$$V_{avg} = q\, E(T \mid T<t^0) = q \int_0^{t^0} f_t(t)\, t\, dt \tag{2}$$

If stochastic fluctuations in V can be ignored, the shed will not overflow if $V_{avg} \leq C$. Therefore, we can view V_{avg} as the shed capacity C_{req} required to avoid overflow. With stochastic fluctuations, considered later, C_{req} must be appreciably larger than V_{avg} if overflow is to be unlikely.

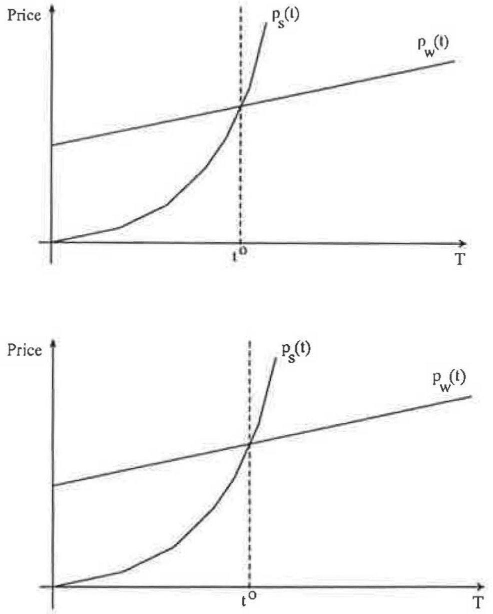


FIGURE 1 Typical shed and warehouse price functions.

Interest here is in the case where C is not sufficient to accommodate all the traffic: $q\, E(T) > C$. Operations will then be most efficient if the shed operates near capacity. Definitely, this is to the advantage of the shippers because as much flow as possible then avoids the warehouse. Maximizing utilization does not necessarily correspond to maximizing shed revenue, but this is likely to be a secondary objective for the terminal operator; minimizing the operating cost added by traffic to the warehouse is likely to be of greater importance, especially if there is competition from other ports.

Because V_{avg} increases with t^0, full shed utilization without overflow is achieved if the shed price function's indifference point t^0 satisfies Equation 2: t^0 can be found numerically for any given $f_T(t)$.

Any shed price function $p_s(t)$ that intersects $p_w(t)$ at such a t^0 (and such that $p_s(t) < p_w(t)$ for $t < t^0$, and $p_s(t) > p_w(t)$ for $t > t^0$) will result in full shed utilization and no overflow. Thus, there is an infinite number of shed price functions that satisfy the optimality condition. Although cargo flow patterns and storage utilization are fixed if t^0 is given, the form of $p_s(t)$ in the interval $[0,t^0]$ does influence the cash flow among the warehouse, the shed, and the shipper. Figure 2 depicts two price functions with identical shed utilization: $p_s^1(t)$ favors the shippers, with low fees, and $p_s^2(t)$ maximizes shed revenue.

An in-between linear price function would seem adequate in this case. Although constant tariffs have their advocates (*5*), nonlinear price functions (with increasing tariffs for longer stays) can be effective in some of the scenarios about to be examined.

The model just described assumes that flow and length of stay are independent of storage prices. Although it is reasonable to assume that the volume shipped is independent of storage prices—after all, these represent a relatively small fraction of the total transportation costs incurred by the

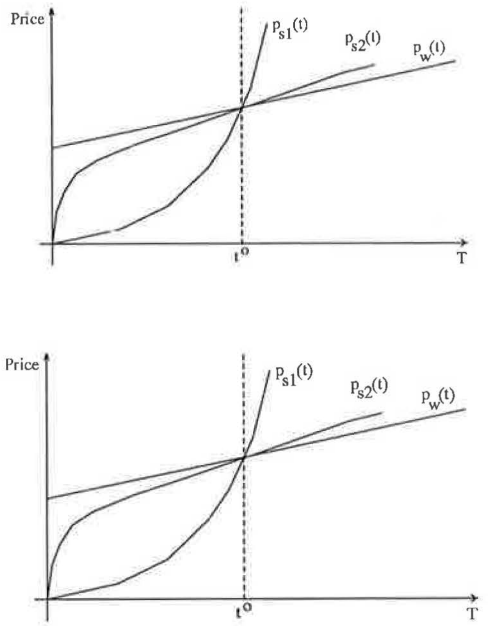


FIGURE 2 "Equivalent" shed price functions.

shipper—the same cannot be said for the time in storage. More likely, as storage prices increase, shippers will try to reduce the time in storage and $F_T(t)$ will shift towards shorter stays.

If shed tariffs were increased to eliminate overflows as recommended, both the indifference time and the average shed storage time would decline. As a result, even with constant throughput, the average shed accumulation would be less than predicted and some shed space would be wasted. Clearly, if storage times depend on price, the method suggested underestimates the effect of price changes. Thus in this paper, total cargo throughput is considered given, but its accumulation is assumed to depend on storage prices.

Attempts are made to overcome the limitations of this model in the remainder of this paper. The next section introduces a model of shipper behavior that attempts to explain how shippers choose their storage time. The following section examines situations without a warehouse, under both deterministic and stochastic demand, and the final section adds the warehouse. The amount of information needed to implement each policy is discussed, as well as the policies themselves. Both discriminating strategies (which offer different tariffs to different customers) and nondiscriminating strategies are considered. The calculations can be easily automated in spreadsheet form and numerical examples are presented.

SHIPPER BEHAVIOR

Shipper costs can be classified as moving expenses (including transportation and handling) and holding costs (capital tied up in inventory and storage rent costs) (*6*). Moving costs tend to decrease with time in storage, t, as cargo can then be consolidated into more efficient shipments. Holding costs, on the contrary, increase with time in storage, t. It has already been shown that the rent costs—represented by the price functions $p_s(t)$ and $p_w(t)$—usually increase with t.

Here interest is in examining the behavior of a cost-minimizing shipper when the storage rent price functions are changed. The sum of all the logistics costs, not including the port storage charges, is called external costs. They typically decrease with t when t is small, eventually reaching a minimum and then increasing. (For t close to zero, shippers would have to retrieve items from the shed on short notice, which would be expensive. As t increases the external costs decrease, because items can then be carried in larger batches, which reduces moving costs—inventory costs are a negligible part of the external costs for small t. If t continues to increase, the moving cost economies of scale eventually disappear, but inventory costs continue to increase; as a result, the external cost must eventually increase.)

The external savings function, $s(t)$, represents the shipper's external cost savings (per unit volume) if the freight is stored near the port for an average of t days rather than being collected on the first day. By definition, the savings should vanish for small t; in most cases $s(t)$ should be concave with a single maximum. In our examples, $s(t)$ will be approximated by a quadratic function. [In reality, $s(t)$ should be determined from observed data. The quadratic form is used for the examples because it is likely to be a good approximation and because it yields simple and intuitive mathematical results.]

Presented with a storage price function $p(t)$, the shipper is assumed to choose the length of stay t^* that maximizes its actual (net) savings: $s(t) - p(t)$. This is represented by the vertical separation between the two curves in Figure 3a. For the optimal t^*, the marginal savings obtained by using the storage must equal its marginal cost. This can be written as

$$s'(t^*) = p'(t^*). \tag{3}$$

In practice, it is easier to estimate $s'(t)$ than $s(t)$. Because $s'(t)$ suffices to determine t^* (see Figure 3b), the marginal savings and storage price curves $s'(t)$ and $p'(t)$ are often worked with.

Additional measures of performance obtained from the marginal curves include the shed/warehouse revenue per unit flow:

$$p(t^*) = p(0) + \int_0^{t^*} p'(t)\, dt \tag{4}$$

The shipper's total savings per unit flow, equal to the area between $s'(t)$ and $p'(t)$ in the interval $[0,t^*]$ (see Figure 3b):

$$s(t^*) - p(t^*) = s(0) - p(0) + \int_0^{t^*} (s'(t) - p'(t))\, dt \tag{5}$$

The sum of the storage revenue and the shipper's net savings, corrected by the cost of operating the storage facility per unit of flow, $h(t)$, is a measure of total benefit per unit flow (or "system benefit") generated by the operation of the facility, w. Because $h(t)$ should be nearly independent of t if the storage facility is below capacity, it is assumed that it is constant, that is, $h(t) = h$. Thus, the system benefit is

$$w = s(t^*) - h = + \int_0^{t^*} s'(t)\, dt, \tag{6}$$

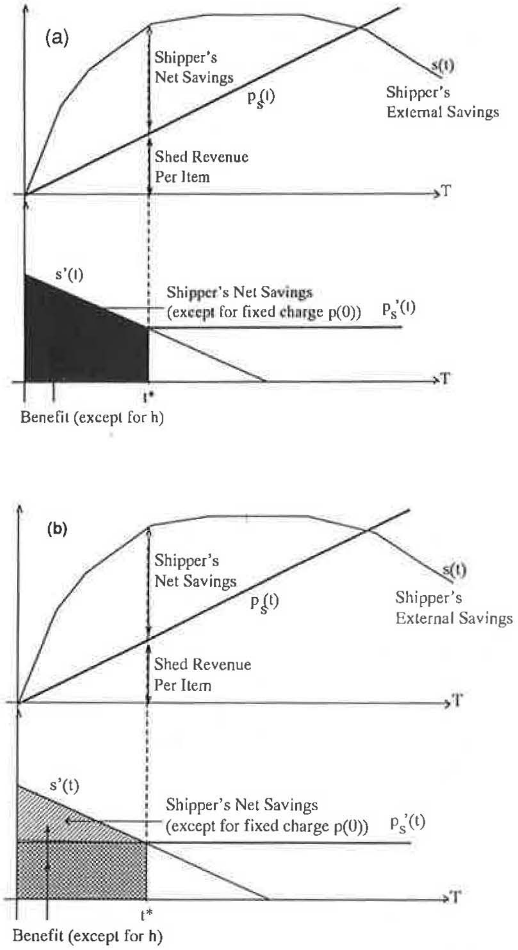


FIGURE 3 (a) Savings and price functions for one shipper. (b) Marginal savings and price functions for one shipper.

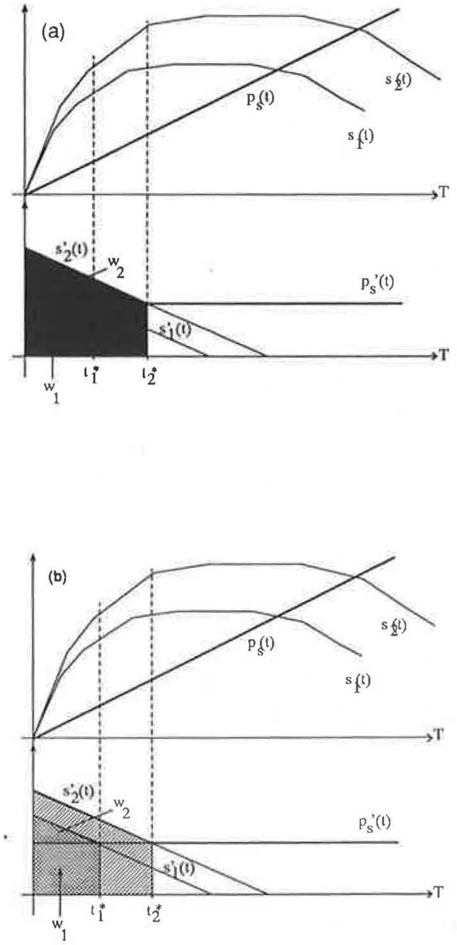


FIGURE 4 (a) Savings and price functions for two shippers. (b) Marginal savings and price functions for two shippers.

which, except for the constant h, is the shipper savings; that is, the area below $s'(t)$ in the interval $[0,t^*]$ as depicted in Figure 3b. Because system benefit is independent of $p(t)$ for a given t^*, any two price functions yielding the same t^* also yield the same system benefit.

Although the storage/retrieval cost is assumed to be fixed for a given storage facility, this cost can be quite different for different facilities. If a warehouse is remotely located, then its fixed storage/retrieval cost, h_w, will be much greater than the equivalent cost for a shed, h^s. This will become important when systems with two storage facilities are considered, as total system benefit will be used for comparing strategies.

In later sections, differences across shippers will be captured by differences in their external savings functions. These differences will be the result of the shippers' inland locations, the value of their freight, and so on. Pricing strategies that differentiate across commodities can also be easily constructed. They are discussed in the conclusion. Figure 4 shows the external savings functions for two shippers and a price function; it also depicts the marginal savings functions, the tariff (marginal storage price) function, the desired storage times, and the system benefit per unit flow for the two shippers.

One can see at a glance that if the tariffs, $p'(t)$, were to be increased, t^{1*} and t^{2*} would decrease, and so would the total system benefit. Thus, one would like to lower $p'(t)$ as much as possible subject to the storage capacity limitations. This point will be addressed in the next section.

The relationship between system benefit and tariffs can also be captured analytically. If the marginal price $p'(t)$ and marginal external savings $s'(t)$ functions are linear

$$p'(t) = \alpha + \beta t \quad \text{and} \tag{7}$$

$$s'(t) = a - b t \tag{8}$$

Then, assuming that $a > \alpha$, t^* and w are given by

$$t^* = (a - \alpha)/(b + \beta) \tag{9}$$

$$w = \frac{b(a^2 - \alpha^2) + 2a\beta(a - \alpha)}{2(b + \beta)^2} - h \tag{10}$$

As expected, t^* and w decrease if the tariff coefficients (α and β) increase.

NO WAREHOUSES

Deterministic Demand

In this section, a situation where many shippers must utilize a single storage facility is investigated. Each shipper sends or receives through the port q_i volume units of freight per unit time, at a steady rate ($\Sigma q_i = q$). The external savings function for shipper i is denoted $s_i(t)$.

A pricing policy that maximizes system benefit while ensuring that the shed capacity is not exceeded is sought. A discriminatory pricing policy would allow different price functions for different customers; in the most general case, each customer could be offered a different price function $p_{si}(t)$. A nondiscriminatory pricing policy would assume that all shippers are treated equally, with the same shed price function $p_s(t)$ for all. Nondiscriminatory policies are more common, but they may also be less efficient since they embody additional restrictions.

The remainder of this subsection shows that for the current situation—with no warehouse and steady demand—discriminatory and nondiscriminatory strategies are equivalent; in fact, a constant tariff is optimal: $p_i'(t) = p_s'$.

Because total system benefit per day, W, only depends on the price policy through the equilibrium times t_i^* for each shipper

$$W = \sum_{i=1}^{n} q_i \left[s_i(t_i^*) - h\right] \tag{11}$$

and because the total freight accumulation in the shed at any time is also a function of these variables

$$V_{\text{avg}} = \sum_{i=1}^{n} q_i \, t_i^*, \tag{12}$$

only the optimal t_i^* need to be found. Any price functions yielding these t_i^* will be optimal. The optimal times maximize W, subject to $V_{\text{avg}} \le C$ and $t_i \ge 0$ (for all i).

If the maximization of system benefit without the capacity constraint yields a V_{avg} strictly smaller than C, then the resulting times are optimal. These are the times that maximize the individual s_i curves, which are obtained for a pricing policy with zero tariff. Thus, if shed space is plentiful, then allowing free storage maximizes system benefit. System benefit is also maximized if the port charges a fixed price per unit volume independent of length of stay, provided the charge is so low that no shippers are discouraged from using the shed.

If, as is more likely, shed space is at a premium, the capacity constraint will hold as an equality. Consideration reveals that any positive t_i^* must satisfy for optimality

$$s_i'(t_i^*) = \alpha \tag{13}$$

where α is the Lagrange multiplier for the capacity constraint. To achieve this result the discriminatory pricing functions must satisfy

$$p_{si}'(t_i^*) = s_{si}'(t_i^*) = \alpha \tag{14}$$

Note that α can be viewed as the optimal tariff at each t_i^*.

Because it is the same for all i, discrimination is clearly unnecessary. A nondiscriminatory pricing function with constant tariff should satisfy the above condition. Simply let $p_{si}(t) = \alpha t$, for all i, and increase or decrease α until the average volume in the shed closely matches its capacity.

This simple policy maximizes system benefit without any knowledge of individual shipper behavior.

Example

Let us consider a simple case where the $si(t)$ are quadratic functions $s_i'(t) = a_i - b_i\, t$.

For a given α, the condition $\{s_i'(t_i^*) = \alpha;\ \text{if } t_i^* > 0\}$ yields

$$t_i^* = \max\left\{0, \frac{a_i - \alpha}{b_i}\right\} \tag{15}$$

This expression recognizes that the shipper can only benefit from storage if $\alpha < a_i$. If $\alpha > a_i$ then the tariffs increase too rapidly for the shed to be of use to shipper i. (In Figure 3a, the pricing curve would be steeper than the external savings curve near the origin, and thus $t_i^* = 0$.)

As α is increased, thus, shippers with the smallest a_i are excluded from the shed—or are forced to use it for a minimal amount of time. If α is optimal, the remaining shippers must use up the shed's capacity; that is

$$V_{\text{avg}} = \sum q_i\, t_i^* = \sum q_i\, a_i/b_i - \alpha \sum q_i/b_i \tag{16}$$

where the summations are only taken for i such that $a_i > \alpha$. A simple expression for α is obtained if all the a_i are large, so that no shippers are excluded. The summations in Equation 16 then are independent of α, and

$$\alpha^* = \frac{\sum q_i\, a_i/b_i - C}{\sum q_i/b_i} \tag{17}$$

A simple computer spreadsheet was developed using these expressions. The spreadsheet can be used to test different price functions when the shipper data are given; the shed price functions and the external savings functions are assumed to be quadratic. In addition to system benefit, other performance measures, such as shed revenue and percent of occupied capacity, are calculated.

In this example, the optimal shed price function for a situation where five shippers must utilize the shed is calculated. The data set is as follows:

Shipper	*1*	*2*	*3*	*4*	*5*
a_i	10	11	12	13	14
b_i	0.5	0.5	0.5	0.5	0.5
q_i	500	500	500	500	500

The static shed capacity, C, is 2,000 units.

Expression 7 predicts $\alpha^* = 8$. The spreadsheet confirms that nonlinear price functions are inferior and that the best pricing policy is indeed to charge a flat rate of $8.00 per unit of cargo per day. The resulting system benefit table, showing benefit values in thousands of dollars per day for different α and β, is partially reproduced in the following (negative system benefit values indicate shed overflow):

	β		
α	0.0	0.1	0.2
7.00	−235.00	117.20	186.99
7.25	−141.97	203.19	179.38
7.50	−38.89	194.70	171.62
7.75	76.03	186.00	163.70
8.00	205.00	177.08	155.61
8.25	194.84	167.95	147.37
8.50	184.38	158.59	138.97
8.75	173.59	149.02	130.40
9.00	162.50	139.24	121.68

Stochastic Demand

More realistically, it is now assumed that the volumes shipped change from day to day, without any seasonal trend. Then, the volume from shipper i arriving on any given day can be viewed as the outcome of a random variable Q_i with time-independent mean and variance:

$$E[Q_i] = q_i \quad \text{and} \tag{18}$$

$$\text{var}[Q_i] = I_i\, q_i \tag{19}$$

where I_i is a coefficient with volume units.

The volume in the shed, V_i, can also be viewed as a random variable changing from day to day. Because the system is ergodic, Little's formula holds and $E(V_i) = q_i\, t_i$, where t_i is the average time in storage for items i.

The variance of V_i depends on the behavior of shippers, but the expression

$$\text{var}[V_i] = q_i\, t_i\, I_i \tag{20}$$

will be used for illustrative purposes. This expression holds if shipper i sends (receives) constant size shipments so infrequently that two of its shipments are almost never in storage simultaneously. (In that case, the constant I_i can be shown to represent the size of a shipment.) The expression also holds for frequent and variable size shipments, provided that all the shipments remain in storage for a fixed time t_i.

If shippers act independently, then the total volume in storage $V = \Sigma\, V_i$ must satisfy

$$E[V] = \sum q_i\, t_i \quad \text{and} \tag{21}$$

$$var[V] = \sum q_i\, t_i\, I_i \tag{22}$$

Without a warehouse, overflow must be avoided. Thus, the capacity constraint is modified as follows:

$$\sum q_i\, t_i + K\left(\sum q_i\, t_i\, I_i\right)^{1/2} \leq C, \tag{23}$$

where K is a number of standard deviations (comparable with 3) that will ensure that random fluctuations in the shed's accumulation are unlikely to reach its capacity.

If the coefficients of variation I_i are different from zero, the Lagrangian optimality condition no longer implies that all $s_i'(t_i^*)$ should be equal, as was the case in the deterministic problem. It is now

$$s_i'(t_i^*) = \alpha\left[1 + K\, I_i/2\left(\sum q_j\, t_j\, I_j\right)^{-1/2}\right]. \tag{24}$$

This indicates that discriminating pricing functions, which allow shippers with small I_i to stay longer, may be desirable. The same system benefit level can be achieved with a nondiscriminatory price function satisfying $p_s'(t_i^*) = s_i'(t_i^*)$; this function will exist if all the t_i^* are different.

Because the best nondiscriminatory function is likely to be awkwardly shaped, in practice one may want to select the best candidate from a family of acceptable price functions, even if the resulting system benefit is lower. This problem can be solved easily. One would express t_i as a function of the parameters in the price function, which would then become the decision variables of the optimization problem: maximizing W, subject to the stochastic capacity constraint. Because a reasonable family of functions would only include a few parameters (e.g., 3 at most), the optimization problem can be solved easily within the scope of a computer spreadsheet.

Example

An example with only two shippers is used because the optimal solution can then be easily obtained analytically, for comparison with the numerical spreadsheet solution.

The data are as follows:

Shipper	*1*	*2*
a_i	10	12
b_i	0.5	0.5
q_i	500	600
I_i	400	1000

The safety coefficient, K, is 2, and the shed capacity is still 2,000 units.

The analytical solution, obtained using Equation 25, is $\alpha = 4.075$ and $\beta = 0.204$.

If this price functions were adopted, cargo from Shippers 1 and 2 would spend 8.414 and 11.254 days in storage, respectively, and the average shed accumulation would be 10,955 units ($\Sigma\, q_i\, t_i$), with 9,045 units of storage to spare as a buffer. The total system benefit would be $115,928 per day.

The spreadsheet finds $\alpha = 5.25$ and $\beta = 0.1$ as the optimal coefficients, yielding a system benefit of $114,447 per day:

	β			
α	0.00	0.10	0.20	0.30
4.25	−858.28	−872.93	114.41	103.71
4.50	−861.13	−875.92	111.47	100.89
4.75	−864.13	−879.02	108.44	98.00
5.00	−867.30	−882.24	105.34	95.05
5.25	−870.63	**114.44**	102.15	92.04
5.50	−874.13	111.00	98.87	88.97
5.75	−877.78	107.44	95.52	85.83
6.00	−881.60	103.78	92.08	82.63
6.25	114.42	100.00	88.56	79.36

Although the coefficients α and β are different from the analytical ones, for t in the range of optimality (8 to 12), the two $p_s'(t)$ and the corresponding times in storage are very close. For the new set of parameters, the times would be 7.92 and 11.25 days (as opposed to 8.414 and 11.254). The total system benefit in both cases is also similar: $114,437/day versus $115,928/day.

Although the solution obtained using the spreadsheet is marginally worse than the one obtained analytically, the spreadsheet method can be applied to cases in which there are many shippers. The spreadsheet also supplies at-a-glance information on other measures of performance and can accommodate simple constraints easily.

SHEDS AND WAREHOUSES

In this section, a case in which cargo can be stored either at the shed or at one or more remotely located warehouses is analyzed. Although shed capacity is limited, it is assumed that enough warehousing space is made available to accommodate demand; that is, there is no capacity restriction at the warehouse. Because shed overflows can now be routed to the warehouse without serious disruptions to port operation, stochastic phenomena need not be considered as explicitly as in the previous section. Focus here is on a deterministic model and stochastic effects are discussed qualitatively.

For the maximization of system benefit, it is assumed that the cost of sending one unit of flow through the warehouse is given by an increasing function of the time in storage t_w:$h_w(t_w)$. Paid by the port, the warehouse or the public (but not by the shipper who is charged a fee $p_w(t_w)$ for the service), this cost accounts for handling inside the warehouse, transportation between the port and warehouse, the provision of secure storage space, as well as noise and congestion in the surrounding area. In most cases, $h_w(0)$ is considerably greater than the handling cost through the shed h_s.

Two related questions are examined: For a given warehouse price function $p_w(t)$ outside the port's control, how should the shed price function be chosen? If $p_w(t)$ is under the port's control, how should the two price functions be chosen jointly? The answer to the first question will help with the second.

Fixed Warehouse Price Function

Given shed and warehouse price functions, it is assumed that shippers choose the most cost-effective duration and form of storage. As before, pricing strategies will be compared on the basis of their contribution to system benefit (i.e., joint benefit to port and shippers). It is assumed that the given warehouse price function is nondiscriminatory. Therefore, the following quantities associated with shipper i are fixed as follows:

t_{wi} = shipper's chosen storage time at the warehouse, as explained previously;
s_{wi} = shipper's external savings per unit volume if the warehouse is used; that is, $s_i(t_{wi})$;
h_{wi} = cost generated by the shipment of said volume unit: $h_w(t_{wi})$;
w_{wi} = system benefit generated by the same volume unit: $s_{wi} - h_{wi}$.

In addition to these constants, the total system benefit generated per day is only a function of the fraction of flow sent by each shipper through the shed x_i, and the associated time in storage t_{si}. The total system benefit is

$$W = \sum q_i \{x_i [s_i(t_{si}) - h_s] + (1 - x_i) w_{wi}\}. \tag{25}$$

If the system benefit obtained when all the flow is routed through the warehouse (a constant, $\Sigma q_i w_{wi}$) is subtracted from this expression, an equivalent objective function W' is obtained:

$$W' = \sum q_i \{x_i [s_i(t_{si}) - h_s - w_{wi}]\}. \tag{26}$$

This expression can be interpreted as the shed's contribution to system benefit. We seek the $0 \le x_i \le 1$ and $t_{si} \ge 0$ that maximize W' while satisfying the shed capacity constraint

$$\sum q_i x_i t_{si} \le C. \tag{27}$$

As occurred in the previous section, if two shippers use the shed—$(x_i, t_i, x_j, t_j) > 0$—then their marginal external savings must be equal: $s_i'(t_{si}) = s_j'(t_{sj})$. The argument is simple. If $s_i' > s_j'$, then increasing the time in the shed by a small amount $\varepsilon/(q_i x_i)$ for shipper i, and decreasing it by $\varepsilon/(q_j x_j)$ for shipper j, satisfies all the constraints and increases system benefit by $\varepsilon\ (s_i' - s_j') > 0$.

As a result, if the x_i are given, the positive t_{si} in the optimal solution must satisfy $s_i'(t_{si}) = \alpha$ for some α. It is not difficult to see along the same arguments that if one shipper j does not use the shed, the $s_j' \le \alpha$. Clearly, α represents a tariff; if α was known the t_{si} could be identified as per the construction of Figure 3a, with a price function $p_s(t) = \alpha\ t$. The problem thus reduces to finding α and $\{x_i\}$.

Because the t_{si} are fixed conditional on α, for a given α the optimal $\{x_i\}$ are the solution to a knapsack maximization problem with W' as the objective function and $\Sigma\ q_i x_i t_{si} \le C$ as the constraint. The optimal solution, thus, satisfies

$$\begin{aligned} x_i &= 0, \text{ if } [w_{si} - w_{wi}]/t_{si} < \tau, \\ 0 \le x_i &\le 1, \text{ if } [w_{si} - w_{wi}]/t_{si} = \tau, \text{ and} \\ x_i &= 1, \text{ if } [w_{si} - w_{wi}]/t_{si} > \tau \end{aligned} \tag{28}$$

for a constant τ that ensures the capacity constraint is met as an equality. The resulting system benefit $W'(\alpha)$ should then be compared with the system benefit for other tariffs; the largest can be chosen.

Note that the optimal tariff should be the same for all shippers, as happened in the previous section. The optimal splits $\{x_i\}$ can be obtained with discriminatory shed price functions (with the right ordinates at the optimal t_{si} to ensure that the shipper's choice is as desired); also as before, this would require information on the individual $s_i(t)$ functions.

Nondiscriminatory Policies

In the absence of this information—or if price functions must be kept fair and simple—we may wish to choose a nondiscriminatory price function with constant tariff, $p_s(t) = \alpha$ t, and let each shipper choose its split and storage times.

The construction of Figure 3a reveals that t_{si} and $s_i(t_{si})$ are decreasing functions of α. Because the attractiveness of the shed to shipper i (as measured by $s_i(t_{si}) - \alpha\ t_{si}$) decreases with α, x_i also decreases with α. Consequently, both W' and the left side of the shed's capacity constraint decrease with α.

Obviously, thus if one wishes to accommodate the resulting shed volumes without overflow (e.g., to avoid disgruntled customers), the smallest tariff consistent with the shed's capacity must be optimal. No information is needed to reach this decision.

If the demand varies unpredictably from day to day and overflows are to be avoided, the tariff should be a little larger. The average accumulation in the shed will then be a little smaller than its capacity, allowing the accumulation fluctuations to be absorbed. The desired tariff would satisfy

$$W' = \sum q_i \{x_i [s_i(t_{si}) - h_s - w_{wi}]\} \tag{29}$$

$$\sum q_i x_i t_{si} + K (q_i x_i t_{si} \mathrm{I}_i)^{1/2} = C \tag{30}$$

(Note that the left side of this equality still decreases with α.)

If overflows are acceptable, then it may be optimal to set a tariff so low that systematic overflows ensue even in the deterministic case. But detailed information on the $s_i(t)$ is needed to determine the precise tariff and the value of $W'(\alpha)$. If this information is available, one might want to choose the price function from a larger family of curves (e.g., quadratic).

For a given $p_s(t)$ shipper i's decisions (x_i and t_i) are known. These can be used to determine the proportion of shed traffic that is *not* diverted to the warehouse, y

$$y = \min \left\{ 1, \frac{C}{\sum q_i x_i t_{si}} \right\} \tag{31}$$

In the deterministic case, if all the shippers have the same probability of being routed to the warehouse (against their wishes), then it is a simple matter to calculate W′ (α)

$$W' = \sum q_i \{ y x_i [s_i(t_{si}) - h_s - w_{wi}] \} \tag{32}$$

For stochastic demands, the expression for W' is identical, but the overflow will be somewhat greater than y. The appropriate queueing expression (e.g., for a multichannel queue without a buffer, as would apply to telephone systems) should be used.

The best price function can be found by testing the members of the price function family using a spreadsheet. In all cases though, if some traffic is flowing to the warehouse the shed must be fully used.

Example

In this example, five shippers may use a shed or a warehouse for temporary storage. The table below summarizes the data for the problem:

Shipper	*1*	*2*	*3*	*4*	*5*
a_i	10	11	12	13	14
b_i	0.5	0.5	0.5	0.5	0.5
q_i	500	500	500	500	500

The capacity of the shed is 20,000 units, and the warehouse is assumed to have unlimited capacity. The handling cost associated with shed usage, h, is 5 \$/unit, and use of the warehouse costs $h_w(t) = 40 + t$ \$/unit. The price of warehouse storage to the shipper is $p_w(t) = 50 + 2_t$ \$/unit.

Initially, let us determine a nondiscriminatory policy with a constant tariff such that all shed volume can be accommodated without overflow. As discussed earlier, in this case the optimal policy is to charge the smallest tariff consistent with the capacity of the shed.

In practice, the desired result could be achieved by starting with a very high tariff and decreasing it until the shed reached its capacity, or by starting with a low tariff and increasing it until no more shed overflow were observed. For the data presented in the preceding, the spreadsheet indicates that the lowest no-overflow tariff would be 4.6 \$/day/unit.

If this tariff were adopted, Shippers 1, 2, and 3 would use the shed, storing their cargo for about 11, 13, and 15 days, respectively. Shippers 4 and 5 would choose to use the warehouse for 22 and 24 days. The sheet would be almost fully utilized, with no overflow, and the total system benefit generated would be approximately \$259,000/day.

It will now be assumed that all the preceding information is available to the shed authority, and pricing policies that create systematic overflows are considered acceptable. The objective is simply to maximize system benefit, which can be accomplished by setting up a system benefit table analogous to the ones in the previous examples as follows.

	β		
α	*0.00*	*0.10*	*0.20*
2.00	260.00	259.60	254.34
2.25	260.32	259.07	253.07
2.50	260.53	258.39	251.64
2.75	**260.61**	257.57	253.54
3.00	260.56	256.59	251.82
3.25	260.36	255.44	245.63
3.50	260.00	256.91	242.66

As this table shows, it is possible to increase system benefit by reducing the shed tariff to 2.75 \$/day/unit. This tariff would cause approximately 57 percent of the traffic to be routed to the warehouse because of shed overflow, but the total system benefit would increase to approximately 261,000 \$/day. In this example, the availability of additional information would represent an additional system benefit of about 2,000 \$/day.

Variable Warehouse Price Function

The x_i and t_{si} that maximize W' remain the same whether $p_w(t)$ can be changed or not. We have already seen that for a given warehousing price function, there is a discriminating set of shed price functions that can achieve the optimum.The question now is whether the optimum can be achieved without discrimination.

We now show that the optimal system benefit is achieved if $p_w(t) = h_w(t)$, the cost of sending a unit of flow through the warehouse when the storage time is t, and $p_s(t) = h_s + \alpha\ t$, in which the α is the lowest shed tariff that avoids overflow.

With these price functions, the shed times only depend on α and are denoted by $t_{si}(\alpha)$. The shed will be chosen, $x_i = 1$, if

$$s_i(t_{si}(\alpha)) - [h_s + \alpha\ t_{si}(\alpha)] > s_{wi} - h_w(t) \text{ or}$$

$$\frac{w_{si} - w_{wi}}{t_{si}(\alpha)} > \alpha \tag{33}$$

If this inequality is reversed, the shipper prefers the warehouse, $x_i = 0$; if the relationship is a pure equality the shipper is indifferent about the form of storage. If α is chosen equal to τ (as small as possible without creating overflow), then these conditions are identical to the knapsack condition for $\{x_i\}$, specified in the previous subsection. Therefore, the solution is optimal.

The conclusion is simple: system benefit is maximized if the storage facilities are priced at cost and a constant tariff is added to the fixed capacity shed to prevent overflows.

CONCLUSIONS

Temporary storage facilities and regular warehouses accomplish distinct functions and should therefore be analyzed and managed differently. Establishing shed pricing policies using procedures developed for regular storage facilities or by trial and error will usually lead to sub-optimal utilization of the facility.

Efficient use of temporary storage facilities at transportation terminals, not just ports, can be achieved through the adoption of rational pricing policies. To determine such policies, management must define the operational objectives of the facility, taking into account the consequences of overflow.

Optimal shed pricing policies are affected by the capacity of the sheds, by the characteristics of its users, and by the availability of warehouses. With this information, the shed pricing strategy that maximizes a given objective (e.g., system benefit, shed revenue, a combination of these, etc.) can be found using a computer spreadsheet, as demonstrated in the body of this report. If system benefit is the objective, the best shed pricing policy often is very simple and can be identified analytically.

Data requirements for the optimization are modest. Even in situations in which the $s_i(t)$ are needed, the quadratic approximations for the savings functions $s_i(t)$ should be adequate in most practical cases. That being the case, the coefficients a_i and b_i should be easily estimable from shippers' responses to past rate changes and/or from shipper surveys. An empirical determination of the best functional form for the $s_i(t)$ is beyond the scope of this paper, however, as it would require before and after data.

The results of this paper can be used to develop pricing schemes that discriminate across both shipper and commodity type. Shippers that transport more than one commodity can be simply viewed as an aggregation of single-commodity shippers. If one wishes to discriminate across commodities only, all shippers transporting the same commodity would be viewed as a single shipper.

The results of this paper apply to terminals other than bulk and container ports, since nothing in the derivations was port specific. The model applies, for example, to the pricing of short-term and long-term airport parking services—if as a first approximation we ignore that h_w and h_s may depend on the traveler i. If both parking rates are determined by the airport commission then to maximize system benefit these services should be priced at cost, with a short-term parking surcharge proportional to time. The surcharge, perhaps changing seasonally, should be low enough to ensure that the short term lot is not underutilized.

ACKNOWLEDGMENT

This research was supported by the University of California, Berkeley, Transportation Center.

REFERENCES

1. United Nations Conference on Trade and Development. *Steps to Effective Shed Management.* Monographs on Port Management, No. 7, 1987.
2. Maritime Administration. *Current Trends in Port Pricing.* U.S. Department of Commerce, Office of Port and Intermodal Development, Aug. 1978.
3. United Nations Conference on Trade and Development. *Port Pricing.* 1975.
4. J. Imakita. *A Techno-Economic Analysis of the Port Transport System.* Praeger, New York, 1978.
5. E. Bennathan and A. Walters. *Port Pricing and Investment Policy.* Oxford University Press, 1979.
6. C. Daganzo. Logistics Systems Analysis. In *Lecture Notes in Economics and Mathematical Systems,* No. 361, Springer-Verlag, Berlin, Germany, 1991.
7. M. Taleb-Ibrahimi. *Modeling and Analysis of Container Handling in Ports.* Ph.D. thesis, Dept. of Industrial Engineering and Operation Research, University of California, Berkeley, 1989.

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

Risk of Dangerous Goods Spills in Abegweit Passage: Ferry Versus Bridge Crossing

PETER BEIN

The relative risks of hazardous material spills in the 13-km-wide Abegweit Passage between Prince Edward Island and mainland Canada are analyzed, and counteractive measures are discussed for an existing ferry crossing and an alternative link by a bridge. The spills can originate from trucks hauling dangerous goods on board ferries or over the bridge, ships involved in collisions with the ferries or in strikings of the bridge piers, and ferry or bridge maintenance operations. A methodology is developed for the analysis of the marine spill risks associated with the vessel traffic stream crossing (a) a ferry route and (b) a bridge line. Because study-specific data are available neither on spill sizes nor on the conditional probability of a release from a vessel or truck damaged in an accident, an upper bound of probabilities and sizes of spills is estimated. The analysis results represent current traffic volumes and makeup of dangerous goods shipments. They do not reflect possible effects of future legislative, technological, and operations management changes that will undoubtedly aim at preventing and countering the effects of spills. Petrochemical products are the most likely spill commodity, and the potential size of a spill is similar for the two transportation alternatives. The return periods are orders of magnitude higher for the ferry than for the bridge. The return periods and sizes of spills can be improved by instituting traffic management systems for vessels and trucks. Bridge and waterborne emergency response, containment of spills in the bridge drainage system, and more stringent operating and maintenance procedures should reduce the volume of hazardous materials spilled into the water.

Prince Edward Island (PEI) has been linked to mainland Canada by a ferry service provided by the federal government since 1876. The service is subject to disruptions due to inclement weather and technical problems, delays during the peak season, and escalating operating costs. Private-sector groups expressed interest in providing a Northumberland Strait crossing that would offer improved transportation. Out of numerous proposals submitted by private consortia to Public Works Canada (PWC), three bridge options remained by September 1988.

The analysis presented addresses spills from dangerous goods transportation over a proposed generic bridge compared with the existing ferry crossing. The study focuses on the transportation risks of spills that might affect the biophysical environment. The actual consequential risks of such events in terms of environmental impact were not analyzed. Risks arising in the construction phase of the bridge were also excluded.

MARINE ENVIRONMENT

Environmental acceptability was one of the principal considerations in assessing the viability of the crossing proposals (*1*). The marine ecosystem is susceptible to damage resulting from an accidental spill of dangerous goods. The strait is one of the richest fishing areas in Atlantic Canada, and tourism is PEI's second most important industry.

Spills would have direct, measurable effects on the fisheries and tourism. Long-term effects on the local ecosystem would also be significant. Recognizing these risks, PWC requested that all bridge proposals outline an environmental protection plan that specifies mitigating, monitoring, and contingency-planning activities to deal effectively with possible discharge of hydrocarbons and other hazardous materials into the marine environment.

The marine environment is challenging to both bridge construction and vessel traffic year round. Sea ice conditions in the Northumberland Strait pose the most difficult winter navigation in southern Canada. Sea currents and tides in the strait are strongest in the Abegwait Passage. Adverse marine conditions aggravate the risk of marine accidents in the vicinity of bridges (*2,3*). Winds, fog, snow, and ice affect the safety of vehicular traffic on a bridge. The elements would also hamper any spill containment and cleanup attempts.

EXISTING FERRY CROSSING

The bridge alignment would be close to the existing ferry route between Port Borden, PEI, and Cape Tormentine, New Brunswick (Figure 1). Four ferries (Table 1), owned and operated by Marine Atlantic, make a total of almost 12,000 trips per year on a continuous schedule year round. Sailing frequency is lower in the winter months (Table 2). The average crossing time is 100 min, which includes waiting and boarding time.

In 1989, the ferries carried 687,000 passenger vehicles and 153,000 commercial vehicles both ways over the strait, yielding an average of 68 vehicles per sailing. Because of the increase in visitors during summer months, about 40 percent of the total annual passenger vehicle traffic is transported across the strait in July and August. Operating expenses amounted to almost $35 million, 60 percent of which were federal subsidies.

3955 West 14th Avenue, Vancouver, British Columbia, Canada V6R 2X2. Current affiliation: Ministry of Transportation and Highways, 3B-940 Blanshard Street, Victoria, British Columbia, Canada V8W 3E6.

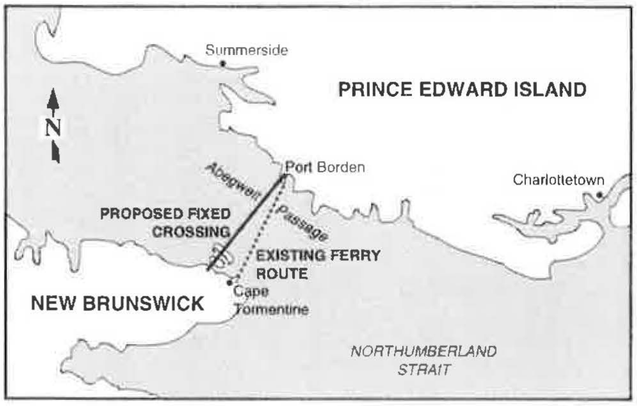


FIGURE 1 Location map.

In 1954, one crossing per week was introduced for the segregated transportation of trucks hauling dangerous goods. At present an average of five such sailings are made weekly.

PROPOSED BRIDGE

The crossing is considered one of Canada's most challenging engineering projects of the century. The structure would be one of the longest highway bridges in a marine environment anywhere in the world. It would span 13 km of the Northumberland Strait at its narrows, called the Abegweit Passage, where the deepest water is 36 m.

Because of the length of the crossing, the bridge design involves a large number of low-level spans supported in concrete piers spaced at 200 m. A vertical clearance of 28 m would allow for safe passage of recreational and fishing craft. One elevated main span with a 200-m-wide by 49-m-high clearance would accommodate oceangoing vessels. Aberrant vessels exceeding 28 m air height would strike the side spans with their masts and other upper parts. Whereas these accidents would not directly damage the hulls, subsequent vessel behavior may lead to striking of the side piers and to spills.

The navigation channel would be located closer to the island than to the mainland, because most of the ports in the strait are on the PEI side. Also, this side of the strait experiences more open water and less severe ice in winter. The piers adjacent to the navigation channel would be protected from vessel impacts by islands.

The bridge deck would be 11 m wide between New Jersey–type barriers. This width would accommodate two lanes satisfying requirements for driver safety and comfort and would allow for shoulders that could be used for emergency access, parking of stalled vehicles, and maintenance operations. A median crash barrier would also be provided to enhance bridge user safety.

TABLE 2 FERRY SAILING FREQUENCY

Period	No. of Ferries	One-way Trips/Day
December-April	2	12
May-June	3	16
July-August	3	22
September-mid October	3	16
Mid October-November	2	14

The new bridge would divert traffic, particularly trucks, from the nearby Caribou–Woods Islands ferry service. Traffic would also increase by an induced amount. The traffic capacity of the proposed bridge is estimated at 2,000 vehicles per hour. The total crossing time would be 15 min one-way. The trucking industry alone anticipates annual savings of $5 million to $8 million from reduced travel time.

DANGEROUS GOODS

Spills of the following dangerous goods can occur in the study area:

- Hazardous freight carried by trucks, either on board a ferry or over the bridge;
- Hazardous cargo on board marine traffic through the passage; and
- Propulsion fuel supply contained in fuel tanks of ferries and all vessels passing through.

Hazardous Freight Carried by Trucks

A total of about 9,200 shipments of dangerous goods were carried by truck on board the special ferry sailings in 1988. The shipments comprised at least 150 different types of substances, of which only nine were selected for analysis on the basis of one or more of three criteria: high hazard to the marine environment, large relative shipment size, and large relative number of shipments.

Typical shipments in 1988 of the selected nine hazardous substances by truck on board the ferries are summarized in

TABLE 1 FERRY VESSEL CHARACTERISTICS

Characteristics	Abegweit	Holiday Island	John Hamilton Gray	Vacationland
Ferry Type ^{a}	P/V/T	P/V	P/V/T	P/V
Delivery Year	1982	1971	1968	1971
Length Overall, m	122	99.1	122	99.1
Breadth, m	21.5	20.9	20.4	20.6
Draft Loaded, m	6.17	5.05	6.20	5.05
Maximum Speed, m/s	9.21	8.75	9.21	8.75
Economical Speed, m/s	5.27	6.17	6.43	6.17

^{a} P = passenger, V = vehicle, T = train Source: Marine Atlantic

Table 3. Spring and summer sample months have 40 to 50 percent more shipments than fall and winter months, which must be partly due to the reduced frequency of ferry sailings between October and May. Extrapolated over the full year, the total number of truck trips with the selected dangerous goods is 1,500.

Truck shipments of paint, corrosive liquids, and sodium hydroxide were the most frequent, but of small average size with a large variance. Half the shipments were paint, which is most likely to be packaged in small containers. The most probable packing of corrosive liquids and sodium hydroxide is drums.

Automotive and aviation fuels constituted the largest total quantities of dangerous goods and the largest shipment sizes, and they exhibited the smallest variance. This must be due to uniform capacity of tanker trucks used in fuel delivery.

Hazardous Cargo on Marine Traffic

Table 4 gives total numbers of dangerous goods shipments on nonferry vessels through the crossing area between 1978 and 1986. As in truck transportation, the largest share is taken by petroleum products. No data are available to derive shipment sizes. Instead, vessels indicated in Table 5 were selected to represent shipment size and tank capacity.

Vessel Propulsion Fuel

Fuel tank sizes of typical vessels in the strait are summarized in Table 6. Potential spills from ruptured fuel tanks of the vessels are small compared with tanker spills but large relative to the size of gasoline and aviation fuel shipments by truck.

PROBLEM DECOMPOSITION

Scenarios

Comparison of the risk of dangerous goods spills into the Northumberland Strait can be simplified into the following scenarios. For the ferry alternative, the scenarios are as follows:

TABLE 3 TYPICAL 1988 DANGEROUS GOODS SHIPMENTS BY TRUCK ON FERRY

	January	May	August	October	Total
Petrol Gas (Transport Canada Class UN1075)					
n	1	4	8	2	15
sum	50.0	100	257	75.0	482
mean	na	25.0	32.1	37.5	32.1
cv	na	100	32	33	52
Gasoline (UN1203)					
n	1	0	3	0	4
sum	0.06	na	49.3	90	49.4
mean	na	na	16.4	na	12.3
cv	na	na	90	na	118
Paint (UN1263)					
n	31	74	92	60	257
sum	11.2	28.3	25.3	13.0	77.8
mean	0.36	0.38	0.28	0.22	0.69
cv	222	272	149	126	227
Petrol Distillates (UN1268)					
n	0	5	4	1	10
sum	na	0.60	2.26	0.43	3.29
mean	na	0.12	0.56	na	0.33
cv	na	108	129	na	156
Corrosive Liquids (UN1760)					
n	34	31	23	22	110
sum	10.3	32.8	5.80	11.6	60.5
mean	0.30	1.06	0.25	0.53	0.55
cv	114	399	185	158	420
Sodium Hydroxide Solution (UN1824)					
n	28	14	15	11	68
sum	13.7	24.0	2.56	7.06	47.4
mean	0.49	1.71	0.17	0.64	0.70
cv	130	238	63	199	293
Aviation Fuel (UN1863)					
n	4	4	4	3	15
sum	172	185	180	132	669
mean	43.0	46.1	45.0	44.0	44.6
cv	0	43	7	2	24
PCB (UN2315)					
n	0	1	0	0	1
sum	na	0.14	na	na	0.14
mean	na	na	na	na	na
cv	na	na	na	na	na
Pesticides (UN2783)					
n	4	10	0	1	15
sum	25.2	34.0	na	0.03	59.2
mean	6.30	3.40	na	na	3.95
cv	175	173	na	na	192

n = total number of shipments; sum = total quantity shipped in tonnes; mean = mean shipment size in tonnes; cv = coefficient of variation in percent; na = not applicable

Source: Marine Atlantic records *(4)*

TABLE 4 DANGEROUS GOODS SHIPMENTS ON NONFERRY VESSELS

Dangerous Goods	Number of Shipments 1978-86	Number of Shipments Annual Average	Percent Total
Bunker C Oil	6	0.7	3
Diesel 32 Oil	32	3.5	16
Gasoline	43	4.8	21
Petroleum	114	12.7	57
Stove Oil	4	0.5	2
Unspecified	2	0.3	1

Source: Vessel Traffic Services, Canadian Coast Guard. Data for vessel traffic through the crossing area *(5)*

TABLE 5 REPRESENTATIVE TANKER CARGO CAPACITIES

Tanker Name	Size, GRT[a]	Capacity, tonnes	No. of Tanks	Tank Capacity tonnes	Tank Capacity m^3
Irving Ours Polaire	4,940	7,040	12	590	750
Irving Nordic	7,750	11,500	12	960	1200
Irving Canada	23,600	37,800	14	2700	3400

[a] GRT = gross registered tons Source: reference *(5)*

TABLE 6 FUEL TANK CAPACITIES OF REPRESENTATIVE VESSELS

Vessel Name	Type, GRT[a]	Size, tonnes	Fuel Tank Capacity, tonnes
Point Viking	tug	200	50
Point Halifax	tug	400	200
Leslie Gault	freighter	1600	206
Soodoc	freighter	4490	156
Farnes	freighter	8100	844
Holiday Island	ferry	3040	238
Abegweit	ferry	13500	182

[a] GRT = gross registered tons Source: reference *(5)*

1. Collision of through vessels with ferry,
2. Accidents during ferry sailings with hazardous material trucks on board, and
3. Ferry operational pollution.

For the bridge alternative the scenarios are as follows:

1. Striking of through vessels against bridge piers,
2. Hazardous material truck accidents on the bridge, and
3. Bridge operational pollution of the strait.

Model and Data Compatibility

The preceding structuring of the problem exhausts all relevant spill risks. It permits a comparison of component risks for the alternatives without any loss of realism while using only limited data. Scenarios 1 and 2 involve similar potential consequences for each alternative, but the mechanisms leading to the occurrence of each of these scenarios are distinct for the two alternatives. Consequently, the method presented in this paper aims at developing a compatible measure of the chance of occurrence for each of the scenarios. That measure cannot rely too much on historical data, because such information is scarce and not directly related to the study project, especially for vessel encounters with ferries and bridges. Models fed by study-specific data would be preferable.

The probability of a hazardous cargo spill is the product of the probability of an accident and the conditional probability of a release given that an accident occurs. Data are limited concerning these probabilities for hazardous materials transportation on merchant vessels, ferries, and bridges. An upper bound approach based only on the unconditional probability of an accident was therefore adopted. Actual spill size is subject to similar analytical limitations.

Counteractive Measures

Legislation, technology, and management of dangerous goods transportation can mitigate accidents and consequences of spills. Traffic management, with special attention to dangerous goods hauled by either land or water, has the largest potential in accident prevention. Remedial technology, such as double hull construction of tankers, is bound to reduce the probability of a release in the future. Contingency response can lessen the size of a spill and its adverse consequences, but the success of marine containment and cleanup operations depends heavily on favorable weather conditions.

These factors are not taken into consideration in the present analysis. Whereas their implementation will reduce the frequency and severity of spills, the relative improvement may be similar for each of the two transportation modes. The relative risk of one alternative compared with another would then not change.

SCENARIO 1: THROUGH VESSEL COLLISION WITH FERRY OR BRIDGE PIER

General Model

A general model for frequency of mishaps (*6,7*) serves both transportation alternatives:

$$Nc = k * N * Pa * Pg \qquad (1)$$

where

Nc = number of vessels colliding with ferry or number of vessels striking bridge piers,
k = 0.5 for ferry and 1.0 for bridge,
N = annual average traffic volume of through vessels,
Pa = probability of aberrance of through vessels, and
Pg = geometric probability of contact of through vessels with ferry or bridge piers

Factor *k* for collision with ferry reflects the fact that two ships are involved. Otherwise, the collision would be counted twice. *N* and *Pa* are identical for the two alternatives.

The model has been applied previously to the assessment of barge impacts on an urban arterial bridge (*2*), vessel impacts on the proposed Northumberland Strait bridge (*3*), and to vessel strikings of bridges in general (*8*). In any analysis using this model, *N, Pa*, and *Pg* are specific to

- Vessel types in the traffic stream;
- Geographical region, as it determines marine environmental conditions and, partly, human behavior;
- Navigational aids systems in the region; and
- Geometry of the obstacle.

Geometric Probabilities

As seen by through vessels, a ferry is a movable object crossing their path, and a bridge is a stationary object with multiple potential points of contact represented by piers.

Collisions with Ferries

The ferry traffic is converted into an equivalent solid object (*6*). The solid object becomes a target for the through vessels. The numerical result is the same if the through traffic is assumed to be the target of ferry attacks. From the geometry of a vessel crossing the ferry path,

$$Pg = Q * D/V \qquad (2)$$

where

Q = number of ferry crossings per year,
D = equivalent width of contact of the two vessels involved in a crossing collision, and
V = ferry speed over ground.

For a ferry course perpendicular to the through traffic,

$$D = 0.707 * (Li + 2 * Lj) \qquad (3)$$

where Li = ferry length overall and Lj through vessel length overall.

Bridge Strikings

For bridge strikings (*8*), *Pg* is the sum of the geometric probability of striking main piers, *Pgm*, and the geometric probability of striking side piers, *Pgs*:

$$Pg = Pgm + Pgs \qquad (4)$$

These probabilities are

$$Pgm = a * (Bm + w)/Lm \qquad (5)$$

and

$$Pgs = b * (Bs + w)/Ls \qquad (6)$$

where

a and b = functions depending on closing distance of the vessel from the bridge
Bm and Bs = main and side pier diameters,
Lm and Ls = main and side span lengths, and
w = effective width of the vessel.

For the closing distance functions, *a* and *b* (*8*), the following averages in the interval from zero to one bridge length's distance are used:

Closing Distance	*a*	*b*
0.0–0.1	1.30	0.00
0.1–0.3	0.40	0.80
0.3–1.0	0.10	0.90
Average	0.28	0.79

Ratio of Mishap Frequencies

One of the most difficult data items to obtain, and one of the most significant variables, is the aberrance probability, *Pa* (*2,3,8*). In the present analysis, it may be sufficient to produce a ratio, *R*, of *Nc* values calculated by Equation 1 for the bridge strikings and ferry collisions as follows:

$$R = V * (Pgm + Pgs)/(0.5 * Q * D) \qquad (7)$$

Typical geometric data on ferries, tankers, and bridge piers and spans (*5*) were used. *R* values of 54 and 36 were obtained for present ferry sailing frequency and for a projected 50 percent increase, respectively. These results mean that if similar consequences can be expected from spills associated with the two transportation alternatives, the bridge would be significantly riskier regarding tanker spills than the ferry.

Return Periods and Consequences

Return Periods

The reciprocal of Equation 1 yields a return period of the encounters of through vessel traffic with ferries and bridge piers. The return periods for the total traffic and for laden tankers separately are summed up in Table 7.

Pa = 0.00025 is used for both transportation alternatives. D in Equation 3 is not sensitive to vessel type and is assumed to be 0.25 km for all vessel types. It is also assumed that ferries operate 20 hr/day and that all through traffic transits the area during ferry operating hours year round. For 24-hr operation of the through vessels, the return periods should be increased by a factor of 1.2.

Consequences

Scenario 1 will not involve the entire cargo contents of a vessel. Typical tankers in the area have six to seven cargo holds on each side (Table 5). Not more than two of these tanks can be ruptured in a collision with a ferry or in a bridge pier striking. The pessimistic prediction is then 2,400 to 10,800 tonnes of tanker cargo spilled at 500-year intervals due to bridge strikings. Similar spills would occur as a consequence of tanker collisions with ferries at 36 to 54 times longer intervals, depending on ferry sailing frequency.

Damage to fuel tanks of any vessel, including a ferry, is not likely, unless the penetration reaches into the double bottom, where fuel tanks are usually located. If every mishap resulted in fuel tank rupture, then a spill of 200 to 800 tonnes of diesel or heavy fuel would occur at 38-year intervals for the bridge alternative and at 1,300- to 1,900-year intervals, depending on sailing frequency, for the ferry alternative.

Mitigation Measures

The return periods could be reduced drastically if an effective vessel traffic management (VTM) system were instituted. The systems have proven effective in preventing potential accidents in waters with high traffic density (*7,9*). A reduction in aberrance resulting from such a system would lengthen the return periods. However, the ratio of mishap frequencies (Equation 7) would not change much if VTM were introduced with both transportation alternatives.

A full-scale VTM system covering Northumberland Strait is not justified for the present vessel traffic volume, but a scaled-down system is in order whether or not a bridge is built. On April 25, 1986, the *Holiday Island* nearly collided with a freighter in restricted visibility due to the ferry master's error. Ferries in the strait occasionally run aground or come close to collision when forced off course by fishing vessels on approaches to docks.

The following recommendations have been made to enhance the safety of vessels navigating under the bridge (*5*):

- Reduce two proposed navigation lanes under the bridge to one and schedule one vessel to pass the bridge at a time,
- Move the location of the navigation channel further offshore to give vessels more room to maneuver,
- Provide visual guidance by means of buoys fitted with radar reflectors to define the navigation channel and to assist vessels in lining up their final approach,
- Provide strobe lights marking the berms on either side of the navigation channel and a sector light on each side of the deck above the center of the channel to illuminate the approaches,
- Place low-intensity navigation lights on each pier or throughout the length of the bridge to assist the passage of small craft outside the main channel, and
- Maintain a traffic control center with radar and radio communication capability and restrict navigation during the ice season (January to April).

Some of these measures are limited by natural constraints. The channel location needs to be balanced against higher construction costs of main piers in deeper water and more difficult winter navigation further offshore. To ensure sufficient clearance for the buoy tenders working in the strong tides of the Abegweit Passage, it may not be possible to lay buoys close to the bridge. The buoys would be lifted for the winter season, and traffic would be rerouted north of the PEI or restricted to ice navigation only in good visibility.

SCENARIO 2: HAZARDOUS MATERIAL TRUCK ACCIDENTS ON FERRY OR BRIDGE

The spectrum of possible spills from trucks would reflect the relative frequency of shipments by class of material, the size of shipment, and the type of packaging. According to Table 3, the most likely shipment is paint, but the quantity spilled would be small owing to the small average shipment size and the use of small containers for packaging. The largest possible spill would not exceed one truckload of fuel.

TABLE 7 RETURN PERIODS OF SCENARIO 1

				Return Period, years		
				Bridge	Ferry Collision	
Vessel Type	N	Pgm	Pgs	Striking	Q=12,000	Q=18,000
All vessels	260	0.16	0.24	38	1,900	1,300
Laden tankers	18	0.17	0.28	500	27,000	18,000

Ferry

The following events might lead to hazardous cargo release from a truck on board a ferry: rough seas; ferry grounding, sinking or foundering; ferry striking of a fixed object; ferry collision with another vessel; and on-board fire or explosion.

Fires or explosions on ferries are extremely rare events owing to stringent precautions. Dangerous goods ferry sailings could be canceled during inclement weather. Trucks could suffer damage on a grounded ferry. This happened recently in British Columbia when the grounded *Queen of Alberni* listed heavily once the tide ran out.

Vehicle tie-downs to the ferry deck could reduce the risk of truck damage in groundings or strikings of fixed objects. In a collision, however, the bow of the other vessel involved may penetrate the vehicle deck area, causing rupture of the tie-downs and direct damage to the trucks. Positioning of tank trucks on the inside lanes of the ferry deck and trucks with cargo in small containers on the outside lanes would solve the problem. The outside lanes could also be kept entirely clear of dangerous goods vehicles.

According to the records of the ferry operator, the only accidental release from a truck on board took place in 1954, in the first year of exclusive sailings for dangerous goods. The mishap probably occurred because of lack of experience. A tank of a tanker truck carrying gasoline was punctured in rough seas. It is now known whether or how much of the gasoline flowed overboard.

The single event is not a sufficient basis for calculating the frequency of mishaps occurring during hazardous materials sailings. Technology and procedures have improved substantially owing to environmental awareness and regulatory requirements of hazardous materials transportation. Also, because of lack of detailed historical records of the special sailings, it is not possible to relate the data to an objective measure of transportation productivity, such as vehicle-kilometers or tonne-kilometers.

An upper bound estimate of the return period of collision of hazardous material ferry with another vessel can be calculated from Equation 1. For two sailings per day, the return period is 30,000 years. A dangerous goods truck spill from such a collision would be even less likely, because the containers would have to be damaged and the hazardous material would have to find its way overboard.

Bridge

Truck accident rates on the proposed bridge were estimated from the following rates at other locations (*4*): 0.787 accidents per million vehicle km (mvk) on the Mackinac Strait Bridge in Michigan (1986 to 1988), 0.697 accidents/mvk on the Seven Mile Bridge in the Florida Keys (1986 to 1988), and 0.946 accidents/mvk on two-way, controlled-access freeways in Nova Scotia (1978 to 1983). Data from these locations is not disaggregated as to type of vehicles involved, type of accident, and severity of accident. These figures represent upper bounds of hazardous cargo spill probabilities. Although estimates of 0.36 to 0.62 for the conditional probability of a release from a dangerous goods truck involved in a highway accident are available (*4*), these data have not been considered for analytical consistency with the truck-on-ferry scenario.

If each accident results in a release, and 9,200 shipments of dangerous cargo are made over the length of the bridge per year, the upper bound on the return period of a release is about 10 years. Even with a typical 0.5 rate of release, this return period would be unacceptable. The following mitigative and contingency measures have been requested for bridge design and operation (*1,10*):

- Control and monitor traffic in adverse weather conditions, during maintenance lane closures, and after accidents;
- Inspect vehicles hauling oversize loads and dangerous goods, limit their passage to hours of low traffic and good weather conditions, and dispatch under escort if required;
- Provide median crash barrier on the bridge deck to prevent head-on collisions and guardrails along the shoulders to prevent vehicles from falling into the water;
- Provide emergency telephones and video traffic surveillance to facilitate quick responses to accidents and fires on the bridge;
- Institute procedures and resources for fire fighting, emergency cleanup of roadway, towing of disabled or leaking vehicles, and emergency storage of such vehicles; and
- Provide check valves in bridge downspouts to contain the spilled material on the deck.

SCENARIO 3: OPERATIONAL SPILLS OF HAZARDOUS MATERIALS

Between 1979 and 1988, five releases of dangerous goods from the Northumberland Strait ferry vessels took place during normal operations (*4*). The releases included leaks and fueling spills of 50 to 2300 L of diesel fuel and lubricating oil, and they occurred every 2 years on the average (Table 8). Most of these accidents were caused by negligence and human error and could be prevented in the future by improved operating procedures, better preventive maintenance, and stricter periodic inspections.

There is a possibility of spill incidents involving vessels and road vehicles engaged in operating and maintaining the bridge, its navigational aids and furniture, and the pavement surface. By judgment, risks of these incidents may be lower than in ferry operations, because no large vessels will be involved. Maintenance activities, such as preservation of the structure from the marine environment or application of antifouling chemicals, must be monitored to ensure that the marine habitat is not contaminated.

CONCLUSIONS

Spills in the Abegweit Passage can occur from vessels involved in collisions with the existing ferry or with the proposed bridge. They can also originate from trucks transporting dangerous goods on board the ferry or over the bridge. Because site-specific data on accident frequencies and the release rates for dangerous goods from vessels and trucks are lacking, only a comparative risk analysis of the two tranportation alternatives is possible.

Petrochemicals are the most likely spill commodity. The potential maximum size of a spill is similar for the two trans-

TABLE 8 SPILL SUMMARY

	Ferry		Bridge	
Scenario	T, year	Spill	T, year	Spill
1a [a]	18000-27000	2400-10800 t	500	2400-10800 t
1b [b]	1300-1900	200-800 t	38	200-800 t
2	30000	40 t	10	40 t
3	2	50-2300 L	nd	nd

[a] tanker spill from two tanks; [b] spill from vessel fuel tank;
T = return period assuming 100% conditional probability of release; nd = no data

portation alternatives, but the return period is several orders of magnitude higher for the ferry than for the bridge (Table 8). The size of the spill decreases by at least one order of magnitude each time the scenario changes from tanker mishap, to vessel fuel tank rupture, to truck spill, to operational spill. A similar pattern can be seen in the return periods, except truck-on-ferry accident is the most unlikely event.

The short return periods and large spill quantities can be improved by instituting traffic management systems for vessels and trucks, by providing on-site emergency response and containment of spills in the bridge drainage system, and by requiring more stringent operating and maintenance procedures.

ACKNOWLEDGMENTS

This paper is based on the author's subconsulting services to Coles Associates, Ltd., and Delcan-Stone Webster Joint Venture, who were commissioned by Public Works Canada to study the Northumberland Strait Crossing. The paper also incorporates the author's own research, which has not been included in the principal consultants' reports. The contribution of the British Columbia Ministry of Transportation and Highways to the preparation of the paper is acknowledged with gratitude. The author is solely responsible for the contents of the paper.

REFERENCES

1. Federal Environmental Assessment Review Office. *The Northumberland Strait Crossing Project, Report of the Environmental Assessment Panel.* Federal Environmental Assessment and Review Process, Panel Report 34, Environmental Canada, Hull, Quebec, Canada, 1990.
2. P. Bein. Probabilistic Model of Barge Impact Energy on the Annacis East Bridge Piers. In *Modelling Under Uncertainty, Proc., 1st International Conference on Modelling Under Uncertainty,* (S. B. Jones and D. G. S. Davies, eds.). Fulmer Research Institute (England). Conference Series 80, Institution of Physics, Bristol and Boston, 1986, pp. 297–306.
3. P. Bein. Risk Modelling of Vessel Impacts on a Multispan Bridge. *Proc., International Conference Structures Under Shock and Impact (SUSI), Cambridge, Mass., 1989.*
4. Delcan-Stone & Webster, *Comparative Transportation Risk Analysis,* Northumberland Strait Crossing Project, Public Works Canada, 1989.
5. Coles Associates Ltd., P. Bein, and Allardice & Associates Ltd. *Northumberland Strait Bridge Vessel Traffic and Bridge Safety Study.* Public Works Canada, 1987.
6. Y. Fujii. Integrated Study on Marine Traffic Accidents. *Proc., IABSE Colloqium on Ship Collision with Bridges and Offshore Structures,* Copenhagen, Denmark, International Association for Bridge and Structural Engineering Report Vol. 42, 1983, pp. 91–98.
7. Y. Fujii. Recent Trends in Traffic Accidents in Japanese Waters. *Journal of Navigation,* Vol. 35, No. 1, Jan. 1982, pp. 90–99.
8. P. Bein. Methodology for Assessment of Vessel Impact Energy on Bridge Piers and Spans. In *Transportation Research Record 1275,* TRB, National Research Council, Washington, D.C., 1990, pp. 81–88.
9. V. H. M. Lighthart. An Inquiry into North Sea Navigation. *Journal of Navigation,* Vol. 38, No. 1, Jan. 1985, pp. 90–99.
10. Delcan-Stone & Webster, *Bridge Concept Assessment.* Northumberland Strait Crossing Project, Public Works Canada, 1989.

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

Evaluation of Minimum Bridge Span Openings Applying Ship Domain Theory

AKSEL G. FRANDSEN, DAN F. OLSEN, HENRIK T. LUND, AND PAUL E. BACH

The background for this study is the Great Belt Fixed Link Project, Denmark, which includes the construction of a large span suspension bridge crossing an international shipping route. As part of a comprehensive vessel collision study for the proposed bridge, analyses of vessel collisions to bridge piers at several U.S. and Canadian bridges have been carried out. By use of empirical rules for navigation span opening requirements derived from ship domain theory, it has been possible to use vessel collision experience from bridges with different span openings, vessel traffic flow, navigational conditions, and environmental conditions. The results, achieved through the analyses of existing bridges, support the use of the empirical rules in the derived form to estimate the minimum span opening for the East Bridge. The results confirmed the need for a large span as found by computer-based maneuvering simulations. The empirical rules are considered to be useful tools, which could be applied to a first-step estimation of the minimum navigation span opening of bridges and also as part of the analysis of navigational safety at existing bridges. The study included development of another method to evaluate the relationship between bridge design and ship traffic by estimation of the number of close encounters in the vicinity of the bridge on the basis of the assumption of Poisson-distributed vessel arrival.

The background for the reported work is the ongoing Great Belt Fixed Link Project, which will connect Zealand and Funen in Denmark with a combined bridge and tunnel link via the small island of Sprogoe. The Great Belt Strait is approximately 17-km wide at the point of crossing and Sprogoe is located approximately in the middle. An international shipping route passes through the eastern part of the strait and is the only deep-water route connecting the Baltic Sea with the North Sea. The traffic flow is approximately 20,000 vessels per year. At the moment there is intensive ferry traffic across the strait (a total of approximately 50,000 movements per year), most of which will disappear after the fixed link is installed.

The fixed link consists of three parts. The western part of the link will be a combined rail and road bridge. The Eastern Channel crossing will consist of a bored tunnel for train traffic and a suspension bridge (the East Bridge) for motor vehicles. The East Bridge will have a number of piers located in navigable water and thus be exposed to the risk of vessel collisions.

Preliminary investigations for a fixed link was carried out during 1977 to 1979 and included a study of the risk of vessel collision (*1*). In 1989, the Great Belt Link Ltd. asked COWIconsult to undertake a new comprehensive investigation of the interaction between vessel traffic and the planned bridge structures across the Eastern Channel. The vessel collision study was carried out in cooperation with Ben C. Gerwick, Inc., San Francisco.

The work included collecting data on the existing conditions for the vessel traffic in the Great Belt, forecasting expected traffic development, collecting vessel accident statistics and data on environmental conditions, evaluating the effect of the planned bridge structures on the navigation conditions, and evaluating risks of collisions as well as predicting potential consequences of the possible collisions. The results of the investigations have formed the basis for a new, improved vessel–bridge collision model. Methods to reduce the risk of vessel collision have been investigated. A conceptual design of a vessel traffic service system has been developed in cooperation with representatives from the Danish Navy and the Danish Maritime Authorities.

The navigation span opening has proved to be one of the most important design parameters for the design of the bridge. Different methods have been applied to evaluate the effect of the span opening on the navigational conditions. The resulting span opening requirements have led to rejection of bridge design alternatives with span openings of less than 1,600*m*.

Computer-based maneuvering simulations were carried out in cooperation with experienced Great Belt pilots at the Danish Maritime Institute, the Copenhagen School of Navigation, and the Naval Tactical Trainer at Frederikshavn Naval Base. These analyses were significant in the clarification and verification of the effect of different navigation span openings and different changes of the navigation route under normal as well as adverse weather conditions. Because the resulting span opening requirement surpassed earlier estimates, it was found advisable to try to verify this result by an alternative method.

The second method used worldwide experience of vessel behavior and knowledge of the local vessel traffic and other main navigational conditions, and the method offers an estimate of the minimum span opening. Empirical rules for minimum span opening as a function of traffic volume, vessel sizes, and so on were formulated from ship domain theory. Vessel collision records from large bridges worldwide were collected and the empirical rules were verified by testing on a number of U.S. and Canadian bridges.

Earlier studies on vessel collisions have investigated severe accidents at large span bridges (*2*). Collisions with severe

---

A. G. Frandsen, D. F. Olsen, and H. T. Lund, COWIconsult, Consulting Engineers and Planners AS, Teknikerbyen 45 DK-2830 Virum, Denmark. P.E. Bach, Ben C. Gerwick, Inc., Consulting Construction Engineers, 601, Montgomery Street, San Francisco, Calif. 94111.

damage to a bridge are rare and difficult to treat statistically. In this study records of all vessel collisions to a number of bridges have been obtained and used in the analyses. Furthermore, a concept for estimation of the number of close encounters has been developed on the basis of traffic data and an assumption of Poisson-distributed vessel arrival. For instance, the method can be used to evaluate whether the shipping route should be considered a one-way or a two-way traffic route. The study has proved the advantage of using several different approaches to estimate the minimum span opening. The empirical rules developed on the basis of ship domain theory can be of interest to other bridge designers as a first step in the sometimes lengthy and complex process of determining a span opening, which will provide safe vessel passage of a bridge. Methods of transfer of vessel collision experience from other bridges and the empirical methods for evaluation of minimum span opening are described in this paper.

PURPOSE OF STUDY

The purpose of the study has been to develop methods to use vessel collision experience from other bridges to evaluate the risk of collision to the piers of the proposed Great Belt East Bridge. One of the main tasks in this connection has been to develop methods to evaluate whether a bridge is designed to provide safe navigation according to the actual vessel traffic, navigational conditions, and environmental conditions at the bridge location. This has led to formulation of empirical rules for estimation of minimum navigation span opening and a calculation method for estimation of the number of close encounters in the vicinity of a bridge.

EMPIRICAL RULES

Empirical methods to estimate the minimum navigation span opening of bridges have been considered in the following. The general idea is, through statistical analyses, to estimate the navigation span opening needed for the vessels to pass the bridge with a given high level of safety under normal conditions. The span opening is sufficient when vessel collision to a bridge occurs only under extreme conditions, such as navigational errors and technical errors, possibly in combination with adverse visibility and weather conditions. Analysis of the space requirements for vessels under different navigational circumstances is treated in the well-known ship domain theory.

Ship Domain Theory

To navigate safely, the captain of a vessel tries to keep a fairly large distance from other vessels, fixed objects, shallow water, and so on. The distance varies considerably for the specific vessel speed, visibility, type of encounter, and a number of navigational aspects. This safety area around the vessel is denoted as the "ship domain." The ship domain can also be approached through the "bumper area," defined as the area a vessel actually occupies in the waterway and includes a zone around the vessel in which other vessels' bumper areas should not overlap. The safety distance is smaller in the side direction than in the course direction. Figure 1 shows a sketch of a waterway with two vessels of the same size in a head-on encounter in a narrow waterway, and the approximate ship domains and bumper areas. The vessels pass at the shortest acceptable distance, as the bumper areas touch and each vessel is on the border of the other vessel's ship domain.

Bumper Areas for Vessels at Service Speed

Yamaguchi (*3*) carried out analyses of minimum navigation channel opening for the Honshu-Shikoku Bridge Authority in 1968. His conclusions were derived from maneuverability of vessels and observed distribution of separation from drilling platforms at sea. Yamaguchi concluded that the minimum navigation channel opening for a one-way shipping lane with vessels traveling at service speed is approximately $3L$, where L is the overall length of the vessel. For a two-way shipping lane the minimum opening was found to be approximately $4.5L$.

Fujii and Tanaka (*4*) analyzed the vessel movements in several Japanese straits with vessels traveling at service speed (10 to 15 knots). Their analyses are of a large amount of data obtained through radar observations. The observed vessels were mainly smaller vessels in the range up to 10,000 gross registered tonnage (GRT). They found that the bumper area can be estimated with an ellipse with axes depending on the vessel length. They found the following lengths of the axes:

Course direction: $7L \pm L$ (1)

Side direction: $3L \pm 0.5L$ (2)

Later observations by Fujii et al. (*5*) led to the following average values:

Course direction: $8.0L$ (3)

Side direction: $3.2L$ (4)

Observations by Toyoda et al. (*6*) led to almost the same values as Fujii, and observations by Tanaka and Yamada (*7*) led to average values of $7L$ and $3L$, respectively. Other ref-

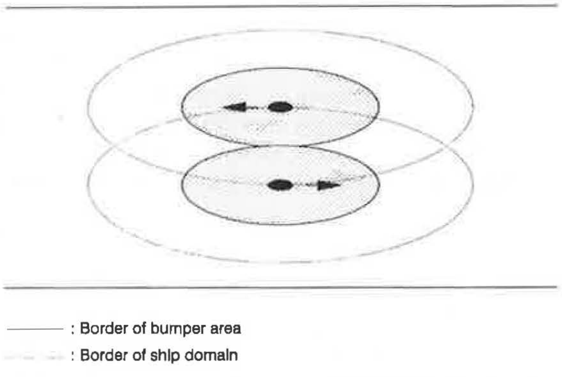


FIGURE 1 Vessels and respective bumper areas and ship domains in a narrow waterway.

erences on the subject are Hayafuji (*8*) and Okuyama et al. (*9*).

It should be noted that these values are average values for different conditions of visibility and other weather conditions. An important condition for use of these values is that the waterway has sufficient width to provide free navigation at service speed and with no obstructions in the channel (islands, shallow water, etc.). It should also be noted that these results have been derived from waters with a higher traffic density than most European and U.S. waters and with a large fraction of small vessels.

Goodwin (*10*) studied the size of bumper areas by observing vessel traffic in the Dover Strait. Her studies resulted in much larger bumper areas, indicating a minimum channel opening of 0.5 nautical miles (approximately 900 m) for one-way lane. This work was done on the basis of much fewer observations than were the Japanese observations. The relatively small traffic density in the Dover Strait compared with the Japanese straits probably makes these observations less representative for the minimum bumper area.

Equations 3 and 4 were developed on the basis of the largest and most representative set of data. Therefore, these bumper areas are used in the derivation of an empirical rule for estimating the minimum navigation span opening of a bridge crossing a waterway with free navigation.

Bumper Area for Harbor Speed (Hard Core Model)

As mentioned previously, the results derived from Equations 3 and 4 are valid only for waters in which vessels can navigate at service speed. In cases in which the traffic in the waterway is restricted in any way, a different bumper area must be applied. The theory for very restricted waters has been treated in the "Hard Core Model."

Fujii et al. (*5*) and Fujii and Yamanouchi (*11*) studied the Hard Core Model for narrow channels and harbor traffic in which the vessels are traveling at reduced speed. Fujii studied the phenomenon, for instance, in the ports of Tokyo and Yokohama. The following bumper area axes were a result of these studies:

Course direction: $6.0L$ (5)

Side direction: $1.6L$ (6)

The average speed of the observed vessels was 6 to 8 knots. These results are for somewhat fewer radar observations than in the case of the bumper area for vessels at service speed, again with the main part being smaller vessels.

The Hard Core Model should be used only

- If very limited areas such as ports or narrow rivers are being considered, or
- If the following conditions are fulfilled
  - —Waterways with restrictions on vessel speed; no head-on, overtaking, or crossing encounters; and a suitable traffic management system to ensure the restrictions are observed;
  - —Vessels traveling at harbor speed (however, the vessels should still be controllable with the rudder);
  - —The distance to the nearest bend in the route should be long enough to ensure that the navigation is not affected by the bend.

Vessels are expected to maintain service speed and thus the full bumper area as long as the channel width is wider than the minimum channel width.

For a one-way lane, the minimum channel width is equal to the width of the bumper area of a vessel at service speed. To maintain service speed in case of two-way traffic, a channel width corresponding to the total bumper area width of two meeting vessels plus a separation zone between the bumper areas is necessary.

The Japanese investigations give no clear picture of the width of the minimum separation zone between the lanes. The matter is discussed in Fujii et al. (*12*), which summarized the work of Toyoda, Sakaki, Tanaka, Fujii, and others. A rough average of the results shows that vessels at anti-directional encounter do not pass with less than $3.5L$ to $5.0L$ distance between the vessels. Using the domain theory, this corresponds to a separation zone of $0.3L$ to $1.8L$.

In many straits and rivers, the official navigation channel is rather narrow, but outside the channel the water is deep enough for middle-size vessels in loaded condition and large vessels in ballast condition. This should be taken into consideration when estimating the actual width of a navigation channel.

Formulation of Empirical Rules

For one-way traffic, the domain theory suggests a minimum navigation span opening equal to the width of the bumper area of a typical large vessel passing the bridge. The typical large vessel should be a representative for the largest group of vessels passing the bridge, however, not the largest vessel. In the following the typical large vessel is found by estimating the 95 percent fractile vessel size from traffic statistics on the basis of dead weight tonnage (DWT) or draft. This fractile indicates that 95 percent of the total number of vessels passing are less than or equal to the size of the typical large vessel. By using an empirical conversion equation from tonnage or draft to vessel length, it is possible to estimate the typical vessel length.

For two-way traffic the following equations for the minimum navigation span opening of a bridge can be derived from the ship domain theory. For waterways with vessels traveling of service speed

$$W = (2 \cdot 3.2 + a)L \qquad (7)$$

where W = navigation span opening m and a = coefficient for width between lanes (separation zone) and separation between bumper areas and piers.

For waterways with vessel traveling at reduced speed

$$W = (2 \cdot 1.6 + b)L \qquad (8)$$

where b = coefficient for width between lanes (separation zone) and separation between bumpers areas and piers.

As mentioned previously, investigations in Japan suggest a separation zone of approximately $0.3L$ to $1.8L$ in case of vessels traveling at service speed. In the following, a minimum separation zone and separation between bumpers areas and bridge piers of $1.0L$ in both cases is assumed, that is, $a = b = 1.0$. The situation in a waterway crossed by a bridge and with two typical large vessels passing is illustrated in Figure 2. An encounter of two vessels of same size is shown. It should be noted that these empirical rules are valid only if effects of bends and other obstructions in the navigation route can be neglected.

Shoji (*13*) has estimated that the minimum distance from a bridge line to the position of the nearest turn in the navigation route should be at least $8L$ and preferably $20L$. If the distance is smaller, the turn will result in more complicated navigation conditions. These results are based on analysis of collisions at bridges worldwide, and the vessel lengths used are the size of the colliding vessel. Similar results have been obtained from the maneuvering simulations carried out in connection with this study.

Calculation for the Great Belt, Eastern Channel

The typical large vessel for the Great Belt Eastern Channel is found as the 95 percent fractile vessel to be 40,000 DWT. The corresponding vessel length is found to be approximately 200*m*.

According to local pilots, the traffic in the Eastern Channel passes at service speed and Equation 7 is applied to estimate the minimum required navigation span opening as follows:

$$W_{\text{Min}} = 7.4 \cdot 200 = 1{,}480m$$

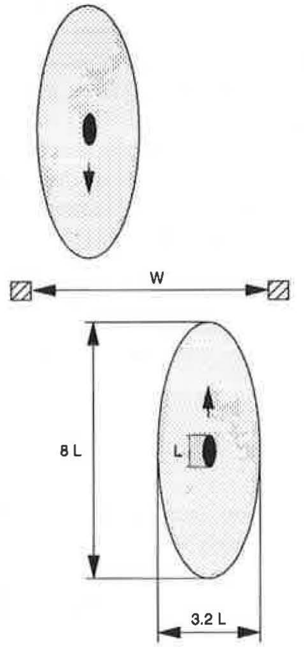


FIGURE 2 Parameters in the empirical rules for determining the minimum span opening requirement for a bridge.

In the computer-based maneuvering simulation analyses of this ship collision study (COWIconsult, for the Great Belt Link Ltd., 1989, unpublished data) it is found that navigation span openings of less than 1,400*m* are insufficient, even if the navigation route is straightened. This means that almost the same value is found for the minimum navigation span opening with the two different estimation approaches. Consideration of local navigational conditions led to a resulting span opening requirement of 1,600 *m*.

Evaluation of Traffic Density

In connection with the evaluation of minimum main span openings of bridges crossing a waterway, it is necessary to evaluate the density of the vessel traffic. If the traffic is sparse the vessel traffic can possibly be considered as one-way traffic, because vessel encounters in the vicinity of the bridge are unlikely.

Two different models for evaluation of the traffic density have been utilized:

- Traffic density based on area, and
- Traffic density evaluated using a "Bumper Chain Model."

The traffic density based on area is defined as the average number of vessels per unit area of the waterway per unit time. The density can be compensated for by the differences in bumper areas by use of weighting factors (L^2-converted traffic density). With a reference vessel of 1,000 GRT, approximately 70*m* long, the Great Belt Eastern Channel has a density of 0.05 vessels/km^2 and a L^2-converted density of 0.17. For comparison the densities for Uraga Strait in Japan is 0.7 and 1.10, respectively, and for Dover Strait 0.015 and 0.065. Thus the L^2-converted density in the Great Belt is about ⅙ of that of Uraga Strait and 3 times that in Dover Strait.

The Bumper Chain Model is based on the assumption that vessels in a narrow waterway do not overtake each other. Thus, the most dense situation occurs when vessels in a lane pass in a long line, bumper area to bumper area. The density is thus defined as the percentage of the number of vessels in the most dense situation. Again, the bumper areas should be estimated on basis of the actual vessel size distribution. At the Great Belt Eastern Channel the bumper chain density is 3 percent, whereas in Uraga Strait the density is 24 percent.

The methods can be used to estimate the actual traffic density in a strait relative to a theoretical maximum value and relative to the density in other straits. No statistical analyses have been found in the literature concluding what the practical maximum density for a strait is. Likewise, no references have been found stating a limit for when the traffic density in a two-way channel is so low that the traffic can be considered one-way traffic.

The traffic separation in the Great Belt Eastern Channel was introduced in 1976, as it was considered necessary to secure the traffic safety in the area. According to the authorities and the pilots operating in the area, it is essential to maintain the traffic separation after the bridge has been built. This indicates that traffic in the Great Belt Eastern Channel has to be considered two-way traffic.

In the analyses of span openings of existing bridges, the traffic density is therefore evaluated in the following way. If the traffic density calculated with the two methods described previously is greater than or equal to the density in the Great Belt Eastern Channel, the traffic is considered two-way traffic. If the traffic density is considerably smaller than the density in the Great Belt Eastern Channel, the traffic is considered as one-way traffic. In the latter case, a closer analysis of the traffic in the specific strait or river has been carried out by application of, for instance, the close-encounter method described later in this paper. If there is a traffic separation in the navigation channel, the traffic will in any case be considered two-way traffic because the vessels are expected to keep the intended lane under all circumstances.

Codes and Guidelines

Only few codes and guidelines exist for evaluation of minimum bridge navigation span opening. During this study only two codes or guidelines were found of interest.

On the basis of ship domain theory, the Japanese Government in 1973 passed a Maritime Safety Law (*14*), requiring that the minimum width of a fairway for international vessel traffic is 700*m* for one-way passage and 1,400*m* for two-way traffic (the length of a typical large vessel is generally set to 200*m* for the major Japanese waterways). Accordingly, the Maritime Safety Law has been applied to the major Japanese bridges developed in recent years, namely, the Bisan Seto Bridge providing two separate navigation routes of each 700*m* width and the Akashi Kaikyo Bridge with a span of 1,990*m* across the 1,500*m* route for two-way passage.

Greiner, Inc., is preparing a guide specification for the Federal Highway Administration, U.S. Department of Transportation (*15*) on the subject of vessel collision with bridges crossing navigable waterways. This specification will include recommendations for navigation span openings.

Application to Existing Bridges

To check the empirical rules for minimum navigation span opening, the rules have been tested on existing bridges. In connection with this vessel collision study, a worldwide review of major bridges with navigational conditions somewhat similar to the Great Belt East Bridge has been carried out. Bridge authorities, marine safety authorities, and engineering companies in the different countries have been addressed. The authorities in the United States and Canada have provided useful information on vessel collisions and vessel traffic at selected bridges. Therefore, the analyses in this report concentrate on bridges in these countries.

Collision statistics have been obtained from a number of different sources. The main sources of information have been the Vessel Casualty Data Base and other material from the U.S. Coast Guard and the Marine Casualty Data Base of Transport Canada. All vessel collisions reported within the last 10 years at the selected bridges have been included in the analyses. Additional information has been collected from published articles and reports on the accidents. It should be noted that the analyses were performed with limited knowledge of the bridge design, navigational conditions, and so on at the selected bridges. The information has been mainly in the form of plan and elevation diagrams for the bridges, nautical charts of the waterways, and trip/draft tables from nearby harbors.

The information varies in quality and amount of data provided. In some cases, the size of a vessel in question is only known by the draft, GRT, or DWT. For this reason, a number of empirical conversion equations have been applied to estimate some information, for example, the length of the vessel from the GRT or DWT. Rules have been taken from Fujii et al. (*5*) and from Knud E. Hansen ApS (*16*). In some cases accurate information about the actual span opening has not been available. In these cases, the navigation span width (measured from centerline to centerline of main piers) has been applied.

The calculation of the minimum navigation span opening of a specific bridge is carried out by means of the theory and rules described previously. The characteristic vessel length is taken as the 95 percent fractile of draft or tonnage. The traffic data is found mainly from trip/draft tables from nearby harbors. In each case it is evaluated if one- or two-way traffic can be assumed. As an example of estimation of minimum navigation span opening, the calculation for the Newport Road Bridge, Rhode Island, is now summarized. From 1987 trip/draft tables (*17*), it was determined that the 95 percent fractile for the draft is 8.7*m*. This corresponds to a vessel length of approximately 105*m*, assuming loaded condition. The trip/draft tables show a total annual number of bridge passages of approximately 6,300, of which only a few were large vessels. Analysis of the traffic density and calculation of the number of close encounters at the bridge indicate that the traffic can be assumed to be one-way traffic.

The analysis of the navigational aspects of the waterway shows that free navigation with vessel traveling at service speed can be expected. Under these circumstances the minimum span opening can be estimated from Equation 4 to be $3.2 \cdot 105 = 336m \approx 340m$ (rounded to the nearest 10*m*). This indicates that the actual span opening of 488*m* is sufficient.

Such estimates have been carried out for 26 bridges in Canada and the United States. These bridges have been selected by the following criteria:

- Main span openings of the bridges were greater than 200*m* (with a few exceptions),
- Data on vessel traffic and on a typical large vessel have been available, and
- One or more bridge piers are placed in navigable water.

All the bridges that were examined are shown in Table 1. There are two main groups of bridges. The first group contains the bridges for which the empirical rules for the minimum span opening are fulfilled and the second group contains the bridges for which the empirical rules were not fulfilled.

The first group contains 12 bridges, of which two collisions (at the Greater New Orleans Bridge and the Newport Road bridge) have been reported within the last 10 years. The second group contains 14 bridges. During the same time, 46 collisions have been reported for the second group of bridges. The Greater New Orleans Bridge was hit by a barge in 1985. The span opening of approximately 480*m* is wide enough for

TABLE 1 COMPARISON OF ACTUAL SPAN OPENING, MINIMUM SPAN OPENING REQUIREMENT, AND THE OBSERVED NUMBER OF COLLISIONS WITHIN THE LAST 10 YEARS FOR 26 U.S. AND CANADIAN BRIDGES

Bridges Following the Empirical Rules:

Bridge Name	State	Open Year	Navigation Span Opening As Built (m)	Navigation Span Opening Min. (m)	C^a A T	T^b R A F	C^c O L L
Delaware River Mem.	Delaware	1951	655^S	190	F	2	0
Golden Gate	California	1937	1280^S	410	F	2	0
Greater New Orleans	Louisiana	-	480^S	350	V	2	1
Lions Gate	Br. Columbia	-	396^C	290	H	1	0
Longview	Oregon	1930	366^S	350	F	2	0
Luling	Louisiana	1972	370^S	250	V	2	0
Mackinac Straits	Michigan	1957	914^C	320	F	1	0
Mc Cullough Mem.	Oregon	1936	242^S	180	V	1	0
Newport Road	Rhode Island	1969	488^S	340	F	1	1
S.F.-Oakland Bay	California	1936	2x702^S	400	F	2	0
Tappan Zee	New York	1955	369^S	300	V	1	0
Verrazano Narrows	New York	1964	1298^S	1180	F	2	0

Bridges Not Following the Empirical Rules

Bridge Name	State	Open Year	Navigation Span Opening As Built (m)	Navigation Span Opening Min. (m)	C A T	T R A F	C O L L
Carquinez Strait	California	1927/1958	2x305^C	420	F	1	1
Francis Scott Key	Maryland	1978	335^C	420	V	2	2
Houston Ship Chan.	Texas	1982	229^S	420	V	2	0
Huey P. Long	Louisiana	1935	229^C	250	V	2	6
Laviolette	Quebec	1967	305^C	350	V	1	0
New Westminster Rail	Br. Columbia	1904	2x49^C	530	V	1	12
Ogdenburg-Prescott	N.Y./Ontario	1960	335^S	350	V	1	1
Québec	Quebec	1917	232^C	350	V	1	2
Richmond-San Raphael	California	1956	300^C	450	F	1	1
Second Narrows Rail.	Br. Columbia	1969	137^C	290	H	1	1
South. Pacific Rail.	Louisiana	1907/1971	98^S	220	F	2	3
Sunshine Skyway	Florida	1954	263^S	530	F	1	3
		1987	366^S				0
Vicksburg	Louisiana	-	265^S	320	V	2	11
Wm. Preston Lane	Maryland	1952/1973	457^C	1250	F	2	1

Dash (-) means that the opening year has not been obtained

S - Span width, i.e. distance between centers of piers
C - Span opening (horizontal clearance), i.e. width of navigable channel

^{a}CAT - Waterway category:
F: Free navigation. V: Very limited waterway. H: Harbor navigation
^{b}TRAF - Traffic category:
1: One-way traffic assumed. 2: Two-way traffic assumed
^{c}COLL - Number of collisions within the last 10 years

the present traffic according to the empirical rule. However, the navigation channel does not apply to all the conditions of the empirical rule, as there are strong bends in the route close to the bridge. Furthermore, the maneuverability of a tug-towed barge is lower than that of a self-propelled vessel. The Newport Road Bridge was hit by a large tanker in 1981, which was attributed to navigation failure in dense fog.

The Laviolette Bridge is in the group of bridges not following the rule but, in fact, the bridge has a span opening almost wide enough according to the empirical rule (305*m* compared with 350*m*). Considering the accuracy of the calculation method, the bridge is, in practice, following the rule. The Houston Ship Channel Bridge has the main piers located on only 3*m* of water, that is, not in navigable water for larger vessels. It is therefore not surprising that no collisions to the piers have been reported.

Altogether, the analyses indicate that for the cases in which the empirical rules are followed, very few collisions have taken place within the last 10 years. In the cases where the rules are not followed one or more collisions have taken place within the last 10 years. The results achieved through these analyses support the use of the empirical rules in the derived form to estimate the minimum span opening for the East Bridge. The overall span opening requirements were found to be surprisingly independent of local environmental conditions such as currents, wind, and visibility.

CLOSE ENCOUNTER METHOD

An obvious extension of the empirical rule is to estimate how often a situation arises where two antidirectional vessels meet in the vicinity of the bridge and their total bumper area widths and separation zone width exceeds the actual span opening. For instance, the method can be used as a tool in the evaluation of whether the shipping route should be considered a one-way or a two-way traffic route, which is important for the evaluation of the minimum span opening. The method has been developed by Ostenfeld-Rosenthal (COWIconsult for the Great Belt Link Ltd., 1990, unpublished data).

Calculation Method

By application of Equation 7 to the vessel lengths L_1 and L_2, the total space requirement for navigation at service speed is

$$3.2L_1 + 3.2L_2 + 0.5L_1 + 0.5L_2 = 3.7\,(L_1 + L_2) \qquad (9)$$

If this total width exceeds the navigation span opening, the situation is referred to as a close encounter. The total zone length in the traffic direction has been estimated to be 16 times the length of the largest of the meeting vessels.

The occurrence of vessels in a zone around the bridge requires a statistical description of the vessel traffic. The Poisson process is generally accepted as a good description of such events—and it has in this study also been found to fit the vessel traffic in Great Belt very well. Because several of the involved parameters depend on the vessel type, it has been found necessary to use a simulation approach to calculate the yearly expected number of close vessel encounters as a function of the bridge span opening. A simulation program has been developed and a calculation for the proposed Great Belt East Bridge and a number of existing bridges has been carried out.

Figure 3 shows that with the present assumptions the Great Belt Bridge should have a navigation span of 1,800*m* in order to completely avoid close encounters. A span of 1,600*m* would mean approximately 17 close encounters per year, and a span of 1,200*m* would mean approximately one close encounter per day.

Applications to Existing Bridges

The number of close encounters has been calculated for some of the bridges in Table 1. Only bridges with one navigation span for both directions have been analyzed. The results of the calculations are shown in Table 2 together with the approximate annual traffic volume at the specific bridge.

The results for the Greater New Orleans Bridge and the Longview Bridge show that a close encounter occurs approximately once a day, which is relatively high considering that the span openings apply to the empirical rules. This is because of the span opening and the heavy traffic in the waterways, causing many multi-encounter situations. At the William Preston Lane, Jr. Memorial Bridge there are approximately two close encounters per day—a rather high number, which supports the conclusion that the span opening of this bridge is too narrow. The results for the Golden Gate Bridge, the Sunshine Skyway Bridge, the Newport Road Bridge, the Tappan Zee Bridge, and the Richmond-San Rafael Bridge show low numbers of close encounters, which result mainly from the low traffic density and low proportion of large vessels. The analysis indicates that the main risk for these bridges is not the multi-encounter situations, but rather one-vessel situations with loss of control.

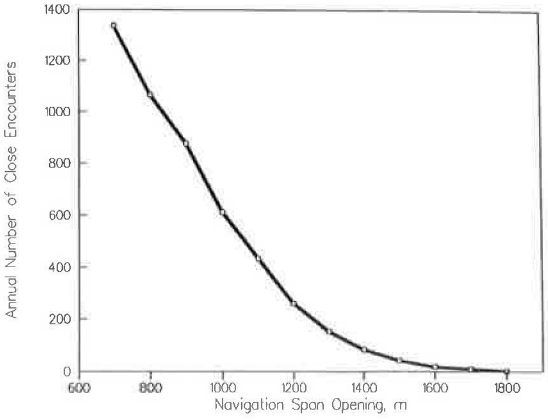


FIGURE 3 Number of close encounters as a function of span opening of the proposed Great Belt East Bridge.

TABLE 2 TRAFFIC VOLUME AND CALCULATED NUMBERS OF CLOSE ENCOUNTERS FOR U.S. AND CANADIAN BRIDGES

Bridge Name	Approximate Annual Traffic Volume	Annual Number of Close Encounters
Golden Gate	37,000	0
Greater New Orleans	148,000	300
Longview	113,000	460
Newport Road	6,300	7
Ogdenburg-Prescott	3,000	160
Richmond-San Raphael	8,000	40
Sunshine Skyway	4,000	88
Tappan Zee	4,400	2
Wm. Preston Lane	11,000	640

The analyses show that the number of encounters at a bridge is highly dependent on the vessel traffic and the distribution of vessel-size classes. There is a tendency for bridges that do not follow the empirical rules on minimum span opening to also have a large number of close encounters. It is, however, not possible at this stage to draw general conclusions concerning the relationship between number of close encounters and number of vessel-to-bridge collisions.

CONCLUSIONS

In this study different methods to estimate the minimum navigation span opening of a bridge by the use of empirical methods have been analyzed. Empirical rules have been derived on basis of the ship domain theory. The determination of the average bumper areas is based on a number of independent statistical analyses of the subject from waterways in Japan and Europe. The different rules are applied depending on the traffic density in the vicinity of the bridge, the average speed of the vessels, the size of a typical large vessel passing the bridge, and different navigational aspects at the bridge location.

Application of the empirical rules to a number of existing large span bridges shows practically no collisions within the last 10 years at bridges following the rules, but shows, in general, one or more collisions at bridges with span openings significantly smaller than the required minimum according to the empirical rules.

The use of empirical rules has proved to be a practical tool as a first step in the estimation of the minimum navigation span opening of bridges and the analysis of navigation safety at existing bridges. The rules provide an approximation of minimum span opening using knowledge of main local navigational and climatological conditions.

The empirical rules have been an important factor in the decision of navigation span opening for the Great Belt East Bridge. The results confirmed the need for a large span as found by computer-based maneuvering simulations taking into account detailed information of local conditions (traffic, currents, wind, visibility, alignment, bends in the route, etc.).

The close encounter method offers an interesting supplement to the empirical rules described in the preceding. Further work should be carried out to refine the method and to make sensitivity analyses.

The experience from the Great Belt Fixed Link Project indicates that minimum span opening should be determined on the basis of several different estimation methods. The use of the empirical rules provides a convenient first-step estimation of the minimum span opening for the bridge designer. The knowledge of local navigational and climatological conditions can in a later phase be used as basis for more advanced and time-consuming methods (e.g., computer simulations).

ACKNOWLEDGMENTS

This study was carried out for the Great Belt Link Ltd., Denmark, as part of a comprehensive investigation of all aspects of the ship collision problem for the planned suspension bridge across the East Channel. The authors are grateful for the opportunity to work with this interesting subject in an inspiring cooperation with the Great Belt Link Ltd., and for the permission to publish the results of the study. The authors wish to acknowledge the U.S. Coast Guard, Marine Investigations, Washington, and Transport Canada, Marine Casualty Investigations, Ottawa, for providing useful information on reported vessel collisions. The authors also wish to thank the bridge authorities and engineering companies that have provided information on bridge design, navigational conditions, and so on for the considered bridges. Buckland & Taylor Ltd., North Vancouver, Canada, provided useful information concerning Canadian bridges. Finally, the authors are grateful to the Japanese traffic researcher Y. Fujii, Tokyo, Japan, for his assistance during the study.

REFERENCES

1. A. G. Frandsen and H. Langsø. *Ship Collision Problems*. IABSE Proceedings P-31/80, IABSE Periodica 2/1980, Zurich, Switzerland, 1980.
2. A. G. Frandsen. *Accidents Involving Bridges*. IABSE Colloquium Copenhagen 1983, Volume Band 41, Copenhagen, Denmark, 1983, pp. 9–26.
3. A. Yamaguchi. *The Navigational Safety of the Honshu-Shikoku Bridges*. Study Report, 1968, Honshu-Shikoku Bridge Authority, Tokyo, Japan, 1973.
4. Y. Fujii and K. Tanaka. Traffic Capacity. *Journal of Institute of Navigation (Japan)*, Vol. 24, No. 24, 1971, pp. 543–552.
5. Y. Fujii et al. *Survey on Vessel Traffic Management Systems and Brief Introduction to Marine Traffic Studies*. Electronic Navigation Research Institute Papers (Japan), No. 45, 1984.
6. Toyoda et al. *Traffic Survey Report in Uraga Strait* (in Japanese). Research Group in Tokyo University of Mercantile Marine, Tokyo, 1967.
7. K. Tanaka and K. Yamada. On the Equivalent Number of Vessels of Various Size in the Marine Traffic (in Japanese). *Journal of Navigational Society of Japan*, No. 44, 1970.
8. Y. Hayafuji. Analysis about the Mutual Relative Position of Ships that are on Run in Tokyo Bay (in Japanese). *Report of the Port and Harbour Research Institute*, Vol. 22, No. 1, Tokyo, Japan, 1983, pp. 98–117.
9. Y. Okuyama, Y. Hayafuji, Y. Sasaki, and T. Nakatsuji. A Study on The Marine Traffic Behaviours—Establishment of Methods of Observations and Analysis, *Journal of the Port and Harbour Research Institute*, Vol. 15, No. 1, 1976, pp. 39–49.
10. E. M. Goodwin. A Statistical Study of Ship Domains. *Journal of Navigation*, Vol. 28, 1975, p. 328–343.
11. Y. Fujii and Yamanouchi. On the Hard Core of the Effective Domain in Yokohama Port (in Japanese). *Navigation*, No. 38, Japan, 1973, p. 56.
12. Fujii, Yamanouchi, Tanaka, Yamada, Okuyama, and Hirano. *The Behaviour of Ships in Limited Water*. 24th International Navigation Congress, Leningrad, 1977.
13. K. Shoji. On the Design of the Waterways passing through the Bridges in View of the Analysis on Ship Collision Accidents. *Journal of the Tokyo Mercantile Marine*, No. 36, Tokyo, Japan, 1985.
14. *Marine Safety Law*. The Japanese Association for Preventing Marine Accidents, Tokyo, Japan, 1985.
15. Greiner, Inc. *Vessel Collision Design of Highway Bridges*. Final Report. FHWA, U.S. Department of Transportation, Offices of Research & Development, July 1989.
16. Knud E. Hansen ApS. *Research of Data, Navigation, and Maneuvering for Ships in Connection to the Great Belt Bridge* (in Danish). Statsbroen Store Bælt, Copenhagen Aug. 1978.
17. *Waterborne Commerce of the United States, Parts 1–4*. Department of the Army, Corps of Engineers, New Orleans, 1987.

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

Probability Model of Lockage Stalls and Interferences

HARRY H. KELEJIAN

A model of lock failures as manifested by stalls or interferences and specified in terms of a logit formulation is presented in this paper. Stalls or interferences that correspond to commercial tow and recreational vessel lockages and that result from lock hardware problems or to testing or maintaining the lock or its equipment are first considered. The expected frequency of such lock failures relative to the number of commercial tow and recreational vessel lockages is then explained. These expected frequencies can be viewed as measures of reliability or interpreted as the probability that such failures will occur on any given commercial tow or recreational vessel lockage. The qualitative results corresponding to the underlying variables are consistent with expectations. The usefulness and flexibility of the model in evaluating changes in the values of these variables is demonstrated. Among other things, this demonstration suggests that many major maintenance projects relating to lock chambers can be evaluated by their consequent effect on lock failure probabilities. It is demonstrated that the extent of the renewal of a chamber in response to major maintenance can be calculated.

The following scenario was suggested in a recent study (Charles Yoe, unpublished data). The Army Corps of Engineers operates and maintains 260 lock chambers and 536 dams at 596 sites. These structures are in various states of repair, performance, and obsolescence. Many of them are older than their original 50-year design life. Maintenance, repair, major maintenance, and replacement of these facilities are becoming increasingly necessary and increasingly costly. Furthermore, the recent inland navigation investment program, as reflected by total appropriations for general construction and operations and maintenance has declined from $689 million in fiscal year 1980 to $655 million in fiscal year 1987. After adjusting for price level differences, this 5 percent nominal decline becomes a 35 percent real decline. Continued and even increasing strain on fiscal resources is expected for the foreseeable future. Further details are given elsewhere (*1*).

As a result of increasing needs and decreasing fiscal resources to meet those needs the Corps' decision problem is how best to allocate scarce resources to operation, maintenance, repair, major maintenance, and replacement of structures on the inland waterway. In evaluating the economic impacts of many of these investment decisions, it is necessary to quantify the costs of increasingly unreliable or insufficient service at locks and/or the benefits of improving reliability or increasing capacity. This analysis of reliability generally requires an effort to quantify the probabilities of impaired lock services with and without proposed projects.

This study presents a model of lock failures as manifested by stalls or interferences. A stall is an occurrence which stops lock operation. An interference is an occurrence which slows lock operation during a lockage. For more detail see the Corps' *User's Manual for Data Analysis* (*2*).

The model considers stalls or interferences (henceforth, stalls) that correspond to commercial tow and recreational vessel lockages and that result from lock hardware problems or to testing or maintaining the lock or its equipment. It then explains the expected frequency of such lock failures relative to the number of commercial tow and recreational vessel lockages. This can be viewed as a measure of reliability. It can also be interpreted as the probability that such a failure will occur on any given commercial tow or recreational vessel lockage.

The model is specified in terms of a logit formulation. The explanatory variables relate to characteristics of the lock chambers, to the extent of major maintenance (if any), and to variables which identify the Corps of Engineer district the lock chamber is associated with. Among other things, the usefulness of the model as a tool of prediction and as an instrument for allocating major maintenance funds is demonstrated.

DATA ISSUES

The data underlying this study were taken from the U.S. Army Corps of Engineers' Lock Performance Monitoring System (PMS) data tapes, details of which are reported elsewhere (*2*). The data taken from these tapes relate to lockages at 125 lock chambers for 1981 through 1986. These lock chambers correspond to 14 Corps of Engineer districts. The 125 lock chambers were chosen from the entire list of lock chambers described in the PMS tapes because the corresponding data were of a higher quality in the sense that fewer errors were present and more complete in terms of having fewer missing observations. Data relating to an individual lockage at these 125 chambers were not used unless observations on all of the relevant variables were available.

A description of the 125 lock chambers is contained in Kelejian (*3*). The 14 districts corresponding to these 125 lock chambers are listed in Table 1. It became convenient to describe each district by a number (i.e., District 1, District 2, etc.). These district numbers are also listed in Table 1.

The data file used to estimate the model contained two types of PMS data. The first relates to individual lockages. The second relates to calendar year sums (e.g., total stall time). The individual lockage data represents a one-out-of-twelve sample from the original PMS data tape. The annual sums are based on a 100 percent sample.

Department of Economics, University of Maryland College Park, Md. 20742.

TABLE 1 DISTRICTS AND THEIR ASSOCIATED NUMBERS

District	Associated Number	District	Associated Number
Pittsburgh	1	Huntington	8
Mobile	2	St. Louis	9
Nashville	3	St. Paul	10
Walla Walla	4	Little Rock	11
Wilmington	5	Tulsa	12
Louisville	6	Vicksburg	13
Rock Island	7	Seattle	14

The data file also contained information pertinent to lock chambers described in (*1*). Among other things, this information relates to the age of lock chambers and the cost of completed major maintenance projects. The cost of the maintenance projects were given in current dollars. These data were converted into constant 1982 dollars by deflating by the Construction Cost Index. Data on this index were supplied by Corps personnel. A more complete discussion of the data and their original source is given in Kelejian (*3*).

LOGIT MODEL OF STALL PROBABILITY

Basic Formulation: An Overview

There are typically many lockages that take place during a year at a given lock chamber. Corresponding to each of these lockages there is a probability that a stall will occur.

Let P_{it} be the probability that a commercial tow or recreational vessel lockage taking place during the tth year at lock chamber i results in a stall. Note that P_{it} is indexed to vary from lock chamber to lock chamber (over i) and from year to year, but not from one lockage to another within a year at a given chamber.

The assumption that the probability of a stall is the same for all lockages taking place within a year at a given chamber is clearly an approximation. For example, a lock chamber ages continuously and, therefore, from lockage to lockage. However, one might view the effective aging of a chamber as being very gradual and therefore reasonably well approximated by the age of the chamber as measured in years. If so, and if the other relevant factors change gradually from lockage to lockage, the assumption of a constant stall probability within a year at a given chamber is reasonable.

Let X_{it} be a vector of variables corresponding to the ith lock at time t, which might be taken to explain P_{it}. Let B be a corresponding vector of parameters such that

$$I_{it} = X_{it}B \tag{1}$$

can be taken to be an index determining P_{it}. Then, in the logit formulation P_{it} is related to I_{it} as

$$P_{it} = EXP(I_{it})/[1+EXP(I_{it})] \tag{2}$$

It is not difficult to show that P_{it} lies between zero and unity for all possible values of the index I_{it}. In addition $(dP_{it}/dI_{it}) > 0$ for all I_{it} so that the larger is the index I_{it} the higher is P_{it}. Therefore, variables that are components of I_{it} that increase P_{it} should have positive weights; negative weights correspond to variables which decrease P_{it}.

Details of the Index

In this study, the index relating to the ith chamber at time t, namely I_{it}, is

$$\begin{aligned} I_{it} = {} & \mathrm{b}_0 + \mathrm{b}_1\,\mathrm{Age}_{it} + \mathrm{b}_2\,\mathrm{MPT}_{it-1} + \mathrm{b}_3\,\mathrm{ICE}_{it-1} \\ & + \mathrm{b}_4\,\mathrm{AIT}_{it} + \mathrm{b}_5\,\mathrm{Maint}_{it} + \mathrm{b}_6\,\mathrm{ST}_{it-1} \\ & + \mathrm{b}_7\,\mathrm{SF}_{it-1} + \mathrm{a}_1\,\mathrm{DD1}_i + \mathrm{a}_2\,\mathrm{DD3}_i \\ & + \mathrm{a}_3\,\mathrm{DD7}_i + \mathrm{a}_4\,\mathrm{DD8}_i + \mathrm{a}_5\,\mathrm{DD10}_i \end{aligned} \tag{3}$$

where $\mathrm{b}_0, \ldots, \mathrm{b}_7, \mathrm{a}_1, \ldots \mathrm{a}_5$ are parameters to be estimated and all of the remaining terms on the right hand side of expression 3 are explanatory variables whose definitions are given in Table 2.

In expression 3 Maint_{it} represents the extent of a major maintenance, if any. It was formulated as

$$\mathrm{Maint}_{it} = 1 - \mathrm{EXP}(-\mathrm{cost}_{it}) \tag{4}$$

where $\mathrm{cost}_{it} = 0$ if, up through time t, lock chamber i did not have major maintenance; if such maintenance did take place, cost_{it} is its 1982 dollar cost. The specification in expression 4 implies that $\mathrm{Maint}_{it} = 0$ if $\mathrm{cost}_{it} = 0$. This is the case in which a major maintenance did not take place. If it did take place, $\mathrm{cost}_{it} > 0$ and so $\mathrm{Maint}_{it} > 0$, and the more extensive it was (the higher is cost_{it}), the higher is Maint_{it}. In this sense, the variable Maint_{it} is a positive measure of the extent of a major maintenance.

A number of other variables were also considered but found not to be statistically significant. Results relating to these other variables can be found elsewhere (*3*).

Since age, other things being equal, is associated with lock deterioration, one would expect $b_1 > 0$. Similarly, higher values of mean processing time may be indicative of equipment which is not in top operating condition and so one ex-

TABLE 2 DEFINITIONS OF EXPLANATORY VARIABLES

Variable	Definition
Age_{it}	The age of lock chamber i at time t
MPT_{it-1}	Mean processing time of lock chamber i at time t-1.
ICE_{it-1}	The number of ice days at lock chamber i during year t -1.
AIT_{it}	Average idle time at lock chamber i during year t.
Maint_{it}	A variable describing the real dollar value of a major maintenance (if any) of lock chamber i.
ST_{it-1}	Total stall time due to testing or maintenance of lock chamber i, or its equipment during year t-1.
SF_{it-1}	The stall frequency at lock chamber i at year t-1. The stall frequency is the ratio of stalls to lockages.
DDJ_i	A dummy variable which is unity if the ith lock chamber is in District J, and zero otherwise.

pects $b_2 > 0$. One would also expect $b_3 > 0$ and $b_7 > 0$ because ice formation accelerates decay and a previous stall frequency is indicated of general conditions, which are not radically different from one year to the next.

One would expect $b_4 < 0$. The reason for this is that idle time could be used to perform minor maintenance and repair, and so on. Thus, higher values of AIT_{it} should lower the index, I_{it}, and hence lower the probability of a stall. Similarly, for very evident reasons one expects $b_5 < 0$. On a somewhat more moderated scale, one would also expect $b_6 < 0$. That is, the more testing and maintenance, and corresponding minor repairs, of the lock chamber and its equipment in one year, the better the condition (other things equal) of that chamber in the following year. For the readers' convenience, the sign expectations relating to the coefficients of expression 3 are summarized in expression 5 as follows:

$$\begin{aligned} &b_1 > 0,\ b_2 > 0,\ b_3 > 0,\ b_7 > 0; \\ &b_4 < 0,\ b_5 < 0,\ b_6 < 0 \end{aligned} \tag{5}$$

The coefficient of a dummy variable in expression 3 indicates whether or not the stall probability corresponding to that district is higher (if positive) or lower (if negative) than in the districts not represented in expression 3 after the effects of the other variables in the index have been accounted for. Conceptual arguments do not suggest the signs of these coefficients.

The Issue of Estimation

Assume that P_{it} is neither zero nor unity. Then from expression 2 it can be shown that $P_{it}/(1 - P_{it}) = \text{EXP}(I_{it})$ so that

$$\log_e (P_{it}/(1 - P_{it})) = I_{it} \tag{6}$$

The result in expression 6 is useful in that it leads to a relatively simple procedure for estimating the parameters determining the index I_{it} as given in expression 3. For example, let SF_{it} be the number of stalls at lock chamber i during year t. Then SF_{it} may be expressed as $SF_{it} = S_{it}/L_{it}$ where S_{it} is the number of stalls of the type being considered at lock chamber i during year t, and L_{it} is the corresponding number of lockages. Because the probability of a stall on any given lockage is assumed to be the same for all lockages during the year at a given chamber, SF_{it} can be taken as an estimate of P_{it}. The reason for this is that SF_{it} can be viewed as the ratio of the number of successes (stalls) to the number of trials (lockages).

For ease of presentation, suppose that SF_{it} is neither zero nor unity. Then let

$$u_{it} = \log_e[SF_{it}/(1 - SF_{it})] - \log_e(P_{it}/(1 - P_{it})) \tag{7}$$

so that

$$\log_e(SF_{it}/(1 - SF_{it})) = \log_e[P_{it}/(1 - P_{it})] + u_{it} \tag{8}$$

The first term on the right hand side of expression 8 is equal to the index I_{it} via expression 6. Replacing this index by its expression in expression 3 yields

$$\begin{aligned} \log_e(SF_{it}/(1 - SF_{it})) = {} & b_0 + b_1\,\text{Age}_{it} + b_2\,\text{MPT}_{it-1} \\ & + b_3\,\text{ICE}_{it-1} + b_4\,\text{AIT}_{it} \\ & + b_5\,\text{Maint}_{it} + b_6\,\text{ST}_{it-1} \\ & + b_7\,\text{SF}_{it-1} + a_1\,\text{DD1}_i \\ & + a_2\,\text{DD3}_i + a_3\,\text{DD7}_i \\ & + a_4\,\text{DD8}_i + a_5\,\text{DD10}_i \\ & + \text{uit} \end{aligned} \tag{9}$$

It can be shown that if the number of lockages during year t at chamber i is "large", the term u_{it} has a mean and variance which are approximated by the following expression

$$Eu_{it} = 0,\ \text{Var}(u_{it}) = [L_{it}\, P_{it}\, (1 - P_{it})]^{-1} \tag{10}$$

The implication of expression 10 is that expression 9 can be viewed as a regression model having a heteroskedastic error term. Because the variance of u_{it} involves P_{it}, which is not known, the appropriate estimation procedure is a feasible form of generalized least squares that is based on an estimated value of the variance of u_{it}; this estimated value would be based on an estimate of P_{it}.

In implementing this procedure for the PMS data, two complications arose. The first is that for certain years at certain lock chambers SF_{it} is zero. In these cases, the dependent variable in expression 9 is not defined. The second complication is that in certain years the number of lockages at certain lock chambers, L_{it}, is small. In these cases the large sample approximations in expression 10 are not appropriate and so, therefore, neither is the model in expression 9.

The discussion in Kelejian (*3*) suggests that if the number of lockages for each chamber in each time period is large, the first of these problems can be overcome by replacing the dependent variable in expression 9 by

$$Y_{it} = \log_e\{(SF_{it} + (2L_{it})^{-1})/[1 - SF_{it} + (2L_{it})^{-1}]\} \tag{11}$$

The reason for this is that Y_{it} is defined for all values of SF_{it} in the interval $0 \le SF_{it} \le 1$; furthermore, under reasonable conditions, Y_{it} and $\log_e[SF_{it}/(1 - SF_{it})]$ converge in probability as L_{it} increases beyond limit.

The procedure that was followed in this study is on the basis of a variant of expression 11 and is described in steps detailed in the following. Note that the estimators so obtained are asymptotically efficient because they are equivalent to the corresponding maximum likelihood estimators.

Details of the Procedure

Step 1

Some restriction on the original PMS sample was necessary because the number of lockages in certain years at certain chambers (henceforth, cells) was very small (e.g., as low as

4). The restriction that was imposed was that only data relating to cells for which $L_{it} > Q$ were considered in the estimation procedure. Q was taken as the largest multiple of 50 such that at least ⅔ of the original cells remain in the revised sample. It turned out that $Q = 150$, and the smallest value of L_{it}, say MIN, satisfying $L_{it} > 150$ was MIN = 151. The cut off value of 150 is reasonably large, but not overly restrictive in terms of the scope of the revised sample. For example, the condition $L_{it} > 150$ only eliminates reference to 32 lock chambers, thus leaving 93 such chambers in the sample. The number of cells in the revised sample is 499 which is roughly 67 percent of the original number of cells.

Step 2

Because the number of lockages in each cell of the sample constructed in Step 1 varied from 151 to 1,355, a modified form of Y_{it} in expression 11 was considered; namely

$$ {}^{*}Y_{it} = \log_e\{SF_{it} + (2 \times \text{MIN})^{-1}/[1 - SF_{it} + (2 \times \text{MIN})^{-1}]\} \tag{12}$$

${}^{*}Y_{it}$ was considered for two reasons. First, unlike Y_{it}, ${}^{*}Y_{it}$ does not induce an artificial variation in the dependent variable, which is due solely to the wide range of values of the number of lockages. Second, there is no penalty in terms of asymptotic efficiency in the use of ${}^{*}Y_{it}$ as compared with Y_{it} because ${}^{*}Y_{it}$ and Y_{it} converge as L_{it} increases beyond limit.

Step 3

Taking ${}^{*}Y_{it}$ as the dependent variable, expression 9 was first estimated by least squares. This provided a consistent estimate of the index I_{it}, say IE_{it}, for each of the 499 cells of the sample.

Step 4

The estimated index, IE_{it}, was then used to obtain an initial but consistent estimate, PE_{it}, of the stall probability P_{it} for each of the 499 cells

$$PE_{it} = \text{EXP}(IE_{it})/[1 + \text{EXP}(IE_{it})] \tag{13}$$

Correspondingly, the variance of u_{it} as given in expression 10 was then estimated as

$$\hat{\text{v}}\text{ar}(u_{it}) = [L_{it}\, PE_{it}(1 - PE_{it})]^{-1} \tag{14}$$

Step 5

Finally, with ${}^{*}Y_{it}$ in expression 12 taken as the dependent variable, expression 9 was reestimated by least squares after deflating each variable by the square root of $\hat{\text{v}}\text{ar}(u_{it})$ in expression 14. This is the feasible generalized least squares procedure.

Let the estimates of the parameters of expression 9 obtained in Step 5 be $b_0, \ldots, b_7, a_1, \ldots, a_5$. Then, because these estimates are based on a consistent and efficient procedure, the final estimate of the stall probability for the ith lock chamber at time t was taken as

$$\hat{P}_{it} = \text{EXP}(\hat{I}_{it})/[1 + \text{EXP}(\hat{I}_{it})] \tag{15}$$

where

$$\begin{aligned} \hat{I}_{it} = {} & \hat{b}_0 + \hat{b}_1\,\text{Age}_{it} + \hat{b}_2\,MPT_{it-1} \\ & + \hat{b}_3\,ICE_{it-1} + \hat{b}_4\,AIT_{it} + \hat{b}_5\,\text{Maint}_{it} \\ & + \hat{b}_6\,ST_{it-1} + \hat{b}_7\,SF_{it-1} + \hat{a}_1\,DD1_i \\ & + \hat{a}_2\,DD3_i + \hat{a}_3\,DD7_i \\ & + \hat{a}_4\,DD8_i + \hat{a}_5\,DD10_i \end{aligned} \tag{16}$$

EMPIRICAL RESULTS

Results Relating to the Probability Model

The empirical results obtained by the procedure described in Steps 1 through 5 are given in expression 17. The figures in parentheses beneath the parameter estimates are the absolute values of the corresponding t-ratios. $\hat{r}^2$ is the square of the correlation coefficient between the observed stall frequency, SF_{it}, and its model predicted value $\hat{P}_{it}$ (see expression 15).

$$\begin{aligned} \hat{I}_{it} = {} & -5.956 + .0102\,\text{Age}_{it} + .0071\,MPT_{it-1} \\ & (41.31)\quad (5.130) \qquad\quad (2.997) \\ & + .0066\,ICE_{it-1} - .0899\,AIT_{it} \\ & (4.458) \qquad\quad (1.599) \\ & - 1.197\,\text{Maint}_{it} - .0048\,ST_{it-1} + 23.09\,SF_{it-1} \\ & (1.818) \qquad\quad (3.997) \qquad\quad (8.881) \\ & - .2422\,DD1_i + .8219\,DD3_i - .2121\,DD7_i \\ & (2.651) \qquad\quad (7.292) \qquad\quad (2.716) \\ & + .3416\,DD8_i - .3167\,DD10_i\ ;\ \hat{r}^2 = .366 \\ & (3.888) \qquad\quad (3.093) \end{aligned} \tag{17}$$

The units of measurement underlying expression 17 are: Age is in years; MPT is in minutes per lockage; ICE is in days per year; AIT is in hundreds of minutes; Maint = 1 − EXP($-C$) where C is in hundreds of millions of 1982 dollars; SF is the observed stall frequency; ST is in thousands of minutes.

The value of $\hat{r}^2 = .366$ suggests that, overall, the model offers a reasonable explanation of stall probabilities associated with individual lockages. In interpreting this figure one should note that stall probabilities, as measured by stall frequencies, vary widely across lock chambers and time, and therefore are not easily explained. For example, the R^2 statistic (over the sample underlying expression 17) between the annual stall frequency at a lock chamber, and its age is only .015. More extensive results along these lines are given in Kelejian (*3*). Nevertheless, $\hat{r}^2 = .366$ does imply that 63.4

percent of the variation in stall probabilities is unexplained, and so further studies along these lines could be of value.

On a qualitative level, note that the sign of each estimate given in expression 17 is consistent with prior expectations as described in expression 5. Also note that each of these estimates, if considered alone, is statistically significant at the one-tail .05 level with the sole exception of the coefficient of the average idle time variable. The sign of this coefficient is negative, as anticipated, but its one-tail significance level is .0548. Because strong prior Bayesian beliefs suggest that average idle time is important, and because the one-tail significance level is quite close to .05, the idle time variable was not dropped from the model.

There are no prior sign expectations for the coefficients of the district dummy variables and therefore a test of significance would be determined by a two-tail procedure; clearly the results in expression 17 imply that if these variables are considered individually, each and every one of them would be statistically significant at the two-tail .05 level. The joint significance of the district dummy variables is confirmed by the corresponding F test, namely $\hat{F} = 15.18 > F(.95/5{,}486) = 2.23$.

Districts that are represented in the sample but for which there are no dummy variables in expression 17 are Mobile, Walla Walla, Louisville, St. Louis, Little Rock, and Seattle. Therefore, if a coefficient corresponding to a dummy variable in expression 17 is positive, the stall probability in the corresponding district is higher than in the excluded 5 districts for given and equal values of the other variables in expression 17. Districts 3 and 8 (Nashville and Huntington) fall into this category. Similarly, if such a coefficient in expression 17 is negative, the stall probability in the corresponding district is lower than in the excluded five districts for given and equal values of the other variables in expression 17. Districts 1, 7, and 10 (Pittsburgh, Rock Island, and St. Paul) fall into this category.

One measure of the magnitude of these district effects is the consequent change in the stall probability. For example, in District 1, (Pittsburgh), the sample mean of the index in expression 17 is $I_1 = -5.447$; the corresponding stall probability is $\hat{P}_1 = .00429$. If District 1 were typical, as say described by the five excluded districts, the coefficient of its dummy variable would be zero. In this case, the sample mean of its index would be $IE_1 = -5.2048$, and the corresponding stall probability would be $PE_1 = .00546$. Therefore, whatever the special effects associated with District 1, they lead to a reduction of .00117 in the stall probability. Since these probabilities are small, this small change represents a large percentage change. Specifically, taking $(\hat{P}_1 + PE_1)/2$ as the base, the district effect (at the sample mean) associated with District 1 leads to a 24 percent reduction in the stall probability. Corresponding figures for Districts 3, 7, 8, and 10 are given in Table 3. Consistent with the results for District 1, a glance at the table suggests that these districts also have effects that are important in percentage terms concerning stall probabilities.

Further results relating to the empirical model are given in Table 4. Specifically, the table gives the stall probability corresponding to sample mean values of the variables determining the index in expression 17. This figure, namely .0056, can be interpreted as the probability that the average or typical chamber will have a stall on a given lockage. Conversely, the probability that a stall will not take place at such a typical chamber is .9944. This probability is so high that even if a reasonably large number of lockages take place over a given period of time, the probability that a stall will not occur during that time could remain non-negligible.

TABLE 3 DISTRICT EFFECTS AT SAMPLE MEAN VALUES

District	Probability Changes	Probability Change (%)
Nashville	.0084	77
Huntington	.0041	50
Rock Island	-.0013	-21
Pittsburgh	-.0012	-24
St. Paul	-.0043	-31

TABLE 4 STALL PROBABILITIES AND ELASTICITIES

Stall Probability			Elasticities					
Lowest	Highest	Mean	AGE	MPT	ICE	AIT	MAINT	ST
.0023	.0374	.0056	.386	.287	.106	-.079	-.009	-.027

The table also gives the lowest and highest values of the stall probability based on the values of the index over the chambers and years in the sample. These figures, namely .0023 and .0374, correspond, respectively, to Chamber 1 of the Old River Lock on the Mississippi River (ORLMR) for 1982, and Chamber 1 at the Gallipolis Locks and Dam on the Ohio River (GLDOR) in 1986. These figures differ by more than a factor of ten. As an indication of time variation, the stall probability at the ORLMR for 1986 is .0025; the stall probability is .0096 for 1982 at the GLDOR. Among other things, these results suggest that stall potentials, as measured by stall probabilities, vary considerably from chamber to chamber, as well as over time. Given the results in expression 17, and the model in expression 15, the stall probability can be calculated for any chamber, for any year, as long as the values of the independent variables are known. Clearly, the calculation of such stall probabilities should be helpful in allocating scarce major maintenance funds.

Table 4 also gives estimates of the elasticities of the stall probability with respect to six of the index variables, again at sample mean values. These elasticities were calculated as

$$\mathrm{dlog}_e(\mathrm{P}_{it})/\mathrm{dlog}_e(Z^j_{it}) = {}^{*}Z^j\,\hat{b}_j/(1 + \mathrm{EXP}({}^{*}I)),\ j = 1, \ldots, 6 \tag{18}$$

where Z^j_{it} is the jth explanatory variable (excluding the intercept) in expression 16; $\hat{b}_j$ is its corresponding estimated coefficient given in expression 17, and ${}^{*}Z^j$ and ${}^{*}I$ are the sample averages of Z^j_{it} and $\hat{I}_{it}$.

The elasticities in Table 4 indicate the relative sensitivity of the stall probability with respect to a given percentage change in the value of the corresponding explanatory variable at sample mean values. For example, the elasticity with respect to the age variable is .386. This figure suggests that, at sample mean values, a 1 percent (a 10 percent) increase in the age of a chamber would (other things equal) lead to a .386 percent (a 3.86 percent) increase in the stall probability. Among other things, the figures in Table 4 suggest that stall probabilities for a typical lock chamber are more sensitive to small percentage changes in the age of the chamber, than to small percentage changes in the other variables of the index.

Figures 1 through 4 give further insights concerning the probability model. Figure 1 describes the relationship between the stall probability and the age of the chamber at sample mean values of the other variables involved in the index. Again, since these sample mean values could be viewed as typical, Figure 1 essentially describes a time profile of a stall probability for a typical chamber. As the chamber ages, the probability increases. Calculations based on the diagram suggest that this probability is roughly 20 percent higher when the chamber is 60 as compared with 40 years old.

Figure 2 describes the relationship between the stall probability and the extent of major maintenance, as measured by its 1982 dollar cost, again at sample mean values. As expected, the more extensive the maintenance, the lower the probability. Calculations performed on the basis of the diagram suggest that, for a typical chamber, a 30 million 1982 dollar major maintenance reduces the stall probability by, roughly, 35 percent. Similarly, a 20 million 1982 dollar major maintenance reduces this probability by, roughly, 20 percent. Figure 3 describes the relationship between the stall probability and mean processing time, at sample mean values. The figure suggests that, for the typical chamber, stall probabilities are roughly 45 percent more likely when the mean processing time is 100 minutes per lockage than when it is 40 minutes per lockage.

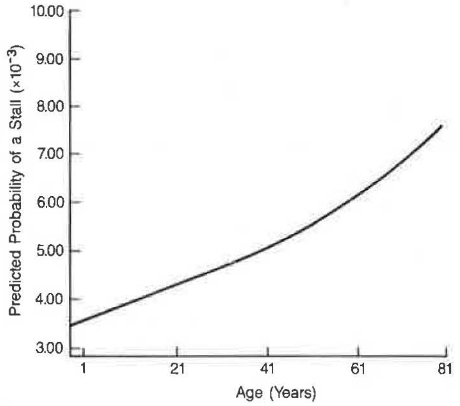


FIGURE 1 Effect of age on the predicted probability of a stall.

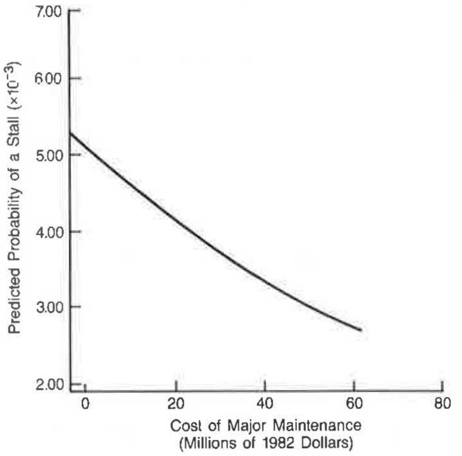


FIGURE 2 Effect of major maintenance on the predicted probability of a stall.

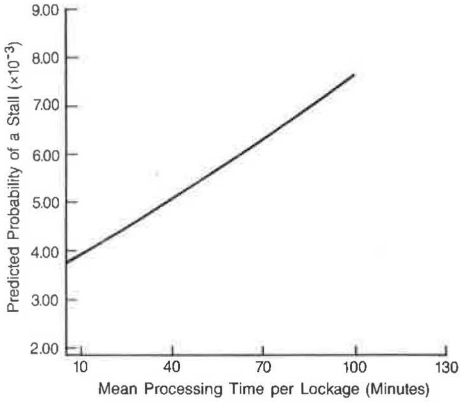


FIGURE 3 Effect of mean processing time on the predicted probability of a stall.

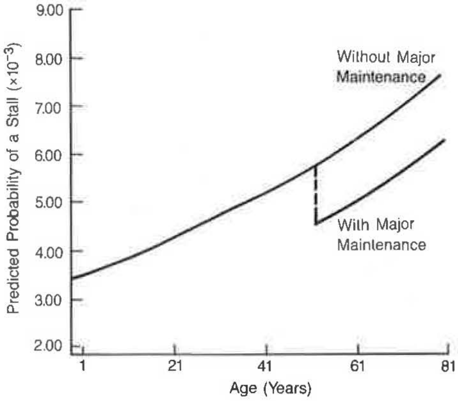


FIGURE 4 Effect of major maintenance on the effective age of a lock.

Finally, Figure 4 describes how major maintenance reduces the effective age of a chamber. The upper curve in that figure outlines the relationship between the stall probability and the age of the chamber if there is no major maintenance and the other relevant variables are equal to their sample means. The lower curve describes the change in the probabilities outlined by the upper curve if a 20 million 1982 dollar major maintenance were undertaken when the chamber is 50 years old. A 20 million 1982 dollar major maintenance was considered in this illustration because it is, roughly, the average cost of such maintenance completed during or before 1987.

If the lower curve, at any age exceeding 50 years, is horizontally extended to the left, it will intersect the upper curve corresponding to an age which is, roughly, between 20 and 25 years earlier. The suggestion is that, for the typical chamber, a 20 million 1982 dollar major maintenance, undertaken when the chamber is 50 years old, reduces the effective age of that chamber by, roughly, 20 to 25 years.

The reduction in the effective age of a particular chamber corresponding to a proposed major maintenance of a certain dollar magnitude can be done in a similar, but more exact way. Specifically, let $\hat{I}^{B}_{it}$ be the value of the index in expression 17 for lock Chamber *i* at time *t* before the major maintenance. Let $\hat{I}^{A}_{it}$ be the value of that index after the major maintenance. Because the index is reduced if major maintenance is undertaken, $\hat{I}^{A}_{it} < \hat{I}^{B}_{it}$ and so the "after" stall probability would be less than the "before" stall probability. The effective age of the chamber after the maintenance is the value of the age variable that equates the before index, $\hat{I}^{B}_{it}$, to the after index, $\hat{I}^{A}_{it}$. That is, let ${}^{-}I^{B}_{it}$ be the net sum of the right hand side of expression 17, before the major maintenance, with the exception of the age variable: $\hat{I}^{B}_{it} = {}^{-}I^{B}_{it} + .0102 * \text{Age}_{it}$. Then the effective age of chamber *i* at time *t* is Age^{E}_{it} where

$$\text{Age}^{E}_{it} = (\hat{I}^{A}_{it} - {}^{-}I^{B}_{it})/.0102 \qquad (19)$$

The reduction in the effective age is therefore $\text{Age}_{it} - \text{Age}^{E}_{it}$.

Suggestions Concerning Further Calculations

Calculations concerning chambers in districts which are not in the sample require an assumption concerning the district effect as described in the index (see expression 17). One possibility is that Corps personnel could use expert opinion to determine the district effect; given this, stall probabilities could be evaluated for any chamber of interest, for any year, as long as the values of the variables determining the index in expression 17 are known. The magnitude of the district effects of Districts 1, 3, 7, 8, and 10 should offer guidance if this route is taken.

Another possibility is to assume that the district effect corresponding to a chamber of interest, which is not in the sample, is equal to the average of the effects of those for Districts 1, 3, 7, 8, and 10. Still another possibility is to consider worst and best case scenarios. For example, the district effect could be taken to be equal to that of District 3, which would be a worst case scenario. Given this, a policy could be evaluated in terms of its effect on the stall probability. The district effect could then be taken to be equal to that of District 10, which would be a best case scenario. Given this, the policy could again be evaluated. Comparisons between the two cases should be of interest.

SUMMARY AND CONCLUSIONS

A probability model of lock failures has been presented. The qualitative results corresponding to the underlying variables are consistent with expectations. The usefulness and flexibility of the model in evaluating changes in the values of these variables has been demonstrated. Among other things, this demonstration suggests that many major maintenance projects relating to lock chambers can be evaluated in terms of their consequent effect on lock failure probabilities. It was also demonstrated that the extent of the renewal of a chamber in response to major maintenance can be calculated.

ACKNOWLEDGMENTS

I would like to thank Craig Hiemstra, Michael Wagner, and Charles Yoe for useful discussions and comments on an earlier version of this paper. I would also like to thank Craig Hiemstra and Michael Wagner for help at various computer-related stages of this study. This study would not have been possible without the support of George Antle of the Army Corps and I am grateful for that support. I would also like to thank Yvonne Sisler who cheerfully typed, and retyped, the various drafts of this paper. Finally, I would like to thank the Computer Science Center at the University of Maryland for its generous support of computer time.

REFERENCES

1. Institute for Water Resources. *The 1988 Inland Waterway Review*. Report 88-R-7. U.S. Army Corps of Engineers, 1988.
2. Institute for Water Resources. *Lock Performance Monitoring System: User's Manual for Data Analysis*. User Manual 85-UM-2. U.S. Army Corps of Engineers, 1985.
3. H. H. Kelejian. *A Study of Lockage Stall Probabilities*. Report to Institute for Water Resources, Fort Belvoir. U.S. Army Corps of Engineers, 1989.
4. G. S. Maddala. *Limited Dependent and Qualitative Variables in Econometrics*. Cambridge University Press, New York, 1983.

The views expressed in this study are solely those of the author, and are not necessarily those of the Army Corps.

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

Simulation of Waterway Transportation Reliability

MELODY D. M. DAI AND PAUL SCHONFELD

A microscopic model for simulating barge traffic through a series of locks has been developed and tested with data for a section of the Ohio River. The model was designed primarily to analyze the economic effects of waterway congestion and service reliability. The results indicate that the model is capable of simulating the system performance sufficiently well for analytic purposes. The results also indicate to what extent coal stockouts would increase at a power plant, or alternatively, how safety stocks would have to be increased, as traffic volumes approach capacity.

The reliability of service times on inland waterways significantly influences barge fleet requirements, operating costs, inventory costs, and stock out costs for customers. Therefore, the service reliability influences the competitive position and market share of inland waterway transportation.

To analyze the effects of congestion and service time variability, a simulation model has been developed. In its earliest applications for which results are presented, the model is used to estimate the relations among capacity and service time variance at successive locks, stock-out probabilities and durations, and inventory safety stocks for an electric power plant supplied with coal through the Ohio River. This model will soon be usable for estimating the benefits and costs of alternative plans for maintaining and improving the waterway system.

LITERATURE REVIEW

The research most relevant here regards the economic costs of lock delays, lock delay models, and waterway simulation models. The estimation of economic benefits is essential for selecting and scheduling lock improvement projects. The U.S. Army Corps of Engineers, which is the agency responsible for U.S. waterways, usually estimates the economic benefits of lock improvements from the transport cost differentials between barges and the next cheapest mode (*1–3*). Such evaluation omits some important logistics costs (e.g., for larger inventories and barge fleet sizes) used to hedge against unreliable deliveries.

In systems with unreliable deliveries, stockouts may occur. There are situations in which the on-site stocks are not sufficient to satisfy the demand (*4*). Stock-out costs include duplicate ordering costs from another source or mode and foregone profits (*5,6*). Baumol and Vinod (*7*) indicate that delays can increase the shippers' inventory costs which include on-site carrying costs and stock-out penalties. On the basis of Baumol's model, Nason and Kullman (*8*) developed a total logistics cost model to predict inland diversions from waterways.

Two models based on queueing theory have been found for estimating lock delays. DeSalvo (*9*) models lock operation as a simple single-server queueing process with Poisson distributed arrivals and exponentially distributed service times (i.e., M/M/1 queues). Wilson's model (*10*) extends DeSalvo's by treating the service processes as general distributions (M/G/1 queues). Both models are designed for analyzing single lock delays. However, the assumption of exponentially distributed service times is not consistent with empirical data (*11*) and the Poisson arrivals assumption is also unreliable. Carroll and Desai (*12,13*) studied the arrival processes at 40 locks on the Illinois, Mississippi, and Ohio river systems, and found that 13 of the 40 locks had non-Poisson arrivals at the five percent significance level.

The results for M/M/1 queues in DeSalvo's model (*9*) are derived on the basis of first-in-first-out (FIFO) service discipline although the actual discipline is primarily one-up-one-down. This assumption can still generate reasonable results since delays mainly depend on volume to capacity ratios. Wilson (*10*) modeled the service processes more realistically with a general rather than an exponential distribution. However, arrivals are still assumed to be Poisson distributed at all locks and no exact queueing results are available for locks with two chambers in parallel. Since analytic queueing models must be kept simple to be solvable, the above two models also neglect the interdependence among serial locks and the stalls (i.e., service interruptions at locks). Both of these factors significantly affect service times and reliability.

The system simulation models developed to analyze lock delays and two travel times originated mainly from Howe's microscopic model (*14*). In that model service times are derived from empirically determined frequency distributions. To avoid some troublesome problems and errors associated with the requirement to balance long-run flows in Howe's model, Carroll and Bronzini developed another waterway system simulation model (*15*). It provides detailed outputs on such variables as two traffic volumes, delays, processing times, transit times, averages and standard deviations of delay and transit times, queue lengths, and lock utilization ratios. Both of these models simulate waterway operations in detail but require considerable amounts of data and computer time, which limit their applicability for problems with large networks with numerous combinations of improvement alternatives. Both models assume a Poisson distribution for two trip generations, which is not always realistic. More important for reliability analyses, neither of these models explicitly accounts for stalls, which

---

Department of Civil Engineering, University of Maryland, College Park, Md. 20742.

are different in frequency and duration from other events and have significant effects on overall transit time reliability.

Hence a waterway simulation model that explicitly accounts for stalls and estimates the effects of service unreliability of inventory costs is desirable for evaluating and scheduling lock improvement projects.

SIMULATION MODEL

Purpose

A waterway simulation model was developed to analyze the relations between tow trips, travel times, delays, lock operations, coal consumption, and coal inventories while taking account of stochastic effects and seasonal variations. This simulation model enables the estimation of inventory levels and expected stock-out amounts for coal, tow travel times along the waterway, and tow delays under a variety of assumptions about tow trip generation, tow motion, lock service, lock operation discipline, coal inventory level, and coal consumtion. These estimates are useful for estimating economic benefits of lock improvements.

Features

This simulation model is focused on how variations in lock service times affect tow delays and how variations in tow delays affect coal inventories. The output of this model can provide the necessary information to estimate inventory costs, stock-out costs, and expected benefits resulting from lock rehabilitation or lock construction.

This simulation model is microscopic. It traces the motion and records the characteristics of each tow. The characteristics of tows include their number of barges, commodity types, speed, origin and destination, direction of motion, and arrival time at various points. In addition, the model determines cumulative deliveries, cumulative consumption, and actual inventories at various plants.

This is an event-scanning simulation model—the status of which is updated by events. There are five types of events. One is the generation of tow trips, which are generated stochastically on the basis of actually observed traffic distributions. The model uses a table to represent the trip generation pattern and is, therefore, not limited to standard mathematical probability distributions.

A second type of event is the tow entrance in a lock, which is determined by tow arrival time at that lock, the times when chambers become available, and the chamber assignment discipline. If a tow arrives before the lock is available, it needs to wait in the queue storage area. Otherwise, it is served according to the chamber assignment discipline, discussed later. In general, the lock service is presently "first come first serve," subject to the chamber assignment procedure.

A third type of event is a coal tow's arrival at its destination, which increases the cumulative deliveries by the amount of coal that tow is carrying. The cumulative consumption and inventory at the destination are also updated then.

A fourth type of event is the update in the status of cumulative consumptions, inventories, and consumption rates for all coal destinations every unit time. This provides detailed information on inventory levels for all coal destinations.

A fifth type of event is a lock stall. Whenever a stall occurs, the affected chamber becomes unavailable until the end of the stall.

The size of problem that the model can handle is limited by the computer capacity and the storage capacity of the Fortran compiler or linker. There are no restrictions on the number of locks, chambers, cuts, waterway links, tows, utility plants, origin-destination (O-D) pairs, and simulation time periods. This model can simulate two way operation on a mainline waterway.

This model is programmed in Fortran-77, which allows the simulation of relatively complex operations. The following is a more detailed description of how tow trip generation, tow travel times, and coal inventory levels are computed. The overall structure of the simulation model is displayed in Figure 1.

Tow Trip Generation

Tow trips are generated randomly, but the mean of their generating distribution is constant for each O-D pair over each simulation time period. The distribution for tow trip generation is represented by a table. It is assumed that the distribution of trip generation times is similar to the distribution of trip arrival times to locks, (for which data are available).

This model assumes that each tow will maintain its size through its trip. As in trip generation, tow sizes (numbers of barges per tow) are also generated randomly. The distribution of tow sizes is represented by a table and is assumed to be the same for each O-D pair. The tow size table is determined from input data and can represent tow size distribution.

Tow traffic is divided into coal and non-coal traffic. Therefore, for the same O-D pairs, there may be different trip rates

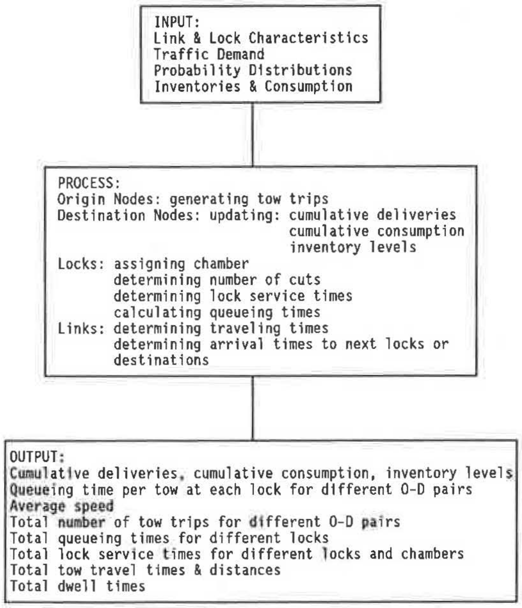


FIGURE 1 Structure and elements of the simulation model.

for coal and non-coal traffic. When coal tows arrive at their destinations, the model updates inventory levels. It is assumed that only a specified fraction of the barges on a coal tow are carrying coal.

Tow Travel Times

Tow travel times are estimated separately for each waterway section, queue storage area, and lock. Section travel times between locks and/or piers are determined by speeds and distances to be covered. Tow speeds are specified as an input to the model in the form of a probability distribution. The distribution of speeds is assumed to be normal. The model assumes that tows maintain constant speeds between origins and destinations and that backhaul speeds are a constant ratio of linehaul speeds.

To avoid generating extreme speed values, a speed range is specified. If speeds are lower than the 2.5 percentile speed or zero, or higher than the 97.5 percentile speed, the speeds are regenerated.

Queueing times at locks are a major focus of this simulation model. Such queueing delays may occur well before traffic levels approach lock capacity since tow arrivals and lock service times are not uniform. These delay times are computed from the difference between the tow arrival times at the queue storage area and their departure from the queue to enter the lock. The storage area has unlimited capacity and is adjacent to the lock.

Lock service times are generated from a specified distribution table. The distribution table can directly reflect actually observed service times. Therefore, the model can be applied to any type of locks. Lock service times will be affected by lock improvements, which are represented by smaller average lock service times or reduced service time distributions. The average lock service times vary for differentl locks, chambers, and numbers of cuts.

The number of cuts is determined by chamber and tow sizes. The maximum cut size (barges handled simultaneously) is exogenously specified for each chamber. A tow may be divided into different numbers of cuts at different lock chambers.

If a lock has more than one chamber in parallel, (main and auxiliary chambers are usually provided), it is currently assumed that the main chamber will be preferred, unless the additional wait time it requires (compared to the auxiliary chamber) exceeds a specified level. This lock selection bias factor reflects the additional work and delays required to break tows into more (and smaller) cuts, move them separately through the auxiliary chamber and then reassemble them. This bias factor has been estimated separately for various locks from empirical data.

The lock service discipline is currently "first come first serve." It is expected that the "N up-N down" service discipline will be simulated later.

Stalls

Stalls are failure conditions in which chambers are not available to serve tows. Stall characteristics differ among chambers and are defined in terms of durations and frequencies, which depend on weather conditions and lock conditions at each chamber. The model assumes that stalls occur stochastically with an exponential distribution.

Inventory Levels

Inventory levels are represented by the difference between cumulative deliveries and cumulative consumption. Whenever inventory levels drop to negative values, this model computes stock-out amounts and durations for the analysis of total costs. This model updates cumulative deliveries and cumulative consumption whenever coal tows arrive at destinations.

Cumulative deliveries are determined from initial inventory levels, inter-delivery times, and delivery amounts. The initial inventory level is exogenously specified for each destination (utility plant). The interdelivery time is generated by the simulation model. The delivered amount is determined from the barge payload and the number of arriving coal barges. The barge payload is currently assumed to be constant for each tow. The number of coal barges is currently assumed to be a constant fraction of tow size. The coal barge fractions vary for different O-D pairs. Although coal barge fractions are constant throughout the simulated period, the amount delivered by each tow is not constant since tow sizes are randomly generated.

Cumulative consumption is a function of consumption rate and time. The mean consumption rate is constant for each utility plant during each simulation period, although it fluctuates randomly around its mean. However, a constant rate is assumed within each period. The consumption rate is updated every time unit and is, therefore, a step-wise linear distribution over time, whose slopes are consumption rates.

Input Requirements

Generally, the model requires four types of inputs related to (*a*) link and lock characteristics, (*b*) traffic demand between origins and destinations, (*c*) probability distributions, and (*d*) inventories and consumption.

Link and Lock Characteristics

The following kinds of information are needed for each link: (*a*) end nodes, (*b*) link length, (*c*) distances between the end nodes and the lock, (*d*) number of chambers, (*e*) average frequencies and durations of stalls, (*f*) maximum cut sizes of chambers, (*g*) average service times of chambers for cuts of various sizes, (*h*) maximum number of barges for each cut size at each chamber, (*i*) bias time for each auxiliary chamber, and (*j*) random number seeds.

Traffic Demand

Traffic demand in tows per day is expressed in the form of O-D matrices by time periods. The lengths of time periods may be different and need to be specified. Additional information needed includes (*a*) dwell time at origins and destinations (both average and standard deviation); (*b*) average number of barges per tow for each O-D pair; (*c*) fractions of coal barges in a tow for each O-D pair; (*d*) payload in short-tons; (*e*) speed (both average and standard deviation); and (*f*) ratio of backhaul speed to linehaul speed (empty/full or upstream/downstream).

Probability Distributions

Probability distributions are specified in this model for (*a*) lock service timers, (*b*) trip generation, (*c*) tow composition (barges per tow), and (*d*) coal consumption at power plants.

The probability distribution tables represent cumulative distribution curves, wherein the abscissas are cumulative frequency, and the ordinates represent the ratio of the tabulated variable to its mean. To reduce the input complexity and specify only ordinates, a specified number of equal intervals is currently used for any cumulative frequency distribution.

Inventories and Consumption

Initial inventory levels in short-tons for different nodes (utility plants) must be specified. In addition, consumption rates in short-tons per day are expressed in the form of node matrices by time period. The information on cumulative deliveries, cumulative consumption, and inventory levels, is provided for intervals whose duration in days must be specified.

Model Output

This model prints out the following results: (*a*) total tow travel time (not including the queueing time, lockage time, and dwell time) in days; (*b*) total tow travel distances in 1,000 mi; (*c*) total dwell times at origins and destinations in days; (*d*) total queueing times in days for different locks and chambers; (*e*) total lock service times in days for different locks, chambers and cuts; (*f*) total number of tow trips for different O-D pairs; (*g*) average speed in mi per day; (*h*) queueing time (both average and standard deviation) in days per tow at each lock for different O-D pairs; (*i*) monthly cumulative deliveries, cumulative consumption, and inventory levels tables in 1,000 short-tons for different utility plants; (*j*) cumulative deliveries, cumulative consumption, and inventory levels tables for specified intervals in 1,000 short-tons for different utility companies; (*k*) graphs of cumulative deliveries and cumulative consumption by specified time intervals for different utility plants; and (*l*) graphs of inventory level by specified time interval for different utility plants.

CASE STUDY

A five-lock section of the Ohio River, centered on the Gallipolis Lock was selected for a case study because that lock constitutes a relative bottleneck in the water capacity. Compared with the four locks nearest to it, (Belleville, Racine, Greenup, and Meldahl), Gallipolis is the oldest and its two chambers are the smallest. A new Gallipolis lock chamber is under construction. The physical characteristics of these six locks are given in Table 1.

In general, a new lock will provide better service quality by reducing service time and improving reliability. The prior expectation is that electric utility plants served by a waterway may be able to reduce the required inventory levels and the expected stock-out costs if the service reliability on the waterway is improved.

The objective of this case study is to compare the inventory levels and expected stock-out amounts of a utility plant downstream of Gallipolis for cases with and without a new Gallipolis lock.

The Stuart utility plant, which belongs to Dayton Power and Light Co., was chosen for this case study. It is located between the Greenup and Meldahl locks. It is 63.5 mi downstream from Greenup and 31.7 mi upstream from Meldahl.

Model Application

This case study focuses on the Ohio river between the Belleville and Greenup locks. Although the model can simulate multiple plants, only one utility plant was analyzed. It included O-D pairs. The simulation period is 1 year.

Link and Lock Characteristics

To simulate the operation between Belleville and Greenup, five nodes and four links are used. The link characteristics are shown in Table 2. The lock characteristics are shown in Table 3.

It is noted that except for Node 5, which represents the Stuart utility plant, all nodes are null nodes that are used as the origins and destinations of non-coal traffic to generate equivalent volumes and congestion levels.

For existing locks, the average lock service times are determined according to the 1984 lock data. Because the new Gallipolis Lock is still under construction, its service times were not available and had to be estimated. The estimated values are slightly smaller than those of the four older locks, which have similar chamber sizes, because the newer lock is assumed to improve service.

TABLE 1 PHYSICAL CHARACTERISTICS OF LOCKS

	Chambers			
Lock Name	Year Opened	Width (ft)	Length (ft)	Lift (ft)
Belleville	1968	110	1200	22
	1968	110	600	22
Racine	1971	110	1200	22
	1971	110	600	22
Gallipolis	1937	110	600	23
	1937	110	360	23
Gallipolis (new)	1991	110	1200	23
	1991	110	600	23
Greenup	1959	110	1200	30
	1959	110	600	30
Meldahl	1962	110	1200	30
	1962	110	600	30

TABLE 2 LINK CHARACTERISTICS

Link	Lock Name	Node In	Node Out	Length (mi)	Distance Between In Node & lock (mi)
1	Belleville	1	2	37.9	21.1
2	Racine	2	3	37.6	16.8
3	Gallipolis	3	4	51.8	20.9
4	Greenup	4	5	94.4	30.9

TABLE 3 LOCK CHARACTERISTICS

Lock Name	Average Service time (in days per cut) 1 cut	2 cuts	Upper Limit of Cut size (in barges per cut)
Belleville	.03512	.09823	18*
	.02389	.07682	8*
Racine	.03425	.09579	18*
	.02427	.07805	8*
Gallipolis	.03563	.07840	6*
	.02088	.06173	3*
Gallipolis (new)	.03000	.09000	18**
	.01600	.07000	9**
Greenup	.03267	.09213	18*
	.02027	.08108	8*

* : based on PMS data
**: based on chamber dimensions

Traffic Demand and Consumption

There were five O-D pairs in this case study. O-D Pair 1 represents coal traffic for the Stuart plant. The other five O-D pairs are non-coal traffic or coal traffic for other utility plants.

The baseline values for average trip rates and tow sizes are determined from 1984 data, and are shown in Tables 4 and 5. The average consumption rates over 12 mo for the Stuart power plant were determined from 1984 coal consumption data and are shown in Table 6.

Other Parameters

The mean and standard deviation of downstream tow speeds are 9.02 and 2.82 mph (216.48 and 67.68 mi/day), respectively. The ratio of upstream speeds to downstream speeds is 0.83. These values were developed on the basis of 1983 statistical data of vessel performance on inland waterways. The barge payload was assumed to be 1,400 long tons or 1568 short tons. (One long ton = 2,240 lbs whereas a short ton = 2,000 lbs.)

Model Validation

The ability of the model to realistically simulate actual operating conditions may be assessed by comparing predictions with actual data. Tables 7 through 9 show such comparisons between results of simulation runs of one year and actual data from 1984. Table 7 shows that traffic volumes are predicted quite accurately by the model, with an average deviation of 1.53 percent. Table 8 shows that the waiting time in queues

TABLE 4 AVERAGE TRIP RATES

	Trip Rate (tows/day)				
	O-D pair				
Month	1-5	1-2	2-3	3-4	4-5
Jan.	1.98	3.06	3.23	3.36	4.88
Feb.	1.97	3.48	3.46	3.76	5.65
Mar.	1.36	4.43	4.77	4.43	6.06
Apr.	1.57	4.68	4.63	3.74	6.31
May	2.27	4.31	4.39	4.33	5.52
June	1.91	6.31	5.76	5.91	10.44
July	2.20	5.55	5.20	5.15	9.10
Aug.	1.98	5.63	5.84	5.54	8.36
Sep.	2.08	5.07	5.61	5.42	8.71
Oct.	2.40	2.44	3.24	3.37	6.55
Nov.	2.13	2.43	2.92	2.95	5.82
Dec.	1.22	2.77	3.14	3.96	6.30

TABLE 5 AVERAGE TOW SIZES

O-D Pair	Tow Size (barges/tow)
1-5	6.8
1-2	9.1
2-3	9.4
3-4	8.4
4-5	6.7

TABLE 6 AVERAGE CONSUMPTION RATES AT THE STUART POWER PLANT

Month	Consumption Rate (1000 short-tons/day)
Jan.	17.23
Feb.	18.03
Mar.	15.26
Apr.	14.90
May	18.35
June	16.70
July	17.32
Aug.	18.52
Sep.	18.80
Oct.	16.29
Nov.	15.33
Dec.	16.48

TABLE 7 TRAFFIC VOLUME COMPARISON

Lock	Volume (tows/year) Data	Model	Deviation (%)
Belleville	4466	4292	3.90
Racine	4591	4580	0.24
Gallipolis	4575	4622	1.03
Greenup	6511	6450	0.94

TABLE 8 WAITING TIME COMPARISON

Lock	Wait Time(min/tow)		Deviation (%)
	Data	Model	
Belleville	21.45	21.81	1.68
Racine	17.26	15.22	11.82
Gallipolis	200.53	137.33	31.52
Greenup	14.46	13.31	7.95

TABLE 9 RELATIVE UTILIZATION OF LOCK CHAMBERS (VOLUMES ARE GIVEN IN TOWS/YEAR)

Lock	Data			Model			Deviation (%)
	Main Chamber	Total Lock	%Main	Main Chamber	Total Lock	%Main	
Belleville	3332	4466	74.61	3134	4292	73.02	2.13
Racine	3848	4591	83.82	3851	4580	84.08	0.31
Gallipolis	3656	4575	79.91	3488	4622	75.47	5.56
Greenup	4500	6511	69.11	4891	6450	75.83	9.72

is predicted reasonably well by the model, although the model significantly underestimates the delays at the Gallipolis Lock. That lock has unusual operating characteristics because it requires disassembly of tows into exceptionally small and oddly composed cuts. A more detailed analysis of operations at Gallipolis may be required to more accurately model its peculiarities. Table 9 shows that the model can satisfactorily estimate the relative utilization of the two chambers at each lock, with an average deviation of 4.43 percent. It should be noted that the model predictions are not only close to actual observation, but are also not systematically biased in any particular direction.

System Congestion and Reliability

In waterways, as in other transportation systems, delays increase much faster than volumes as the capacity is approached and tend toward infinite values. Moreover, the relative variance of service times (e.g., the coefficient of variation = standard deviation divided by the mean) is expected to increase faster than the average service times, with unfavorable effects on system reliability. In a linear network such as that in our case study, the capacity of the entire system is limited by the capacity of the most constrictive element in the series, namely the Gallipolis Lock. Because a new lock will be opened in 1991, which will match the capacity of Gallipolis to that of the other locks in the series, we present simulation results for both the old and new locks.

Table 10 shows the effects of traffic volumes and safety stocks on expected stock-out amounts. It is evident that as volumes (both coal traffic and non-coal traffic) increase from baseline levels (1.0) to levels 50 and 100 percent higher (i.e., volume ratios of 1.5 and 2.0, respectively), the stock-out amounts increase more than proportionately. As safety stock levels are increased from 0 to 150,000 and 300,000 tons, the stock-out amounts consistently decrease. The rate of decrease tapers off (to zero, eventually) as safety stocks are increased.

The effect on stock outs of the new higher capacity Gallipolis Lock is nearly negligible at current volumes (volume ratio = 1.0). However as volumes double, its effect becomes quite significant, since the old lock would reach a utilization rate of 82.85 percent (i.e., 83 percent of capacity). In this case, the decrease in stock-outs ranges from 60,850 tons/day (= 363, 010 − 302,160) or 16.76 percent at zero safety stock to 54,790 tons/day or 40.73 percent at a safety stock of 300,000 tons.

Table 11 shows the effects on stock outs of stalls (failures) at locks. The stalls column indicates stall frequency. Thus 1 indicates baseline conditions (i.e., frequency based on 1980–1987 data), whereas 2 and 3 indicate that frequency is doubled and tripled, respectively. The predicted stock-out amounts are given for both the old and new Gallipolis Locks in the format old/new. The results show that stall duration and frequencies have relatively slight effects on stock outs when volumes are low, that is, when comparing Case 2 or Case 4 with the baseline Case 1. However at high volumes (Cases 9–12), when the system operates closer to its capacity, the effects of stalls become significant and the advantage of the higher capacity of the new Gallipolis Lock is quite substantial.

Total System Costs

The results of this work show how expected stock-out levels increase disproportionately with congestion levels (i.e., volume to capacity ratios) and decrease (with diminishing returns) as safety stocks are increased. Figure 2 shows how the total system costs depend on holding costs and stock-out costs. Holding costs, which include storage costs and interest charges on the safety stock are indicated by the linear function H in the Figure 2. The holding cost is assumed to be $0.10/ton-

TABLE 10 EXPECTED STOCK-OUT AMOUNTS FOR VARIOUS SAFETY STOCK LEVELS AND VOLUMES

Gallipolis Lock	Volume Ratio	Utilization of Gallipolis lock %	Expected Stock-Out Amount (1000 short-tons/day)		
			Safety Stock(1000 short-tons)		
			0	150	300
Old	1.0	38.19	220.88	91.41	7.28
	1.5	59.19	258.58	125.33	29.23
	2.0	82.85	363.01	236.17	134.52
New	1.0	18.73	219.74	90.50	6.97
	1.5	27.42	254.04	121.26	26.73
	2.0	35.92	302.16	176.38	79.73

TABLE 11 EXPECTED STOCK-OUT AMOUNTS (IN 1,000 TONS/DAY)

Case	Multiplier			Starting Inventory (1000 tons)		
	Volume	Stalls	Stall Duration	0	150	300
1	1	1	1	220.1/219.7	91.41/90.50	7.28/6.97
2	1	1	2	221.1/220.0	91.56/90.71	7.29/7.01
3	1	1	3	222.4/220.5	97.69/91.29	7.54/7.10
4	1	2	1	221.2/220.0	91.66/90.73	7.37/7.00
5	1	3	1	221.5/220.2	91.86/90.89	7.49/7.13
6	1.5	1	1	257.2/254.0	124.1/121.3	28.30/26.73
7	1.5	2	1	259.1/254.6	125.9/121.8	29.14/26.89
8	1.5	3	1	261.6/255.8	128.3/122.9	30.89/27.64
9	2	1	1	363.0/302.2	236.2/176.4	134.5/79.73
10	2	2	1	416.4/302.8	282.0/177.0	174.9/83.10
11	2	3	1	579.6/306.2	435.8/180.0	311.7/82.54
12	2	3	2	823.1/320.8	678.5/193.7	553.0/92.80

Key: Expected stock-out amounts given with OLD/NEW Gallipolis Lock. Multipliers are ratios of ASSUMED/BASELINE values. Case 1 represents baseline values.

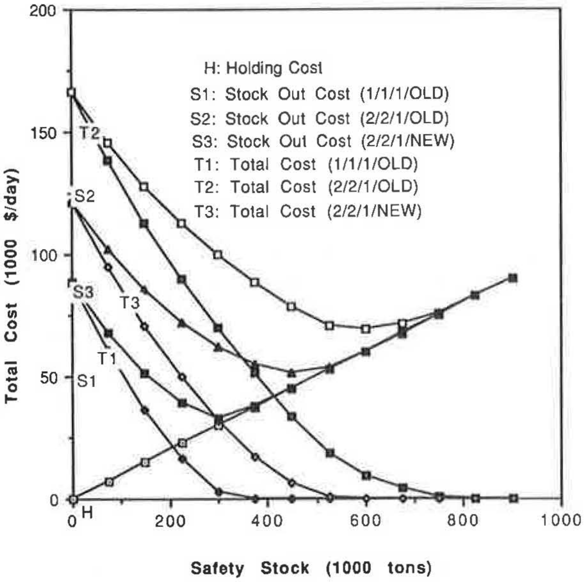


FIGURE 2 Effect of holding costs and stock-out costs on total system costs.

day. If that holding cost were doubled, the slope of the function II would double.

Figure 2 shows the stock out costs for three combinations of parameters, using the key VOLUME/STALL FREQUENCY/STALL DURATION/GALLIPOLIS LOCK. Thus, according to this key, 2/2/1/OLD means that volumes and stall frequencies are twice the baseline values, stall durations are equal to baseline values, and the old Gallipolis lock is being simulated. It should be remembered that our baseline volumes represent 1984 data. A cost of $0.40/ton is assumed in computing the stock out cost curves of Figure 2.

The total system cost is obtained by adding the holding cost to the stock out costs. Because the holding cost is the same for all cases in Figure 2, we obtain one total system cost function for each of the three stock out cost functions. The total cost curves show that as volumes and stall frequencies double (from 1/1/1/OLD to 2/2/1/OLD) the optimal safety stock levels should approximately double from 300,000 to 600,000 tons and that total system costs would more than double from approximately $33,000/day to $69,000/day. If, however, the new Gallipolis Lock was operational, the optimal safety stock level would only be approximately 450,000 tons and the system cost would be approximately $51,000/day, despite doubled volumes and stall frequencies. The curves in Figure 2 show quite clearly the tradeoffs between increased safety locks and increased stock out costs.

Figures 3 through 5 repeat the analysis of Figure 2 with various assumptions about the cost of holding safety stock and the cost of stocking out. They show that as stock out costs increase relative to holding costs, the optimal amounts of safety stocks should increase.

It should be noted that the only sources of delivery unreliability modeled so far are lock operations and lock failures. Safety stock policies of utilities might also be affected by other factors such as probabilistic expectations of coal mine strikes, frozen waterways and coal price changes. It is possible that such factors may dominate the effects of lock performance analyzed to date.

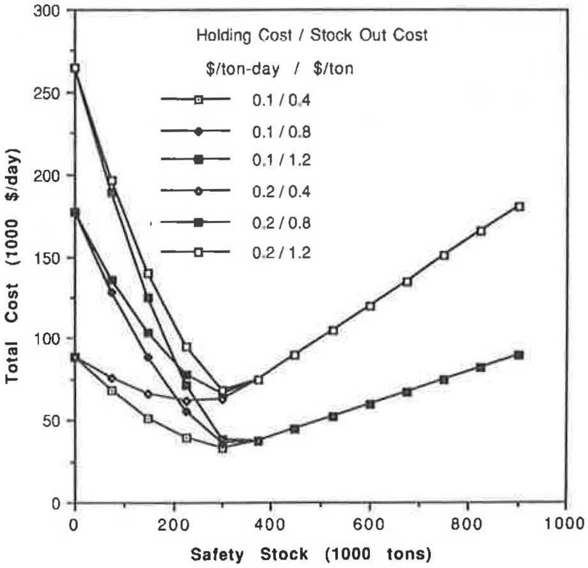


FIGURE 3 Total system costs (1/1/1/OLD).

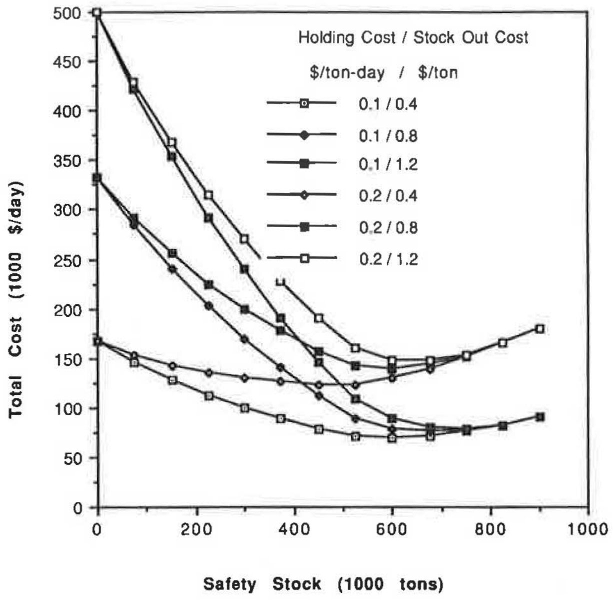


FIGURE 4 Total system costs (2/2/1/OLD).

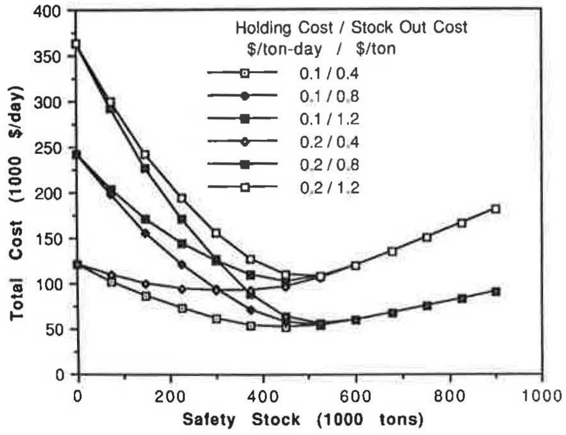


FIGURE 5 Total system costs (2/2/1/NEW).

CONCLUSIONS

Waterway Congestion and Reliability

The results of this work show how expected stock-out levels increase disproportionately with congestion levels (i.e., volume to capacity ratios) and decrese (with diminishing returns) as safety stocks are increased. Such results provide the basis for tradeoffs between inventory holding costs and stock-out costs. The optimized safety stocks resulting from such tradeoffs, and hence their holding costs, would increase as congestion increases and transit time reliability decreases in the system. Such effects are relatively slight when volume to capacity ratios are small. If and when volumes increase substantially above present levels, reliability benefits can justify capacity improvements such as the new Gallipolis Lock.

Model Capability

The simulation model provides estimates of system performance that are sufficiently detailed and accurate for analytic purposes, although its computer requirements are quite modest for a microscopic simulation model. The model's accuracy might be improved by improvements in traffic generation, tow composition, lock selection, and failure generation functions. These improvements might be developed on the basis of a more extensive analysis of empirical data and, possibly, on lock maintenance and failure research. The model may also be extended to translate physical performance measures such as fleet requirements, delays, safety stocks, and stock outs into monetary costs and benefits. Finally, more macroscopic versions of the model are being developed to efficiently analyze alternative investment and maintenance strategies for the national waterway system.

ACKNOWLEDGMENTS

The authors wish to thank L. George Antle and Charles Yoe of the Institute of Water Resources, U.S. Army Corps of Engineers, for their very helpful advice and support in this work.

REFERENCES

1. *Gallipolis Lock and Dam Replacement, Ohio River.* U.S. Army Corps of Engineers, Nov. 1980.
2. C. Yoe. *Lock Rehabilitation A Public Infrastructure Problem: The Value of Increased Productivity in Mean Lockage Performance.* U.S. Army Corps of Engineers, Jan. 1987.
3. J. G. Crew and K. H. Horn. *Logistics Total Cost Prescriptions: Do the Theoretical Results Necessarily Conform with Reality.* Transportation Research Forum, 1980, pp. 319–327.
4. D. J. Bowersox. *Logistical Management, 2nd Edition.* Macmillan Publishing Co., Inc., 1978.
5. M. L. Fair and E. W. Williams. *Economics of Transportation and Logistics.* Business Publications, Inc., 1975.
6. J. L. Heskett, N. A. Glaskowsky and R. M. Ivie. *Business Logistics, 2nd Edition.* The Ronald Press Company, 1973.
7. W. J. Baumol and H. D. Vinod. An Inventory Theoretic Model of Freight Transportation Demand. *Management Science*, 1970, pp. 413–421.
8. S. D. Nason and B. C. Kullman. An Analysis of Inland Waterway Diversions Using a Total Logistics Cost Model. *Transportation Research Forum*, 1979, pp. 138–144.
9. J. S. DeSalvo and L. B. Lave. An Analysis of Towboat Delays. *J. Transpn Economic Policy 2*, 1968, pp. 232–241.
10. H. G. Wilson. On the Applicability of Queueing Theory to Lock Capacity Analysis. *Transportation Research.* Vol. 12, 1978, pp. 175–180.
11. J. L. Carroll and H. G. Wilson. A Zero-sum User Charge System for Rationing the Use of Inland Waterway Locks. *Proc., International Conference on Transportation Research*, 1973.
12. J. L. Carroll, M. S. Bronzini and J. C. Hayward. *Analysis of Waterway Systems: Summary Report.* Pennsylvania Transportation and Traffic Safety Center, Sept. 1972.
13. K. J. Desai. *Analysis of Waterway Systems: A Study of Tow Arrival Processes at Inland Waterway Locks.* Pennsylvania Transportation and Traffic Safety Center, Sept. 1972.
14. C. W. Howe et al. *Inland Waterway Transportation Studies in Public and Private Management and Investment Decisions.* Resources for the Future, Inc., 1969.
15. J. L. Carroll and M. S. Bronzini. Waterway Transportation Simultion Models: Development and Application. *Waterway Resources Research*, Vol. 9, No. 1, 1973, pp. 51–63.

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

Freedom and Trade

DAVID T. HARTGEN, GRADIA M. GBARBEA, AND DEMETRI BACHES

Political changes in Eastern Europe and Soviet democratic movements are likely to bring about changes in trade among nations and increases in transportation requirements. The impact of these changes in freedom, market structure, and governmental status on world trade is estimated in this paper. The primary regional beneficiaries of change are identified. Using a data base consisting of 237 country pairs that report on trade flows, a gravity-type model is calibrated in which 1988 trade flows are related to freedom level, government type, socioeconomic variables, country GNP, shipment times, and extent of free market economy. The model is then used to forecast future (1993) trade under several political scenarios. Results show that baseline trade growth (i.e., trend increases in country GNP) will be about 31 percent during 1988 to 1993; reunification of Germany or freeing up of Communist bloc governments and economies will increase trade by an additional 3.5 to 11.5 percent over the base case. Most of the increases will be limited to trade with Eastern European and Communist bloc nations. On the other hand, a "world freedom" scenario would increase trade about 70 percent, most dramatically in African and Asian developing nations. This compares with a 57 percent increase from vastly improved shipping infrastructure, the benefits of which would flow primarily to currently industrialized nations. It is concluded that trade will increase more if market economies are introduced, rather than if transportation infrastructure is improved. In summary, nations now not free should be encouraged to become so, not be given more transportation infrastructure to increase trade. The shortest path to increased trade is increased freedom.

The 45 years following World War II have seen tremendous economic gains for democratic-capitalist countries and equally dramatic economic stagnation in communist-totalitarian countries. Recent changes in the political structure of nations, particularly in their forms of government, type of economy, and level of freedom raises many questions as to what effects these changes will have on the world economy. The recent collapse of communism in Eastern Europe and its decline worldwide may therefore signal the beginning not only of a "new world order" but a new economic order as well. Economically, this opening-up of Eastern Europe should necessitate greater or expanded trade market (or both) and business opportunities with the rest of the world. The political and social repercussions of these events are numerous and would take much research and study to address adequately. Indeed, events are moving so rapidly that analysis can hardly keep up.

One aspect of this change will be the focus of this paper: the international trade issues raised by these events. The key world trade relations are explored in view of the current political changes and compares them with trade patterns resulting from improved infrastructure.

Also addressed is the extent to which trade will increase and in what form, that is, whether trade will divert to freed nations in Eastern Europe from other countries (a "pie" model) or will increase globally (a "balloon" model) or some combination of these. Areas of the world that will most likely benefit or lose out will also be considered. The impact of transportation improvements on the distribution of goods and services between Eastern Europe and other nations is also examined. Distance, shipment time, and proximity between countries are the most significant transportation variables used in this model. The goal of this analysis is to determine how transportation infrastructure improvements are likely to increase trade.

Since this analysis was completed (summer 1990) events have continued to unfold at a rapid pace. The two Germanys have reunited, combining their fast and slow economies in about the way suggested in this paper. But war in the Middle East has disrupted trade in the region and Iraq's and Kuwait's trade have ceased and their economies have been devastated. Soviet Union international tensions have caused that nation to look inward again, at least temporarily. Romania and Bulgaria's steps toward freedom have been difficult. Poland's search for a market economy is painful. It is hoped that the assessment presented in this paper will remain valid, if not in the specifics, then in the generalities.

BACKGROUND

Throughout history, countries have achieved great status by building strong economic foundations. The rise and fall of nations depends partially on their ability to participate in the world economic markets of their time. Historically, the United States has traded with nearly every other country in the world. U.S. interactions with the rest of the world take several forms: social, economic (goods and services), and political. The United States has generally maintained cordial, if not warm, relations with Eastern European nations in spite of political disparities. But trade with Eastern Europe has been nominal, primarily because of the closed political structure in these economies, coupled with Soviet influences. This closed pattern is now changing, and economic trade (goods and services) is likely to increase. Recent world events will therefore create new markets and new opportunities. By understanding what factors foster growth, which possible scenarios in world political structure promote growth, and which regions of the world may benefit or lose in the new economic structure, efforts can be taken to guide and shape events that lead to beneficial results.

The democratization of Eastern Europe, although sudden, has not occurred in a vacuum. For the last decade, the 12

Department of Geography and Earth Sciences, University of North Carolina at Charlotte, Charlotte, N.C. 28223.

nations of Western Europe have themselves been moving toward a more integrated economy. The unification of the European community into a single market creates an economic entity only slightly smaller than the United States, which is likely to stimulate trade by making the transport of goods to various industrialized western nations more efficient and less costly. Many presently closed national markets would be more open to outside businesses, creating competition and the innovation and improved quality that comes with it. In this scenario trade flows will be most influenced by the ease with which goods will pass between countries. Door-to-door transport time will be reduced as smoother border checks and standardized customs procedures are introduced and as the transportation networks within each country are improved. Most benefits will occur to the European community and to the handful of large multinational corporations that operate in the market. EC 92 is essentially the restructuring of an already existing and highly developed market. Worldwide repercussions of EC 92 are likely to be smaller.

On the other hand, the democratization of Eastern Europe will also change trade flows on a global scale. The collapse of communism has left behind a large market of well-educated and skilled workers, underserved and underutilized by their lagging economies. The business of supplying these countries and using their talents offers a tremendous amount of trading opportunity.

Obviously, the ultimate extent of the changes occurring in Eastern Europe (indeed, in the Soviet Union) cannot be fully determined at this time, as the process is ongoing. But one can safely assert that the common desire of these countries to acquire western tastes and to benefit from the vibrant economies of the industrialized countries, and the desire by western businesses to expand and explore these new markets for international trade, together will substantially increase trade in both goods and services. Particularly, effects on U.S. trade will relate to the following questions:

- Will the United States experience better trade advantages and economic opportunities with Eastern Europe as a result of the current political changes occurring in Europe?
- Will this result in a diversion of international trade from other counties, if indeed there are better trading relations with these new "turning west" countries?
- If trade is diverted from other countries to the new European markets, which countries are likely to loose from this shift and why?
- On the other hand, which countries will gain the most from trade if this new market is viewed as globally advantageous?
- What are the factors that will influence these trade patterns?
- How measurable are these factors that will influence international trade and transportation?
- What are the long- and short-term implications?
- Are the changes in Eastern Europe genuine and stable?
- To what extent can the United States expect increased trade with Eastern Europe?
- What is the role of other industrialized nations such as Japan, West Germany, Great Britain, and so on?
- What would be the economic impact as a result of the reunification of Germany?
- What are the likely impacts of EC 1992?
- What is the USSR role in this social, political, and economic transition?

APPROACH AND SCOPE

To answer the questions raised in this research, a gravity-type model was developed in which trade is related to measures of nation size, freedom, government structure, quality of life, economic activity, and spatial separation. The procedure uses microcomputer and mainframe systems [Excel and Statistical Analysis System (SAS)] to merge various economic indicators, including population, type of government, gross national/domestic product, literacy rate, inflation rate, percentage growth rate, infant mortality rate, population growth rate, degree of freedom, work effectiveness, imports and exports, external debt, and international and national trade transshipment times and distances.

The basic gravity form relates some measure of interaction (T_{ij}) to measures of size and separation:

$$T_{ij} = (K)\ \text{Size}_i^a\ \text{Size}_j^b\ \text{Activity}_i^c\ \text{Activity}_j^d/\text{distance}_{ij}^e \qquad (1)$$

Here, T_{ij} is some measure of trade, "size" is a size measure, "activity" is some measure of economic performance or socioeconomic status, and "distance" is some measure of spatial separation, such as shipment time, distance or a combination. K is a scaling constant. In economic jargon, the size, activity, and distance terms can be thought of as "inputs" (factors of production), and trade is the "output" in produced units of interaction. The coefficients $a, b, c, \ldots$, are constants, determined by calibration, which reflect the sensitivity of the interaction to changes in size, activity, or spatial separation. Models such as this are common in the economic and transportation literature, particularly in intercity travel applications.

It may easily be shown that the coefficients of the model ($a, b, c, \ldots$) are the elasticities of T with respect to each variable; that is, they represent the percent change in T that would result from a 1 percent change in x. This is a convenient result, which allows the forecasting version of this model to be written directly in pivot-point form:

$$\begin{aligned} T_F = T_o\,[1 &+ a(\text{percent change in } x_1) \\ &+ b(\text{percent change in } x_2) + \ldots] \qquad (2) \end{aligned}$$

In this form, forecasts of future trade (T_F) can be made by multiplying the present trade (T_o) by an expansion term [ ] representing the effects of changes in the independent variables. The basis for measuring or hypothesizing future trends in trade relations was calculated by comparing past trade performance (1985 and 1988) with future trade predicted from the model.

The assumption that countries engage in trade because each country is endowed with a comparative advantage in certain resources and a comparative disadvantage in another area is the basis of the model. As a result of specialization, each country is able to export goods reflecting its specialization, while purchasing needed imports. The total trade between two countries will have a dollar value that depends largely on the country sizes, freedom, other factors, and spatial separation. We are modeling here the total goods-only trade; the scope of this paper does not include specific traded commodities between countries, nor does it cover trade in services.

To develop the model a sample of 43 countries was selected. These were chosen to represent the major trading nations in the world, with particular focus on nations in Europe. The specific nations chosen are listed in Table 1, along with selected variables.

DATA ITEMS

The source for the trade data was the *Direction of Trade Statistics, 1989 Annual Yearbook*, published by the International Monetary Fund (*1*). The variables used in this model were selected on the basis of theoretical, practical, and economic considerations. These variables may be generally considered as factors influencing trade between countries. The variables shown in Table 2 were used. In total, trade in our data set represents about one-half of the world total. Explanations for selected variables follow.

- Development Level Identified for all major geographic and economic areas of the world, as indexed by the seven categories listed in *Direction of Trade Statistics*. For convenience and applicability, these categories or groupings were classified as levels—regional classifications that do not necessarily measure the economic structure of country against any other country within the same level or another of classification. The levels are as follows.

—Industrialized—Australia, United States, Canada, Japan, Sweden, France, West Germany, Belgium, Denmark,

TABLE 1 COUNTRY STATISTICS, 1988

Country	Population (Millions)	Growth (%) Pctpop	GNP*/Bill	Growth (%) GDP	Inflation	Unemplym	Billion Exports	Billion Imports	Govt type	Workeff	Dev Level
Industrial Countries											
Australia	16.45	1.2	202.2	1.7	7.7	6.9	29.8	32.1	1	5	1
Belgium	9.87	0.1	155	12.9	1.5	10.8	99	93	1	5	1
Canada	26.31	0.8	471.5	4.1	4.1	7.8	111.5	102.1	1	5	1
Denmark	5.12	0.1	101.3	1.1	4	8.9	25.6	25.5	1	5	1
France	56.01	0.3	939.2	2.3	2.7	10.5	153.6	162.4	1	5	1
W. Germany	60.97	0	908.3	2.2	0.3	0	243	191	1	5	1
Ireland	3.55	0.2	30.6	0.9	2.2	18.5	17.7	14.6	1	5	1
Italy	57.55	0.2	814	3.9	5	12	128.6	138.5	1	5	1
Japan	123.22	0.5	1843	4.8	0.7	2.5	231.2	150.8	1	5	1
Netherlands	14.79	0.5	223.3	4	1	11.1	92.4	91.3	1	5	1
Norway	4.2	0.3	82.6	1.3	8.7	2.1	21.5	22.6	1	5	1
Spain	39.2	0.53	282.2	3.1	5.6	0	27.2	35.1	2	4	1
Sweden	8.39	0.1	105.5	1.4	4.2	0	37.3	32.7	1	5	1
Switzerland	6.95	0.28	126.2	3.2	0.8	0	37.5	41	1	5	1
U. Kingdom	56.93	0.16	556.8	4.3	4.1	0	107	126	1	5	1
U.S.A.	246.04	0.89	4486.2	2.9	3.7	5	216.7	366.3	1	5	1
Sum	735.55		11327.9				1579.6	1625			
Developing Africa											
Algeria	24.94	3	59	2	11	19	8.1	6.1	2	2	2
Angola	8.53	3.5	4.7	1.5	0	1.5	1.5	1.1	3	1	2
Liberia	2.55	3.4	0.97	1.7	3.6	0	0.5	0.3	2	2	2
Nigeria	111.9	3	53.4	3.4	5.5	6.97	6.97	5.5	2	2	2
Africa	35.9	2.2	60	2.4	14	0	21	14	2	3	2
Sum	183.82		178.07				38.07	27			
Developing Asia											
Hong Kong	5.71	1	46.2	13.6	5.5	1.8	48.5	48.5	5	3	
India	83.34	2	231	1.2	8.8	10	11.4	16.7	1	2	3
Singapore	2.67	1.1	23.7	10.9	1.5	3	39	42.5	1	5	3
Korea	43.34	1.3	171	12	7	3	60.7	51.8	1	5	3
China	1112.29	1.6	350	11	18.5	2	57.1	52	3	2	3
Sum	1247.35		821.9				216.7	211.5			
Developing Europe											
Greece	10.04	0.3	46.6	0	16.4	7.4	5.6	12.5	1	4	4
Poland	37.95	0.56	259.8	3	22	0	21.7	21.2	4	2	4
Romania	23.04	0.49	138	3.8	0	0	12.5	10.6	4	2	4
Hungary	10.56	0.2	91.8	1.1	0	0	9.6	9.8	4	3	4
Yugoslavia	23.58	0.61	145	3	70.3	10.4	10.4	11.8	2	3	4
Sum	105.17		681.2				59.8	65.9			
Developing Middle East											
Iraq	18.01	3.8	34	0	27	5	12.4	13	2	3	5
Israel	4.37	1.7	36	1	16	8	9.4	12.9	1	5	5
Saudi Arabia	15.45	4.16	85	6	3	0	25	19	2	3	5
Sum	37.83		155				46.8	44.9			
Western Hemisphere											
Brazil	150.75	2	313	2.9	900	6	26.2	16.6	2	3	6
Mexico	86.36	2.2	135.9	1.4	5219	22.9	22.9	18.6	1	2	6
Argentina	31.91	1.2	74.31	2	188	65	6.3	5.8	1	3	6
Venezuela	19.26	2.5	47.3	4.2	35.5	7	10.4	10.9	2	3	6
Sum	288.28		570.51				65.8	51.9			
Soviet Bloc											
Germany	16.59	-0.06	187.5	2	0	0	27.9	27.6	4	3	7
Czechoslovakia	15.65	0.02	158.2	1.4	0.9	0.9	23.5	23.9	2	3	7
USSR	286.43	0.8	2356.7	2.5	0.7	0	0.97	0.88	2	2	7
Bulgaria	8.97	0.1	67.6	1.8	1.7	0	16.8	16.9	4	2	7
Sum	327.64		2770				69.17	69.28			
Total All	2925.64		16504.58				2075.94	2095.48			

TABLE 2 VARIABLES COMPILED FOR WORLD TRADE MODEL

	Country Variables
*	Development level
	Population (millions)
	Annual percent population growth
	Gross domestic product
	Gross national product
	Annual percent GNP growth
	Infant mortality, deaths/1000 births
	Literacy rate, %
	Per-capita income
	Inflation rate
	Unemployment rate
	Total exports, billion U.S. $ (goods only)
	Total imports, billion U.S. $ (goods only)
*	Government type
*	Work effort
	Separation Variables
*	Land distance
*	Water distance
*	Dock time
*	Shipment time
*	Contiguous
	Trade Data
	1985 exports - from country i to country j
	1985 imports - to i from j
	1988 exports - from i to j
	1988 imports - to i to j

* See text

Ireland, Italy, Netherlands, Norway, Spain, and the United Kingdom;

—Developing, Africa—Algeria, Angola, Liberia, Nigeria and South Africa;

—Developing, Asia—India, South Korea, China, Hong Kong and Singapore;

—Developing, Europe—Greece, Hungary, Poland, Romania, and Yugoslavia;

—Developing, Middle East—Saudi Arabia, Iraq, and Israel;

—Developing, Western Hemisphere—Chile, Argentina, Mexico, Brazil, and Venezuela; and

—Developing, Soviet bloc—Bulgaria, Czechoslovakia, East Germany; and USSR.

● Government type—A constitutional status variable was used as a trade indicator, because the current political changes in Eastern Europe are viewed as facilitating greater trade potential in the region. The degree of political and constitutional freedom is hypothesized to influence trade. For all countries, government type was classified in three categories:

1. Constitutional. Government conducted with reference to recognized constitutional norms includes democracies, republics, constitutional monarchies, and so on.

2. Authoritarian. No effective constitution, or fairly regular recourse to extra constitutional power is confined largely to the political sector.

3. Totalitarian. No effective constitution. Broad exercise of power by the regime in both political and social spheres.

Rather than use dummy variables (e.g., −1, 0, 1) for this structure, a simple 1-2-3 code scale was used. This approach implies numerical properties that are, of course, only approximated by the data. The ratings of individual countries are based on our assessment of their status.

● Work effort—In this context, work effort is defined as the extent that individual's work allows him to participate in the economic environment present in his country, related to the same ability of other individuals in other countries. It may be thought of as a kind of economic quality-of-life. We used this variable to develop a standardized economic development level for comparison purposes, reflecting economic purchasing power for countries with various developmental, political, and social differences. The levels are

1. No structured economy and wages and money are essentially worthless. Revolution may be in progress. Necessary goods are procured through bartering.

2. Daily needs are hard to satisfy for majority of population. Wide disparity in incomes. Small elite group. Inflation is uncontrollable, unemployment high. Buying power is minimal, most purchases are for necessities. Political unrest and riots may result.

3. Consumer goods availability varies by location. Luxury items attainable by small percent of population. Wages do not keep up with inflation. Unemployment can be high for many sectors of the economy regardless of location.

4. Consumer goods available to most of population. Luxury goods take longer to acquire. Buying power is affected at times by inflation. Employment conditions vary widely from one area to another.

5. Consumer goods available to most of population, large supply of luxury goods available to majority. Wages maintain buying power over inflation, which is kept from wide fluctuations. Employment available.

Similarly, we also defined this variable as a code scale, that is, a series of codes approximately an interval scale. The use of dummy variables would be another option.

● Transportation Variables—We defined the following transportation variables:

—Land distance—the number of miles, on land, between two nations;

—Water distance—Number of miles, on water, between two nations;

—Dock Time—Customs, port, and other time delays in transshipment, assumed to average 5 days per dock; and

—Contiguousness—Countries separated by all-water trade routes and countries sharing a land border were regarded as contiguous. Others are noncontiguous.

● Total shipment time—Defined as land distance/200 + water/600 + 5 days per dock −1 (contiguousness)

MODEL CALIBRATION

To forecast trade using this model, we must first calibrate it. That is, we must select those variables that are most important in explaining trade patterns and estimate the model's coefficients. To calibrate such a model it is a common practice to convert it linear form by taking logs:

$$\ln T = \ln K + a\ln \text{Size}_i + b\ln \text{Activity}_j + c\ln \text{dist} + (\ldots \text{other terms}) \qquad (3)$$

The data base of 237 data points consisting of country-country pairs of trade data (1985 and 1988) was merged with the country-specific data. Using the SAS Stepwise Regression procedures, a number of models were developed for different country groups using 1988 trade (imports + exports) as the dependent variable. Initially, all variables were tested, with the most powerful retained for further analysis. Tests were made of models using time and distance as separators, classified by government type and development level. Table 3 shows the models for one analysis, calculated for each group of developing countries, using total shipment time as the spatial separator. These models show some variation in coefficients and variables selected. Note that each of these models contains a GNP-product term and most contain terms for spatial separation (total shipment time), work effort, or government type. For some regions, there is not enough variation in the raw data to allow the calibration process to include all variables in the model. For instance, the Soviet bloc group is (generally) not free nor has wide availability of consumer goods, so these terms cannot enter the trade model. Note also that coefficients (elasticities) for the industrial nations are higher generally than for other nations, indicating greater sensitivity to these variables for this group. We do not believe it logical to assume such sensitivity for policy modeling, however. Therefore, we have chosen to use the aggregate coefficients in Table 3 (shown under the column titled All Observations) as our best estimate of policy impacts for all nations, although this will probably understate the impact of policy changes in less-developed nations.

Note also that the elasticities for GNP-product are in the range of 0.7, elasticities for total shipment time are in the range of -0.8, whereas elasticities for work effort and government type are higher, 4 to 5 and -1 to -2, respectively. This means that, in our data set, international trade is much more sensitive to overall levels of freedom—as reflected in free market economy and constitutional government—than to either country size or spatial separation.

In general, our model calibration showed that total shipment time, GNP, and level of freedom (government type and work effort) were the key variables related to trade patterns. The final model selected accounted for about 65 percent of the variance in 1988 trade, with all terms significant at the 0.05 level. In its policy (forecasting) form, the model is written as:

$$\begin{aligned}\text{Future Trade} = {} & (\text{1988 Trade}) \times [1 + .723 \\ & (\text{percent change in GNP} \\ & \text{product}) \\ & + 1.550 \text{ (percent change in} \\ & \text{“work effort”)} \\ & - 1.313 \text{ (percent change in} \\ & \text{“government type”)} \\ & - 0.791 \text{ (percent change in} \\ & \text{“total shipment time”)]} \end{aligned} \qquad (4)$$

For calibration and forecasting, work effort is the defined as the sum of the work effort code variables for the two countries, government type is defined as the sum of the government type codes for the two countries, and GNP product is the product of the two country's GNPs.

SCENARIOS

To understand the relationship between trade flows and world events, six basic scenarios were developed. They represent changes in world political and social behavior as well as transportation access improvements. The results were analyzed according to the seven defined country development levels to gauge the impact of the models on each region of the world. The scenarios are

1. *Trend:* A five-year GNP trend forecast, from 1988 to 1993. This analysis assumes that recent one-year GNP growth rates will continue for five more years. This model forms the baseline projection for trade volumes, to which each of the following five scenarios were added.

TABLE 3 COEFFICIENTS OF WORLD TRADE MODELS

		Development Level						
		1	2	3	4	5	6	7
Variable	All Observations	Industrial	Africa	Asia	Europe	Mid-East	Western Hemisphere	Soviet Block
n	233	66	21	34	43	15	25	23
R^2	.65	.90	.80	.85	.42	.76	.83	.85
overall F	105.32	132.78	38.55	60.63	15.11	44.29	36.69	38.04
Ln intercept	-1.227	-7.39	-10.76	-2.42	.99	-7.33	-10.23	-4.11
Ln GNP product	.723	.77	.63	1.25	.59	1.31	.90	.56
Ln total shipment time	-.791	-.87	-	-	-.62	-	-1.66	-1.05
Ln work effort	1.55	4.47	5.55	-	-	-	5.72	-
Ln gov't type	-1.31	-2.32	-	-1.10	-	-	-	-
Ln infant mortality	-	-	-	-.93	-	-	-	1.67*

significant coefficients (.05) only
* incorrect sign

2. *Germanys United:* A forecast of change from the impact of a united Germany. To model this scenario, the GNPs of East and West Germany were combined, East Germany's government type was set to constitutional, and the work efforts of both countries were set to 4, to reflect lower West German but higher East German performance.

3. *Communist Bloc Work:* A communist bloc standard of living and production increase without a shift to democratic political ideals. The work effort variable was raised to 5 for each communist country.

4. *Communist Bloc Free:* A communist standard of living and production increase, and a shift to democratic political ideas. The government variable was changed to constitutional to reflect a change in government, and work effort was raised to 5.

5. *World Freedom:* A world shift to democratic and capitalist ideas. For all nations, government types were changed to constitutional and all work efforts were raised to level 5.

6. *Transportation Access:* A major improvement of freight transportation on a world-wide basis. This scenario assumes a 50 percent increase in average land transport speeds, a 33 percent increase in water transport speed, and a 40 percent reduction in dock time. In other words

Shipment time = land distance/300 + water distance/800 + 3 days/dock.

These scenarios were developed to gauge what kinds of events would significantly affect the volume of world trade; they are not forecasts of what events will occur within the next five years. Some are obviously more probable than others. For example, the rise of living and productivity standards and change in political ideology in Eastern Europe may be more likely than world-wide changes or transportation system changes, which depend heavily on technology and infrastructure investments.

FINDINGS

Results of our analysis are summarized in Figure 1 and Table 4 and discussed here.

Scenario 1: Trend

Recent historical trends in trade (1985 through 1988) have been at about 39.9 percent growth overall. Overall, world trade (our total trade) grew from 1069 B$ in 1985 to 1495 B$ in 1988. On a percentage basis, trade with developing Asian nations grew most rapidly, almost 60 percent, Africa and Mid-East trade most slowly. About 70 percent of all trade remained with industrialized nations (Figure 2).

The 1993 trend forecast projection, using recent GNP growth rates to project trade, indicates a slowing from the previous levels to 30.9 percent growth. The percent growth for industrial countries is projected to be 28 percent; the Middle East will register a 32 percent increase; Asia will show a 59 percent growth; Africa a 23 percent increase in trade; Europe, 20.5 percent; Western Hemisphere, 20 percent; and the Soviet bloc, 20 percent. On balance, the trend forecast shows that

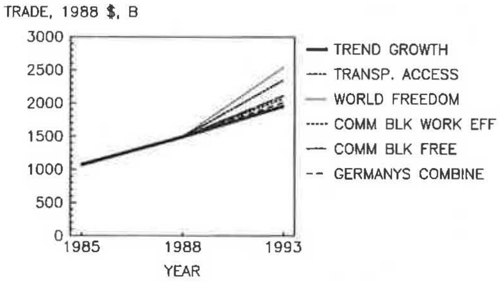


FIGURE 1 World trade, 1985 through 1993.

TABLE 4 FORECASTS OF WORLD TRADE ($ BILLIONS, % CHANGE)

	Total		with Indust. Nations		with Africa		with Asia		with Europe		with Mid East		with West Hemisphere		with Soviet Block	
Scenario	Total*	Aver.*	Total	Aver.	Total	Aver.	Total	Aver.	Total	Aver.	Total	Aver.	Total	Aver.	Total	Aver.
1985 Trade	1069	4.53	741	11.07	22.6	1.03	116	3.13	54.2	1.23	32.7	2.05	70.8	2.72	31.8	1.32
1988 Trade	1495 (39.9)	6.33	1047 (41.3)	15.62	26.7 (18.1)	1.22	184 (58.6)	4.97	69.7 (28.6)	1.58	37.2 (13.8)	2.32	88.7 (25.3)	3.41	41.9 (31.2)	1.75
1. 1993 Trend	1958 (30.9)	8.37	1342 (28.2)	20.03	32.8 (22.8)	1.49	293 (59.2)	8.37	83.9 (20.5)	1.91	48.9 (31.8)	3.06	106.6 (20.2)	4.10	50.4 (20.2)	2.10
2. Germanys United	2011 (34.5)	8.59	1359 (29.7)	20.27	32.7 (22.5)	1.49	299 (62.5)	8.58	87.3 (25.3)	1.99	49.1 (32.0)	3.07	108.2 (21.9)	4.16	77.2 (84.2)	3.22
3. Communist Block Work	2069 (38.4)	8.84	1349 (28.8)	20.13	32.9 (23.2)	1.49	299 (62.5)	8.53	140.3 101.0)	3.19	49.7 (33.7)	3.11	107.6 (21.3)	4.13	91.3 (117.8)	3.81
4. Communist Block Free	2113 (41.4)	9.03	1354 (29.3)	20.21	32.9 (23.2)	1.50	390 (111.9)	8.56	165.8 (137.9)	3.77	50.0 (34.4)	3.13	107.9 (21.6)	4.15	102.8 (145.3)	4.28
5. World Freedom	2539 (69.8)	10.85	1392 (33.0)	20.78	59.2 (121.7)	2.69	469 (154.9)	13.40	222.2 (219.8)	5.04	74.5 (100.3)	4.66	173.5 (95.6)	66.7	148.5 (254.4)	6.19
6. Transportation Access	2350 (57.2)	10.04	1619 (54.6)	24.17	39.2 (46.8)	1.78	339 (84.2)	9.69	102.4 (46.9)	2.33	57.8 (55.4)	3.61	130.5 (47.1)	5.02	61.5 (46.7)	2.56

*Billion U.S. $ Note: Percent changes are calculated against 1988 except 1988-85 comparison.

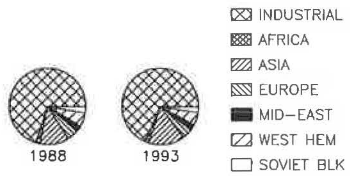


FIGURE 2 World trade by region, trend scenario.

trade by industrialized nations, developing Europe, the Soviet bloc, Western Hemisphere nations and Africa will be slower than the average growth, while trade with Asia and the Middle East will accelerate. Perhaps surprisingly, projected world trade will be 31 percent greater in just five years, even with no political or transportation changes. As GNP grows, so will trade.

Scenario 2: Germany United

The emergence of a united Germany raises many economic questions. The creation of a world economic superpower that will dominate the European continent will clearly affect trade volumes, but the initial short-term 5-year forecast is of interest because the merging process and its effects are not fully understood. According to our analysis, world trade volume would increase only about 3.6 percent above the trend forecast (34.5 percent versus 30.9 percent) if this occurs. But the gains will be highly regionalized, with developing Europe and the Soviet bloc countries reporting the largest gains, 25.3 percent and 84 percent, respectively. The tremendous rise in the trade with Soviet bloc nations shows how dramatically the spill-over effects of a single Germany will help to promote growth in the less developed areas of Europe. The further one moves from the region, the less the impact seems to be. The remaining regions' growth registered a 1 to 2 percent increase above their trend projections (Figure 3).

Scenario 3: Communist Block Work Ethic

If all Communist bloc nations adopt western-style markets, work ethics, and consumer goods availability (the general goal of present USSR economic structuring)—but do not adopt democratic freedoms—we would expect to see an additional 7.5 percent increase in overall world trade in five years (38.4 percent versus 30.9 percent) above the trend forecast. The increases will be most dramatic in the Soviet bloc and developing European nations: 118 percent and 101 percent growth, respectively. Asian trade will also see rapid growth (112 percent). Trade with industrialized nations will grow 29 percent, with the western hemisphere and African trade showing lower growth rates, 21.3 percent and 23.2 percent, respectively. Thus, this scenario produces a modified pie future, in which certain wedges grow substantially more than others.

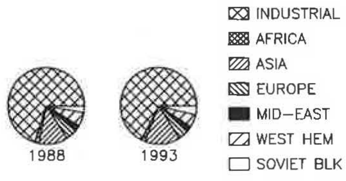


FIGURE 3 World trade by region, Germany united scenario.

Scenario 4: Communist Bloc Free Government

In this scenario, we assume not only western-style markets in the Communist bloc, but also western-style constitutional governments. The effect is not only greater market freedom, but also greater personal freedom. This scenario indicates an approximate 145 percent (triple) increase in trade flow during the next five years for the Communist bloc countries, while trade flows for the world will increase 41.4 percent, or about 10.5 percent above the base forecast. The high Soviet bloc trade figures indicates that these country could unify their economies and/or trade better amongst themselves. This will indeed create a stronger competitive position between the Communist bloc countries and the rest of the world. Of course, our scenario assures no interim political disintegration, which seems to be increasing in probability.

Scenario 5: World Freedom

In assuming global freedom, the work effort variable for all countries was set to 5 and constitutional government type was assumed. This scenario projects a trade increase for the world by almost 70 percent in 5 years. Africa, Europe, Middle East, and the Western Hemisphere show the highest percentage increase (Figure 4). These regions of the world are areas experiencing the most unstable political problems, although the extent of the political unrest varies from country to country and region to region. It does not necessarily account for the capital endowments in these regions, which for the most part are primary resources or raw materials. The United States and other industrialized nations will experience a relatively slower but still substantial percent growth in trade. Those countries that had more political suppression and less freedom naturally experienced greater volume-of-trade increases. The results of this scenario is indicative of the real potential for economic interaction if freedom "breaks out" worldwide.

Scenario 6: Transportation Access

Generally, the greater the total shipment time between countries, the lower the level of trade. Conversely, with shorter shipment times between countries, the greater trade poten-

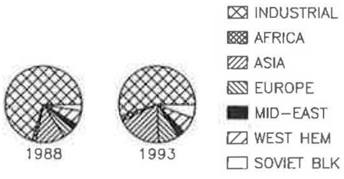


FIGURE 4 World trade by region, world freedom scenario.

tial exists. The effect of significantly improved transportation access on trade is clearly evident. With vastly improved and faster transportation, at rates of 50 percent faster for water, 33 percent faster for land, and 40 percent lower dock time, trade will increase about 57 percent over 5 years. However, the highest trade increases will be in the industrialized nations (i.e., trade flows between the United States and United Kingdom, Japan, South Korea, and Mexico), and trade with developing Asian nations. Other regions will register 46 to 55 percent increases (Figure 5).

This model suggests that if transportation barriers are removed or reduced, more goods will flow throughout the world, but that the effect will be greatest in industrial nations and Asia. As this happens, prices of commodities will become cheaper as the volume of trade increases on the world market. This pattern also suggests comparative advantage in trade as a result of economies of scale for industrialized countries.

POLICY IMPLICATIONS

Reunification of Germany

The ultimate effect of the merging of the two German economies is yet to be determined, because the process is ongoing. However, it would most likely have a greater impact on the East German economy, and a greater positive impact on East Germany than a negative impact on West Germany. German reunification will also stimulate world trade by about 3.5 percent, with very large increases in Soviet bloc neighbor nations.

Our model suggests that an effective way to accelerate the disintegration of communism is to encourage the solidification of market economy and democracy in Germany and the Communist bloc. Our logic is straightforward: East Germany will become another part of Germany, and both countries (and the rest of the Europe desirous of eventually becoming a part of the EC) will have then traded off some degree of economic, social, and political costs and benefits in their individual economies. However, the emergence of a unified German sovereignty will strengthen internal economies and create a better international trade bargaining position with the rest of the world. Another effect is to accelerate trade with Soviet bloc nations thereby hastening their westernization.

Adopting liberalized trade policies, carefully attending to the factors involved in these mixed economic markets (i.e., social and cultural), will put the United States in a more advantageous economic position. Although this approach may appear subtle or perhaps mundane, it is more important, as suggested in Hans Linnemann's (*2*) trade preferential theory and by other experts in international trade, to overcome the political and cultural artificial barriers of these countries than to underestimate them or take them for granted.

The increase in intraregional trade between countries as a result of the political trade barrier reduction is another variation of what Linnemann referred to in his discussion on "equal-impact-of-trade barriers" assumption, wherein ". . . political and economic alliance may have led to a selective lowering of tariff barriers and qualitative restrictions, usually through the establishment of a preferential trading area. Member countries of such a preferential trading area meet less than usual trade resistance in their dealings with other members." In our model, prior spheres of economic influence are being realigned: the result is a substantial economic intraregional trade on the Eurasian subcontinent.

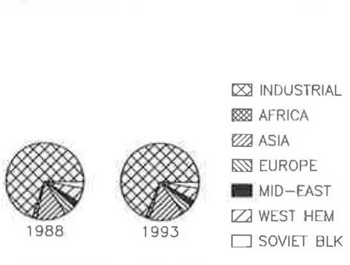


FIGURE 5 World trade by region, transport access scenario.

Communist Bloc

Our models show that a loosening of economic markets and political freedoms within the Communist bloc nations will essentially double their trade, with much of the gain going to developing Europe, less to industrialized nations. Perhaps surprisingly, trade with Africa will not substantially increase, while trade with Asia will increase only if the Communist bloc is politically free, not just an open market. In other words, only those regions of the world already free to benefit in trade from a freer Communist bloc will actually benefit.

World Freedom

Our world freedom scenario is a more simplistic explanation of Akira Onishi's optimistic scenario in his global model of alternative futures of the world economy to the year 2000 (*3*). He focuses on stable development in developing economies, global disarmament, and expansion of development assistance, where defense expenditure is frozen and increase in spending or research and development by both the industrialized nations and the Eastern bloc countries, coordination in macroeconomic policies and overall world trade expansion.

Since recent (1985 through 1988) trade growth has been strong, it is not surprising that our trend forecast produces a strong growth rate. More surprising is our world freedom forecast showing an overall 70 percent growth in trade, over twice the trend rate. Our transportation access scenario, posing almost Herculean improvements in shipment speeds and dock operations, in fact produced only one-third more trade growth worldwide than freeing up of the Communist bloc nations, and less trade growth than a world freedom model. In addition, the primary beneficiaries of that policy were not the developing nations, but those presently industrialized. In essence, our findings call for re-examination of trade-increasing strategies, away from those focusing on transportation access, capitalization, and technology and toward those focusing on the creative engines of free-market democratic economies. It appears that our investment policies are, at the least, cost-ineffective. While investments in infrastructure are needed and will improve trade, policies that encourage freedom and democracy are more effective. Nations now not free should be encouraged to become so, not given more infrastructure to raise trade. In sum, the shortest path to increased trade is increased freedom.

Need for Future Work

This analysis is not complete. Work is necessary to develop sharper forecasts that account for more considerations. Forecasts need to be disaggregated by commodity type, so that country matches can be better identified. Also, the analysis could be disaggregated by country or states, allowing for more targeted analysis of industry group or region. Models for total world trade, time series models, or difference models, and trade deficit models can also be constructed, and certain variables (e.g., transportation time) could be sharpened for each nation. Elasticities suitable for nation groups must be refined for individual nations. Models should also be developed for service and volume of freight, not just dollar value. On balance, we found this modeling structure to be adequate in the aggregate, but too blunt an instrument for analyzing specific countries. Separate models for service trade should be prepared. More detailed analysis of specific country-pair trade trends should also be reviewed. Changes in Eastern Europe, USSR and, of course, the Middle East all warrant that a more careful look at trade patterns should be made. These fruitful areas of further research will be explored in later papers.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the comments of three anonymous reviewers on an earlier draft of this paper, and the thoughtful discussion by the Committee on International Trade and Transportation of TRB, led by Stephen J. Thompson. The views expressed here, however, are solely the authors'.

REFERENCES

1. International Monetary Fund. *Direction of Trade Statistics: 1988 Annual Yearbook*. 24th Ed., New York, 1989.
2. H. Linnemann. *An Econometric Study of International Trade Flows*. North-Holland Publishing Co., Amsterdam, Denmark, 1966, pp. 9–69.
3. A. Onishi. Uses of Global Models: A New Generation FUGI Model for Projections and Policy Simulations of the World Economy. *International Political Science Review*, Vol. 11, No. 2, 1990, pp. 279–295.

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

Cargo Consolidation: Canada-Caribbean Trade

MICHAEL C. IRCHA AND BARRY G. BISSON

Trade between Canada and the Caribbean has traditionally moved through eastern Canadian ports. Recently, advances in continental intermodal services have led to a diversion of Canadian-Caribbean traffic to southern U.S. ports. A market niche study of the feasibility of developing a consolidation center in the port of Saint John, New Brunswick for the Caribbean trade is the subject of this paper. The analysis includes an in-depth evaluation of trade between eastern Canada and seven Caribbean countries, a review of each Caribbean country's economy and Canada's share of their markets, an identification of opportunities for enhancing Canadian exports; a review of the transportation systems connecting Canada to the Caribbean; and the requirements for developing and operating a consolidation center in Saint John. It was concluded that a consolidation center is feasible, particularly if additional traffic to and from other Central and South American countries can be attracted through Saint John. The essential ingredient for success of the consolidation center is the effective marketing of Saint John as Canada's and the New England states' primary Caribbean–South American connection.

The port of Saint John, New Brunswick has traditionally served as a major Canadian point of entry and exit for Caribbean and other Central and South American trade. In recent years, an increasing amount of Caribbean-bound general cargo has been diverted through southern U.S. ports as improved intermodal systems have resulted in decreased freight rates and enhanced service levels. These improvements in this competitive alternative have eroded the viability of the all-water route from Canada to the Caribbean.

In an attempt to reduce the U.S. diversion of Caribbean-bound commodities, a consolidation center for this trade in the port of Saint John was proposed. Such a facility would enable reasonable-sized volumes of general cargo and other commodities to be easily assembled for shipment. Consolidation could make the port of Saint John attractive to Caribbean-bound carriers using larger vessels (resulting in economies of scale and lower freight rates) with improved service frequency.

The University of New Brunswick Transportation Group was asked to undertake this market niche study to evaluate the feasibility of developing a Caribbean consolidation center in Saint John. The sponsoring agencies included External Affairs Canada, Saint John Port Development Commission, Saint John Port Corporation, New Brunswick Department of Commerce and Technology, and the Atlantic Canada Opportunities Agency.

This analysis was limited to the examination of commodity movements to and from eastern Canada (the four Atlantic provinces of New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland as well as Quebec and Ontario) and seven Caribbean countries (Bahamas, Barbados, Cuba, Dominican Republic, Jamaica, Puerto Rico, and Trinidad and Tobago). The consolidation center evaluation included consideration of Canada-Caribbean trade movements, potential opportunities for enhanced Canadian export trade, transportation system needs including all relevant modes, eastern Canadian shippers' perspectives on trade with the Caribbean, and consolidation center operational requirements and options.

CONCEPT

An effective consolidation center depends on efficient intermodal transportation. Arriving individual freight packages can be consolidated into full container loads (FCL) for shipment to the Caribbean. Similarly, import shipments can either be transported inland as FCLs and full truck loads (FTL) or stripped into less than truck load (LTL) size for delivery to nearby destinations.

A review of several existing intermodal terminals (in Canada, the United States, and Sweden) revealed that few, if any, serve in the same capacity as that proposed for the Saint John facility. That is, consolidating a wide range of commodities for a specific geographic destination. Normally, consolidation facilities limit the range of goods handled (for example, specializing in neobulk forest products) and distribute them globally. However, existing consolidation facilities provided the study team with effective standards relating to minimum sizes of consolidation centers, appropriate throughput levels, and the types of facilities and equipment required.

In the Canadian context, inland consolidation facilities play a significant role in the operation of port consolidation centers. These inland facilities enable containers to be stuffed or stripped at a location closest to their point of origin or destination.

As Slack (*1*) has suggested, inland consolidation centers are typically spaced between 800 and 1,400 km apart. Trucks serving a radius of 400 to 700 km are used to deliver goods to and from the inland facility. Unit trains carrying FCLs on flatcars can then be used to transport the consolidated commodities to the port consolidation center.

The Transportation Group, Department of Civil Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3.

EASTERN CANADA-CARIBBEAN TRADE ANALYSIS

Published information from Statistics Canada (*2,3*) along with a special tabulation on exports by water on a tonnage basis (*4*) was used to determine the extent of commodity movement between Canada and the seven selected Caribbean countries.

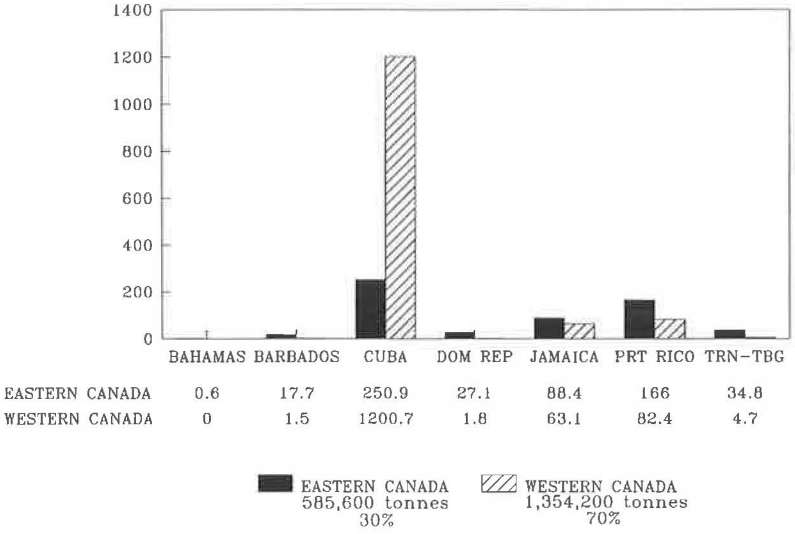
As shown in Figure 1, in 1987, eastern Canada (Ontario, Quebec, and the Atlantic provinces) exported some 30 percent of the total Canadian tonnage to the Caribbean. On a dollar value basis (Figure 2), eastern Canadian exports accounted for almost 70 percent of all the Canadian goods shipped to the Caribbean.

Cuba is the main recipient of Canadian export goods (primarily wheat) in terms of tonnage. In terms of dollar value, Puerto Rico is the main Caribbean trading nation for eastern Canada being the destination for some 38 percent of exported goods (primarily manufactured commodities).

The four Atlantic provinces contributed 79 percent of the eastern Canadian exports to the Caribbean on a tonnage basis and 35 percent on a dollar value basis (Figures 3 and 4). Nova Scotia contributed the greater proportion of export tonnage to the Caribbean at 45 percent of the Atlantic Canada total. New Brunswick provided the highest proportion of exports by value at 43 percent.

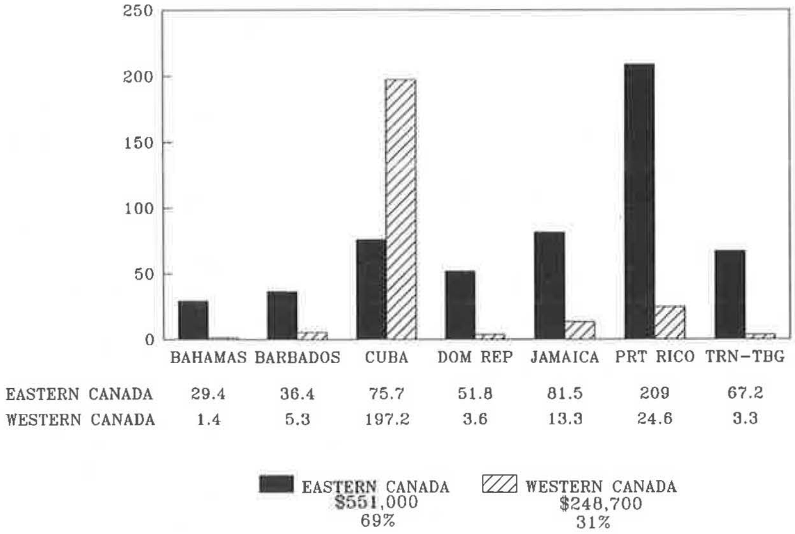
The major 1987 exports from the Atlantic provinces to the Caribbean on a tonnage basis included flour and wheat (28 percent), newsprint (16 percent), other chemicals (13 percent), paperboard (10 percent), potatoes (9 percent), and dimensioned stone (9 percent). On a dollar value basis, the major exports included preserved fish (21 percent), newsprint (21 percent), vegetables (13 percent), other food (13 percent), paperboard (11 percent), and flour and wheat (9 percent).

In 1987, total Canadian imports from the Caribbean amounted to $522 million compared with $800 million worth of exports (Figures 2 and 5). Puerto Rico was the main Car-



	BAHAMAS	BARBADOS	CUBA	DOM REP	JAMAICA	PRT RICO	TRN-TBG
EASTERN CANADA	0.6	17.7	250.9	27.1	88.4	166	34.8
WESTERN CANADA	0	1.5	1200.7	1.8	63.1	82.4	4.7

FIGURE 1 Canadian exports to Caribbean (1987 in tonnes × 1,000).



	BAHAMAS	BARBADOS	CUBA	DOM REP	JAMAICA	PRT RICO	TRN-TBG
EASTERN CANADA	29.4	36.4	75.7	51.8	81.5	209	67.2
WESTERN CANADA	1.4	5.3	197.2	3.6	13.3	24.6	3.3

FIGURE 2 Canadian exports to Caribbean (1987 in $ millions).

FIGURE 3 Eastern Canada exports to Caribbean (1987 in tonnes × 1,000).

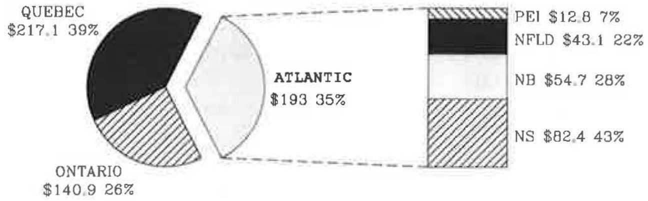


FIGURE 4 Eastern Canada exports to Caribbean (1987 in $ millions).

ibbean country exporting goods to Canada with its commodities valued at $217 million or 43 percent of the total Canadian imports. The major commodities imported by Canada were manufactured goods (23 percent), aluminum ores (18 percent) primarily from Jamaica, and other food (17 percent). Eastern Canada accounted for 94 percent of the imported Caribbean commodities, with the Atlantic provinces importing some 11 percent or about $51 million worth of goods.

The main exports to the Caribbean from the Atlantic provinces were food (including wheat and flour) and paper products supplied primarily by New Brunswick and Nova Scotia. In 1987, some $193 million worth of exports from the Atlantic provinces were shipped to the Caribbean compared with $51 million worth of imports.

The vast array of commodities being exported from eastern Canada to the Caribbean were examined to determine the amount that might be diverted from their current trade routes through the United States and other Canadian ports through a Saint John consolidation center to establish the potential amount of Caribbean-bound throughput such a consolidation center might attract.

CARIBBEAN TRADE ANALYSIS AND COUNTRY PROFILE

Despite the locational advantage of Caribbean countries to Canada, they have often been overlooked relative to other larger export markets (such as Western Europe and the Far East). As individual island nations, each of the Caribbean countries offers little opportunity, but, as shown in Table 1, taken as a whole the Caribbean Basin provides a considerable potential market for Canadian exporters.

The data used to examine the Caribbean countries came from the International Monetary Fund's *Direction of Trade Statistics* (*4*) and individual country profiles provided by External Affairs Canada. Tonnage data were unavailable on a country-by-country basis, thus only dollar value commodity movements were used in this analysis.

There are inherent difficulties in relying only on monetary value information. These difficulties include: change in the world price of a good may result in changes in the value shipped while tonnage remains constant; currency fluctuations affect the value of imports and exports; and countries supplying raw materials may be underrepresented even if their shipped tonnage is large.

Potential export opportunities for Canada and the United States in the Caribbean were identified by examining the current market share of Canadian exporters within each sector of the local market, economic trends and structure of each country, and specific country projections provided by External Affairs Canada. Detailed country-by-country analyses of specific Canadian export opportunities were undertaken.

The Caribbean countries examined have initiated national value-added policies such as the establishment of import quotas and tariffs along with currency devaluations to stabilize and enhance their local economies. The primary objective of these policies is to shift these Caribbean nations from a single commodity-based economy to a more diversified structure.

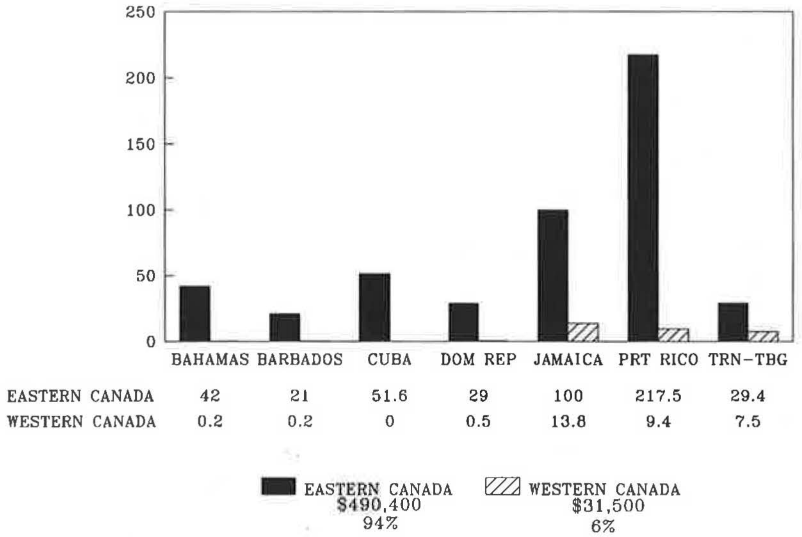


FIGURE 5 Canadian exports to Caribbean (1987 in $ millions).