1249

TRANSPORTATION RESEARCH RECORD

Truck Transportation and Safety Issues

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1989

Transportation Research Record 1249
Price: $7.50

mode
1 highway transportation

subject areas
12 planning
16 user needs
21 facilities design
51 transportation safety
53 vehicle characteristics

TRB Publications Staff

Director of Publications: Nancy A. Ackerman
Senior Editor: Edythe T. Crump
Associate Editors: Naomi C. Kassabian
Ruth S. Pitt
Alison G. Tobias
Production Editor: Kieran P. O'Leary
Graphics Coordinator: Karen L. White
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.

Truck transportation and safety issues.
p. cm.—(Transportation research record, ISSN 0361-1981 ; 1249)
Reports prepared for the 68th Annual Meeting of the Transportation Research Board.
ISBN 0-309-04971-7
1. Trucking—United States—Safety measures. 2. Trucking—United States—Accidents. 3. Trucking—United States—Deregulation. 4. Shipment of goods—United States. I. National Research Council (U.S.). Transportation Research Board. Meeting (68th : 1987 : Washington, D.C.) II. Series.
TE7.H5 no. 1249
[HE5614.2]
388 s—dc20
[363.12'59] 90-6189
CIP

Sponsorship of Transportation Research Record 1249

GROUP 1—TRANSPORTATION SYSTEMS PLANNING AND ADMINISTRATION
Chairman: Ronald F. Kirby, Metropolitan Washington Council of Governments

Freight Transportation Section
Chairman: Richard A. Staley, Arlington, Virginia

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, U.S. Department of Transportation
W. Bruce Allen, Maureen F. Allyn, A. Don Bourquard, Leland S. Case, Patricia M. Davis, Mark R. Dayton, John Glover, Paul C. Hanappe, Susan Henriques-Payne, L. Michael Kenny, William A. Lesansky, George F. List, Edward Margolin, Edward K. Morlok, Jerold B. Muskin, Ernest R. Olson, Howard E. Olson, Edwin P. Patton, Jossef Perl, Ronald D. Roth, Charles D. Sanft, Joe Tsai, 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, Alan M. Clayton, John W. Fuller, William D. Glauz, Peter Griskivich, Burkhard E. Horn, Colin Ian McGillivray, Dan R. Middleton, Richard R. Mudge, John L. Reith, Raymond R. Ruggieri, Ivan F. Scazziga, Susan K. Sheets, William K. Smith, Brian H. Vogel, Patricia F. Waller, Arthur L. Webster II

GROUP 3—OPERATION, SAFETY, AND MAINTENANCE OF TRANSPORTATION FACILITIES
Chairman: James I. Taylor, University of Notre Dame

Users and Facilities Section

Committee on Traffic Law Enforcement
Chairman: Olin K. Dart, Jr., Baton Rouge, Louisiana
John W. Billheimer, George W. Black, Jr., Quinn Brackett, Stephen S. Caruso, Rochard L. Downey, Ted E. Dudzik, William D. Glauz, D.D. Hinton, Kent B. Joscelyn, Roy E. Lucke, Judson S. Matthias, Anthony Dormer May, Jerry G. Pigman, Richard A. Raub, Henry C. Rockel, Brian G. Traynor, Jack Walsh, James W. Yeasted

Committee on Traffic Records and Accident Analysis
Chairman: James O'Day, Salem, South Carolina
Secretary: C. Arthur Geurts, Utah Department of Transportation
Thomas E. Bryer, Myong-Soon Chang, Benjamin V. Chatfield, John T. Dempster, Jr., Nicholas J. Garber, James H. Hedlund, Donald R. Herd, D.D. Hinton, Alan F. Hoskin, Jack A. Hutter, A. Dewey Jordan, Larry G. Karsten, John C. Laughland, Martin E. Lipinski, Philip P. Madonia, Joseph C. Marsh IV, Clarence W. Mosher, Olga Pendleton, Darrell E. Roach, Robert R. Roberts, Johannes Sloth, Alex Sorton, John G. Viner, Charles V. Zegeer, Ralph W. Zimmer

Richard Pain, 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, 1988.

NOTICE: The Transportation Research Board does not endorse products or manufacturers. Trade and manufacturers' names appear in this Record because they are considered essential to its object.

Transportation Research Board publications are available by ordering directly from TRB. They may also be obtained on a regular basis through organizational or individual affiliation with TRB; affiliates or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Transportation Research Record 1249

Contents

Foreword

Four aspects of trucking are covered in this Record. Kang examines the effects of deregulation from the shippers', not the carriers', perspective. Because there has been little research from this perspective since deregulation, the findings are of particular interest. His results suggest that service attributes may be more important than pricing when shippers select a national common carrier.

As truck size has increased, more problems have emerged with intersections that have marginal geometric configurations. DeCabooter and Solberg present a methodology, with accompanying justification and rationalization for using the methodology, to determine which intersections need attention as well as what treatments to utilize.

Overweight trucks are a continuing problem for highway agencies worldwide. A variety of compliance and enforcement programs exists. In their paper Bisson and Gould present a methodology for assessing the effectiveness of these enforcement programs. The authors demonstrated the methodology with the truck enforcement program used in New Brunswick, Canada.

The last two papers deal with truck crashes. In the first, Jovanis et al. compare accident rates for double and single combination tractor-trailers. They used industry-supplied data covering the same routes over a 3-year period. Separate comparisons were made for access-controlled highways, non-access-controlled highways, local streets, and parking lots. On routes approved for doubles operation, they found the double-trailer trucks as safe as or safer than single-trailer trucks.

Khasnabis and Lyoo used the Box-Jenkins method of time series analysis to forecast truck accidents. Over 6 years of monthly accident data from Michigan were used to develop the model, and two types of goodness-of-fit tests were used to check it. For one of the tests the model was used to forecast 20 months of Michigan data that had not been used in model development. The test showed excellent correspondence between the observed data and the model output. Thus, the authors recommend further development of the technique as an accident prediction tool.

Impacts of the Trucking Industry Deregulation on Shippers' Preferences

KYUNGWOO KANG

In an abundance of literature written before the passage of the Motor Carrier Act (MCA) of 1980, researchers discussed and often debated the anticipated effects of regulatory reform on shippers and carriers. Since the passage of the MCA of 1980, most of the studies have focused on carriers, with little research on the effects of deregulation from the shippers' perspective. The results of this study suggest that service attributes appear to be more important factors than pricing attributes in the selection of national common carriers. The study also indicates that both carriers and shippers were in a period of adjustment following the policy changes.

In an abundance of literature written before passage of the Motor Carrier Act (MCA) of 1980, researchers discussed and often debated the anticipated effects of regulatory reform on both shippers and carriers. Most of the studies have focused on carriers, however, with little research from the shippers' perspective.

Information on service attributes is essential for the design and marketing of services for motor carriers, especially in a deregulated environment. This information can provide guidance on marketing strategies. For example, in an attempt to maintain or expand their market shares, many carriers have offered price discount programs. However, some shippers may find other strategies, which emphasize service attributes other than price, more effective. This is the basic argument for less government regulation of the trucking industry; that is, carriers should emphasize their own strengths, such as relative rate discounts or relative special delivery/pickup services for targeted shippers. At the same time, shippers have more options than under the regulated environment to select carriers.

The carrier-selection decision is part of a specialized process whereby a firm purchases the services of a carrier to provide the necessary and vital link among logistics nodes. Usually cost and service are the two basic factors considered in the carrier-selection decision. Winston found that lower rates were more important than services in attracting traffic between mode choices (*1*). As mentioned by Bardi (*2*), "Much has been done with respect to carrier prices and pricing practices and the carrier selection decision. Measurement and evaluation of the logistic implications of the carrier cost determinant is much easier than that of carrier service performance."

The work dealing with carrier service performance in the carrier-selection decision has been directed toward the evaluation of service performance of one mode versus another mode, with emphasis upon the heterogeneous nature of the service supplied by the different modes (*1*). Most carrier-selection analyses present criteria for assessing modal service and cost differences, but do not consider explicitly the selection of a specific carrier within a mode. One of the important questions in the deregulated environment from the carrier's point of view is how carriers can maintain or expand their markets more effectively.

DATA

The data used in this paper were gathered as part of a broader project conducted by a leading private management corporation in the trucking industry. The sample used in the analysis was a survey undertaken in the first half of 1983. Approximately 10,000 questionnaires were mailed, with about a 25 percent response rate, or 2,300 usable replies. In the questionnaire, each shipper was asked for his or her perceptions (images) of seven major national common carriers with respect to their various service and price characteristics.

CROSS-CLASSIFICATION ANALYSIS

The initial analysis involved the computation of relative frequencies of 11 selected shipper perceptions of the service characteristics of the seven national common carriers. The resultant frequency table was very useful in understanding the data structure and in building a baseline statement on the strengths and weaknesses of each carrier.

After the computation of relative frequencies, cross-classification analysis was performed between each of the 11 selected shipper perceptions and the share of shippers. The share of shippers was measured by determining which carriers were most frequently used.

A summary of the analysis is presented in Table 1. Overall, the service categories had the highest positive ratings for frequent users, led by Broad National Coverage, Expanded Terminal Coverage, and Prompt Pickup/Delivery. Surprisingly, the pricing attributes such as Aggressive Discounting and Tailored Prices had the highest negative ratings among frequent shippers.

For each carrier, the data were ranked from highest to lowest among those shippers who used that carrier frequently. For example, approximately 54 percent of shippers that used Carrier A frequently characterized Carrier A as having aggressively expanded terminal coverage since 1980 and 52 percent said that Carrier A offers prompt pickup and delivery.

One interesting finding of this analysis was the relatively lesser importance of pricing attributes such as Innovative Pric-

Port Authority of New York and New Jersey, One World Trade Center, 54 S, New York, N.Y. 10048.

TABLE 1 SUMMARY OF CROSS-CLASSIFICATION ANALYSIS OF SHIPPERS' IMAGE OF SEVEN NATIONAL COMMON CARRIERS

	Shipper Response (%) by Carrier[a]						
Category	A	B	C	D	E	F	G
Broad National Coverage	32.2[b]	70.9	29.3	42.9	74.3	33.7	61.2
Aggressively Expanded Terminal Coverage	54.2	41.6	26.0	22.4	48.5	26.5	36.9
Low Loss/Damage	38.2	42.8	34.2	30.9	42.4	31.9	40.6
Fast Claim Resolution	27.9	29.6	25.0	22.2	30.6	23.3	31.7
Good Tracing System	36.3	52.2	30.4	37.8	49.2	35.1	48.5
Consistency of Service	36.5	45.4	31.6	30.9	49.6	37.4	44.4
Prompt Pickup/Delivery	51.7	53.7	44.3	43.6	55.3	45.7	58.1
Expedited Service	41.4	46.1	37.5	35.6	48.3	36.2	49.1
Innovative Pricing Programs	31.3	31.0	25.0	27.6	32.6	28.8	39.2
Aggressive Discounting	26.4	24.4	21.4	17.5	26.2	21.9	31.1
Tailored Prices	19.4	23.4	16.7	14.6	20.7	15.0	21.8

[a]Carriers' names have been disguised for this analysis to protect the proprietary interest of the firms.
[b]Interpret as "among those shippers who use Carrier A frequently, 32.3 percent said Broad National Coverage was very descriptive."

ing Programs and Aggressive Discounting as compared with service attributes.

ORDERED-RESPONSE MODEL

How can carriers prepare their marketing strategies for various types of shippers? Should carriers be treated the same and if not, what should the differences be? A model was built to test possible answers to these questions using the ordered response approach.

Three ordered categories in the data set exist. 1. Frequent users, 2. Occasional users, and 3. Nonusers. It is assumed that the responses are ordered from 1 to n. Furthermore,

$$Y_i = X_i \cdot \beta_i + \varepsilon_i \tag{1}$$

where

Y_i = dependent variable of interest,
X_i = independent variables, and
ε_i = error term.

Then within the model, the individual shipper falls into the following categories:

Category 3 if $\varepsilon_i < X_i \cdot \beta_i$,
Category 2 if $X_i \cdot \beta_i < \varepsilon_i < X_i \cdot \beta_i + c$, and
Category 1 if $\varepsilon_i > X_i \cdot \beta_i + c$,

where c > 0. It is also assumed that

$$\varepsilon_i - N(0,\sigma^2 I) \tag{2}$$

Also assumed is that the variable of theoretical interest is the interval level (*3–5*). In this case, only an ordinal variable Z_{ij} is observed such that $Z_{ij} = 1$ if Y_{ij} falls in the jth category, and $Z_{ij} = 0$ otherwise, where $i = 1, 2, \ldots, n$, and $j = 1, 2, \ldots, m$.

Y_{ij} is not observable, but it is known to which of the m categories it belongs. Thus, if Y_{ij} is observed such that

$$\alpha_{j-1} < Y_i < \alpha_j \tag{3}$$

it is known that it belongs to the jth category.

From Equations 1 and 3, the probability function of the observed dependent variable Z is written as follows:

$$\alpha_{j-1} < Y_i < \alpha_j = \alpha_{j-1} < \beta' \cdot X_i + \varepsilon < \alpha_j \tag{4}$$

If $\beta' \cdot X_i$ is subtracted from the right-hand side of Equation 4 and the result is divided by σ, then Equation 4 becomes

$$\alpha_{j-1} - \beta' \cdot X_i/\sigma < \varepsilon_i/\sigma < \alpha_i - \beta' \cdot X_i/\sigma \tag{5}$$

From Equation 2, in which the error term is assumed to be multivariate normal, the following results:

$$\text{Prob}(Z_{ij} = 1) = \phi(\alpha_i - \beta' \cdot X_i) - \phi(\alpha_{j-1} - \beta' \cdot X_i) \tag{6}$$

where ϕ is the cumulative standard normal.

The likelihood function for the model is

$$L = \pi_i \, \pi_j \, [\phi(\alpha_i - \beta' \cdot X_i) - \phi(\alpha_{j-1} - \beta' \cdot X_i)]^{Z_{ij}} \tag{7}$$

and the log-likelihood function is

$$L^* = \ln L = \Sigma_i \, \Sigma_j \, Z_{ij} \ln$$
$$[\phi(\alpha_i - \beta' \cdot X_i) - \phi(\alpha_{j-1} - \beta' \cdot X_i)] \tag{8}$$

The ordered probit and logit models differ only in the specification of the distribution of ε_i, namely, the cumulative normal distribution for the probit model and the logistic distribution for the logit model. Also, the latent variable Y_i is interpreted as susceptibility, and α_i as a threshold (*6*).

The maximum likelihood estimate of the parameters can be obtained by maximizing Equation 8 with respect to β and α_k. In this case, CRAWTRAN was used (*7*).

Finally, the variables were ranked as follows. The dependent variable, degree of frequency, was ranked by shippers as

1. if used frequently,
2. if used occasionally,
3. if used very infrequently.

The independent variables Prompt Pickup/Delivery, Aggressive Discounting, Expedited Service, Consistency of Service, Innovative Pricing Programs, and Tailored Prices were ranked by shippers as

1. if very distinctive (excellent),
2. if distinctive (good),
3. if not very distinctive (fair),
4. if not distinctive (poor).

Table 2 shows the results of the ordered-response model for carriers A, C, E, and G. The overall statistical results for the ordered probit model were significant. Service attributes such as Consistently Good Service and Prompt Pickup/Delivery are all statistically significant, as well as of great magnitude compared with the other attributes for selected national common carriers. The pricing attributes such as Aggressive Discounting are statistically significant for Carriers A , C and G; however, the Innovative Pricing Programs category is significant for Carriers E and G.

Another major question was whether the results in Table 2 would be the same for all shippers, regardless of the shipper's special characteristics, such as different levels of annual spending for freight, different lengths of haul, and different types of commodities shipped.

Table 3 shows the separated sample in terms of the shipper's annual spending for freight. The selected sample of relatively small shippers consisted of those who spend under $100,000

TABLE 2 PARAMETERS OF ESTIMATES FOR ORDERED-RESPONSE PROBIT MODEL: ALL SHIPPERS

	Coefficients by Carrier[a]			
Category	A	C	E	G
Consistency of Service	0.2867	0.7084	0.5493	0.6534
	(4.18)[b]	(6.68)	(5.28)	(6.49)
Prompt Pickup/ Delivery	0.2674	0.4230	0.4767	0.6467
	(3.93)	(4.15)	(4.50)	(6.53)
Expedited Service	0.1198	0.0845	0.2711	0.1249
	(1.90)	(0.81)	(2.76)	(1.30)
Innovative Pricing Programs	0.0494	0.1861	0.2224	0.3008
	(0.74)	(1.67)	(2.16)	(2.98)
Aggressive Discounting	0.2769	0.2196	−0.0083	0.2407
	(4.06)	(2.06)	(−0.24)	(2.45)
Tailored Prices	0.0000	0.1733	0.2292	0.0688
	(−0.58)	(1.75)	(2.38)	(0.75)
Threshold	1.0366	1.9705	1.4426	1.8675
	(18.41)	(26.60)	(22.89)	(28.01)
Log-likehood	−737	−876	−840	−961
Observation	772	940	975	1149

[a]Carriers' names have been disguised for this analysis to protect the proprietary interest of the firms.
[b]Numbers in parentheses are *t* statistics.

TABLE 3 PARAMETERS OF ESTIMATES FOR ORDERED-RESPONSE PROBIT MODEL: SMALL SHIPPERS AND LARGE SHIPPERS

	Coefficients for Small Shippers by Carrier[a]				Coefficients for Large Shippers by Carrier[a]			
Category	A	C	E	G	A	C	E	G
Consistency of Service	0.4717	0.4078	0.3312	0.5336	0.3218	0.7107	0.6091	0.7750
	(4.32)[b]	(1.89)	(1.57)	(2.14)	(3.36)	(4.49)	(3.91)	(5.32)
Makes Prompt Pickup/Delivery	0.1430	0.4322	0.4794	0.6189	0.3065	0.4567	0.3910	0.6739
	(1.38)	(2.10)	(2.47)	(2.97)	(3.70)	(2.97)	(2.35)	(4.36)
Expedited Service	0.2250	0.2892	0.1026	0.2746	0.2502	0.1025	0.4629	0.1411
	(2.09)	(1.33)	(0.49)	(1.36)	(3.08)	(0.66)	(2.99)	(0.94)
Innovative Pricing Programs	0.1769	0.3294	0.3246	0.2312	0.2449	0.1529	0.1431	0.4903
	(1.59)	(1.39)	(1.53)	(1.08)	(3.02)	(0.94)	(0.95)	(3.16)
Aggressive Discounting	0.0538	−0.0305	0.1051	0.3759	0.0069	0.4433	0.0182	0.1876
	(0.48)	(−0.33)	(0.53)	(1.76)	(0.10)	(2.95)	(1.22)	(1.22)
Tailored Prices	0.0204	0.3833	−0.0037	0.0469	0.0042	−0.0121	0.3731	0.0713
	(0.19)	(1.94)	(−0.19)	(0.23)	(0.05)	(−0.07)	(2.52)	(0.49)
Threshold	1.1449	2.2001	1.6101	2.1043	1.0539	1.7627	1.3285	1.7218
	(11.85)	(14.39)	(12.91)	(15.01)	(14.34)	(16.56)	(14.26)	(17.36)
Log-likehood	−276	−208	−216	−225	−417	−408	−373	−428
Observation	298	220	235	266	190	140	237	217

NOTE: Small shippers are those who spend less than $100,000 annually for freight. Large shippers spend more than $500,000 annually for freight.
[a]Carriers' names have been disguised for this analysis to protect the proprietary interest of the firms.
[b]Numbers in parentheses are *t*-statistics.

annually for freight. The results indicated that the small shippers were more sensitive to service attributes such as prompt pickup and delivery and consistency of service than pricing attributes such as aggressive discounting.

The sample of relatively large shippers (those who spend over $500,000 annually for freight) revealed mixed results. For Carrier A, both service and pricing attributes were equally critical. However, the service attribute was the major factor for Carrier E. Service attributes were significant for Carriers C and G; however, the pricing attributes were split between these carriers (i.e., aggressive discounting for Carrier C and innovative pricing programs for Carrier G).

Conclusions

One implication of this paper is that carrier management can determine how a particular shipper or group of shippers evaluates various goals in purchasing freight transportation services. The evidence of this study indicates that the relative importance of service and price attributes can be estimated and that these weights may vary by market segments. The service categories were more important variables than the pricing categories for small carriers. The findings for big shippers were mixed.

Some caution is needed before these results are evaluated.

1. The shippers' perceptions (images) may or may not reflect the carrier's actual performance. A carrier may discover that many shippers perceive its performance on certain characteristics as being inferior to their competition when the actual performance is comparable or superior. In this event, the carrier can initiate marketing efforts designed to bring shipper perceptions in line with actual performance.

2. The data used this study are somewhat dated, but the general approach of this analysis may well be suitable for more recent information on the trucking industry.

REFERENCES

1. C. Winston. A Disaggregate Model of the Demand for Intercity Freight Transportation. *Econometrica*, Vol. 49, 1981, pp. 981–1006.
2. E. Bardi. Carrier Selection From One Mode. *Transportation Journal*, Vol. 13, 1973, pp. 23–29.
3. R. McKelvey and W. Zavoina. A Statistical Model for the Analysis of Ordered Level Dependent Variables. *Journal of Mathematical Sociology*, Vol. 4, 1975, pp. 103–120.
4. G. S. Maddala. *Limited-Dependent and Qualitative Variables in Econometrics*. Cambridge University Press, New York, 1983, pp. 46–49.
5. M. Ben-Akiva and S. R. Lerman. *Discrete Choice Analysis: Theory and Application to Travel Demand*. MIT Press, Cambridge, Mass., 1985, pp. 125–126.
6. D. McFadden. Econometric Analysis of Qualitative Response Models. In *Handbook of Econometrics*. (Z. Griliches and M. D. Intriligator, eds.)North-Holland, New York, 1984, pp. 1395–1457.
7. R. Avery. *Qualitative Dependent Variable Program CRAWTRAN*. Carnegie-Mellon University, Pittsburgh, Pa., 1980.

Publication of this paper sponsored by Committee on Freight Transportation Planning and Marketing.

Operational Considerations Relating to Long Trucks in Urban Areas

P. H. DeCabooter and C. E. Solberg

The Surface Transportation Assistance Act (STAA) of 1982 mandated the operation of large trucks (generally 102 in. wide and 41 ft from kingpin to rear axle) and twin tractor-trailer combinations on most Interstates and many primary highways, and in 1987 the Surface Transportation and Uniform Relocation Assistance Act reinforced the trend. Many states have rapidly expanded the highway system for longer vehicles by adding secondary highways, many of which involve urban streets and intersections. Many of the intersections are substandard if compared with the ideal 62-ft wheelbase turning template. However, truck operators and automobile drivers take compensatory measures that allow the longest vehicles to successfully negotiate most of these marginal geometric configurations. Demonstrably, full-scale improvements are unnecessary in many instances in which street widths meet or exceed certain minimum tolerances. However, when intersections are so seriously deficient that the operation of long trucks through them endangers public safety, a rational way to identify them should be available to engineers, local officials, and other decision makers. A methodology is presented that allows decision makers to rationalize this process and defend their judgment.

Under the Surface Transportation Assistance Act (STAA) of 1982, and reaffirmed in the Surface Transportation and Uniform Relocation Assistance Act (STURAA) of 1987, numerous highways in the United States were designated by the Federal Highway Administration and the states for use by long semitrailer trucks. Research has been conducted on the theoretical operational and geometric characteristics of these vehicles. However, the way they function in the real-world setting of actual geometric configurations in competition with heavy traffic volumes is a matter for serious engineering consideration. Many intersections on the designated highway system are geometrically inadequate according to current ideal turning templates for long trucks. Reconstructing a substantial number of these to theoretical standards would be cost-prohibitive. Yet traffic engineers and designers know that while most intersections somehow accommodate trucks and will continue to do so as the trucks get longer, a few will lose this capacity at some point. The ability of engineers to differentiate between the intersections that require only minor modification and those that must be rebuilt to provide acceptable levels of service is of critical concern. A second concern is how to decide which modifications, short of complete reconstruction, will be the most effective.

The Wisconsin Truck Study addresses concerns related to the actual operation of long trucks at downtown intersections on the designated highway system. As shown in Table 1, most states allow long trucks on two-lane urban highway sections. Very few of the intersections in these urban sections were designed for 50-ft wheelbase operation, yet 62-ft wheelbases are now permitted. Furthermore, the distance from kingpin to rear trailer axle is usually the critical dimension. Current design criteria are based on overall length.

This research set out to determine the actual operating characteristics of a typical mixture of long vehicles and the impact of various dimensions of these assemblies on

1. Offtracking,
2. Overall swept path,
3. Opposite lane encroachment of the leading edge of the tractor,
4. Intersection traffic operation, and
5. Intersection design and location of traffic appurtenances.

Early assessments of improvement costs for designated highway systems used relatively crude deficiency criteria. Large-scale expenditures based on such tenuous data are difficult to justify. Also, physical improvements in downtown intersections can be very costly in both economic and public relations terms. Therefore, investment in engineering research that examined all aspects of intersection performance (both operational and geometric) could pay dividends. The underlying premise (especially in evaluating truck operations in constricted urban settings) was that immediate and downstream costs of massive reconstruction may be too much to bear, and that simply blending design and traffic engineering expertise in an applications research setting might suggest more cost-effective and publicly palatable solutions than massive reconstruction.

OBJECTIVES

Five primary goals for this study, to be performed in two separate stages, are as follows:

1. Determine real-world operating characteristics of long trucks at intersections in an urban setting.
2. Evaluate the operations of typical medium- to high-volume urban intersections that do not conform to minimal design standards.
3. Establish realistic intersection design and redesign criteria for urban intersections.
4. Establish criteria for location of traffic control devices and other on-street appurtenances where there is a high percentage of truck traffic.
5. Develop engineering analyses based on statistical inference and mathematical models that would enable assessment of the future impacts of longer-wheelbase trucks as their proportion in the vehicle population increases.

Wisconsin Department of Transportation, State Office Building, 4802 Sheboygan Avenue, P.O. Box 7910, Madison, Wis. 53707.

TABLE 1 STATES ALLOWING OPERATION OF LONG TRUCKS IN URBAN AREAS

Name of State	Approximate Percent of State System (Interstate Plus Numbered Highways) Designated for Large Truck Operation)	Do Two Lane Designated Routes or Access Highways Enter or Go Through Cities ?
Alabama	100 %	Yes
Arkansas	100 %	Yes
California	60 %	Yes
Colorado	57 %	Yes
Connecticut (1)	13 %	No
Delaware (2)	4 %	Yes
Florida (3)	100 %	Yes
Idaho	100 %	Yes
Illinois	43 %	Yes
Indiana	100 %	Yes
Kansas	100 %	Yes
Louisiana	100 %	Yes
Maryland	100 %	Yes
Michigan	67 %	Yes
Minnesota	46 %	Yes
Mississippi	100 %	Yes
Missouri (4)	49 %	Yes
Montana	100 %	Yes
Nebraska	100 %	Yes
Nevada	100 %	Yes
New Hampshire	100 %	Yes
New Jersey	55 %	Yes
New Jersey	100 %	Yes
New York	20 %	Yes
North Carolina (5)	4 %	Yes
North Dakota	100 %	Yes
Ohio	100 %	Yes
Oklahoma	100 %	Yes
Pennsylvania (6)	5 %	Yes
Rhode Island	100 %	Yes
South Dakota	100 %	Yes
Tennessee	100 %	Yes
Texas	100 %	Yes
Vermont	100 %	Yes
Washington (3)	100 %	Yes
West Virginia	17 %	Yes
Wisconsin (6)	53 %	Yes
Wyoming	100 %	Yes

1 Multiple trailers (single trailer semi's allowed on entire system)
2 Requires permit
3 All major cities with state highways entering or traversing
4 Interstate and primary sytem
5 Includes 73,221 miles of two-lane system.
6 Anticipates major increase in city two-lane mileage and/or overall system mileage

INVESTIGATIVE METHOD

Although the information desired was easily identified, the question of how to get it was more complex. Initially the researchers thought a straightforward aerial photographic survey could be conducted. A photogrammetric camera was envisioned as the only necessary equipment to capture hours of measurable incremental data from truck wheelpaths. Numerous possibilities were explored. For the first phase it was decided that two separate methods should be tested:

1. Suspending a photographer with his photographic equipment 200 ft above the selected intersections through use of a mobile crane, and
2. Making on-ground phototriangulation photogrammetry.

In the second phase a contract was negotiated with the Department of Civil Engineering Photogrammetry Laboratory at the University of Wisconsin (UW) to perform the trace-plotting of truck wheelpaths.

The on-ground phototriangulation system developed by the university researchers utilized five nonmetric single-lens reflex cameras mounted on tripods located strategically at the intersections. The cameras were positioned so that turning vehicles were visible within each of their fields of view for the entire turn, and so that good geometric strength in the photogrammetric solution would be obtained. Simultaneous photographs were taken with the cameras for each vehicle at five different points within its turning path. Simultaneity was achieved by electronically firing a master switch connected to each camera. At the time of photographing, control surveys necessary to support the photogrammetric calculations were performed.

Following the photography, photocoordinates of vehicle images and control point images were measured in the UW Photogrammetry Laboratory using a newly developed digital projection system. Initial tests of this device indicated that its accuracy in locating the truck paths was within 3 in.

Four downtown intersections on the Wisconsin Designated Highway System were targeted for intensive field measurements of all long trucks arriving during a standard day-long photographic session at each location. The intersections were selected on the basis of the following criteria:

1. Expected traffic of at least 80 heavy multiunit trucks negotiating both left and right turns during a normal weekday,
2. An intersection angle of at least 90 degrees,
3. Single-lane intersection approaches,
4. Main-approach average daily traffic (ADT) in excess of 4,000, and
5. Enough clear distance to allow all camera setups a sufficiently unobstructed field of view.

The intersections selected were Highway 33 in Horicon, Highway 23 in Montello, Highways 23 and 73 in Princeton, and Highways 44, 49 and 23 in Ripon, Wisconsin. They are shown schematically in Figures 1–4.

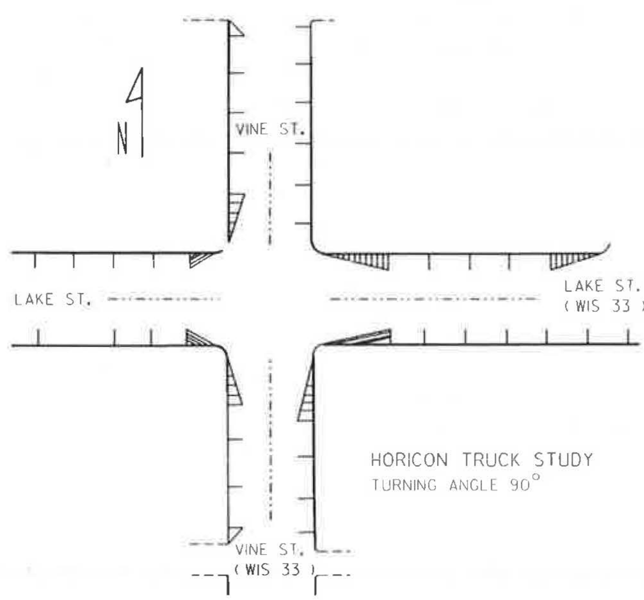


FIGURE 1 Horicon, Wisconsin, intersection layout.

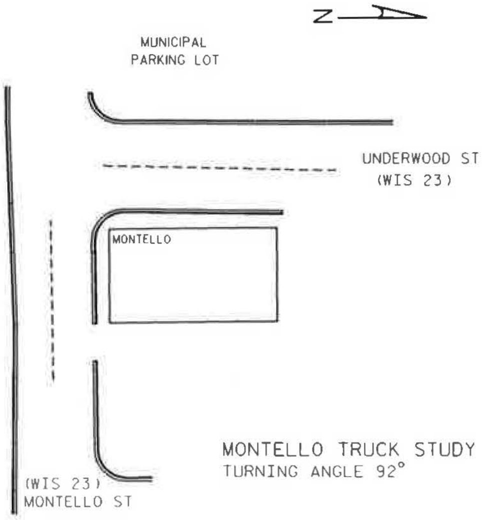


FIGURE 2 Montello, Wisconsin, intersection layout.

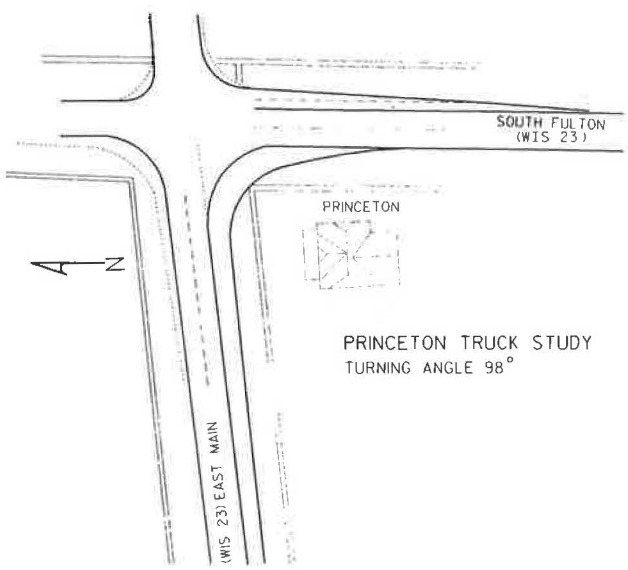


FIGURE 3 Princeton, Wisconsin, intersection layout.

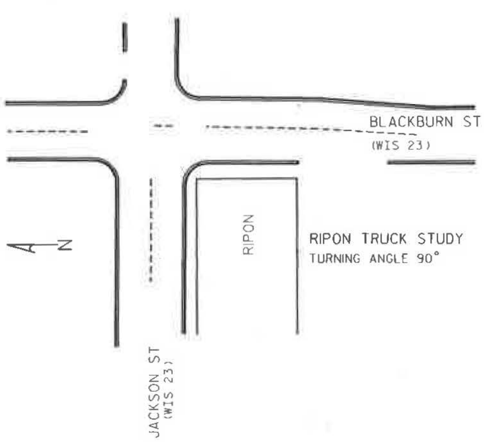


FIGURE 4 Ripon, Wisconsin, intersection layout.

Careful attention was given to working with local officials and law enforcement agencies to make sure that they were fully apprised of the activities of the researchers. Law enforcement personnel were especially helpful in informing property owners adjacent to the study sites and securing permission for the research team to set up photographic equipment, wiring, and other necessary details. In addition, they provided valuable assistance in arranging traffic control, parking prohibitions, and protection for the field personnel.

For the first downtown study session, conducted in Horicon, a driver with a maximum-legal-length control vehicle was hired to circulate through the intersection with the regular traffic stream. This truck is shown in Figure 5. For the second series of urban operational studies, no maximum-length control vehicles were used. Without the control vehicle, few very long-wheelbase trucks (wheelbases approximating 60 ft) appeared in the truck traffic stream. Most were about 57 ft in length or less.

ACTUAL EXPERIMENTAL SESSIONS

Because of weather sensitivity of the photographic work and equipment and the need to avoid traffic disruption of wiring taped across the pavement, all second-phase sessions were conducted during stable summer weather in 1987. This was in contrast to the first-phase sessions, which were conducted in the spring and fall of 1986 and involved overhead photography from a platform 200 ft above. Weather stability during the 1986 sessions was unpredictable and a continual cause for concern.

Intersection selection was governed primarily by entering traffic volumes, numbers of long trucks turning, and the visual field available for the five camera setups. The goal was to photograph a minimum of 80 truck-turning movements per intersection. As each turning truck moved into a minimum of three camera fields, all five cameras were fired simultaneously. This was repeated five times as the truck moved through its complete turning maneuver. The experimental layout allowed five points to be triangulated for each truck turning path, as shown in Figure 6. The result was not as continuous as with the 8 to 10 overhead photographs obtained for individual truck movements in the first phase. However, the turning points established were considered to be sufficient.

OBSERVED RESULTS

The actual wheelpaths of right- and left-turning trucks diverge rather markedly. Truck wheelpaths develop the predictable "humpback" curve for right-turning trucks and the typical crossover encroachment for left-turning trucks (Figures 7 and 8). Indications are that truck operators and other drivers cooperate more or less to compensate for the lack of turning space. As a result, intersection operations are improved in ways not envisioned by theoretical solutions. For example, there were numerous instances in which vehicles would deflect into the parking lanes at the intersection approaches to allow turning trucks sufficient clearance to encroach and complete their maneuvers. It was readily apparent that left-turning trucks consistently use the parking lane as a bypass lane, if it is available.

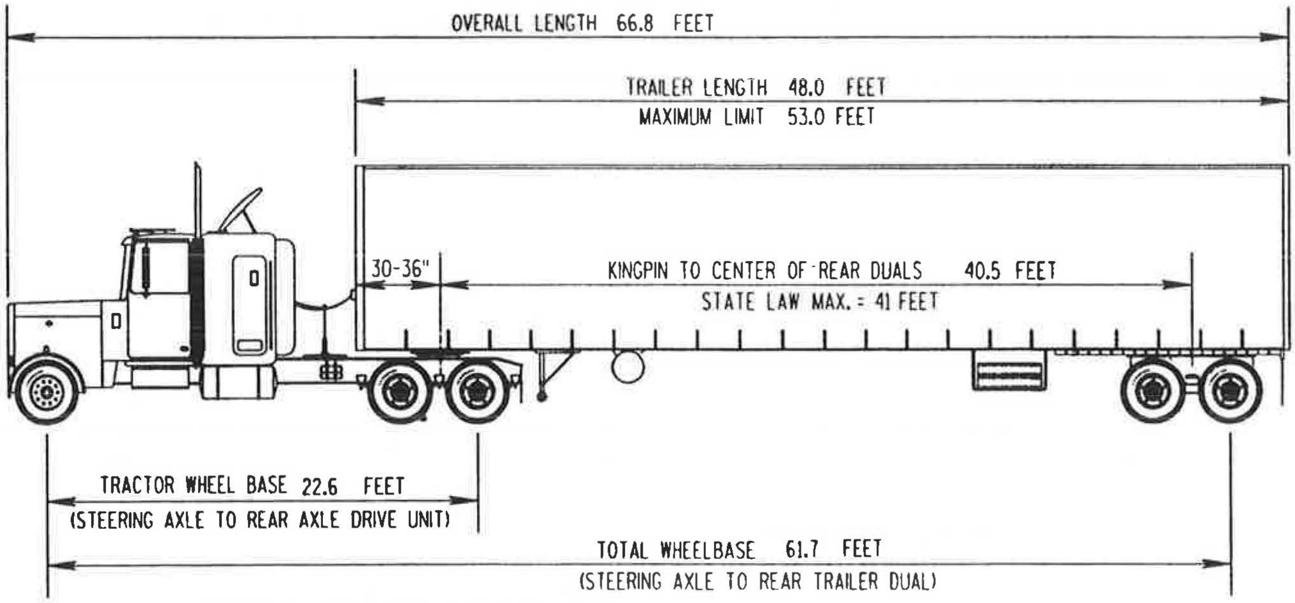


FIGURE 5 Control vehicle dimensions.

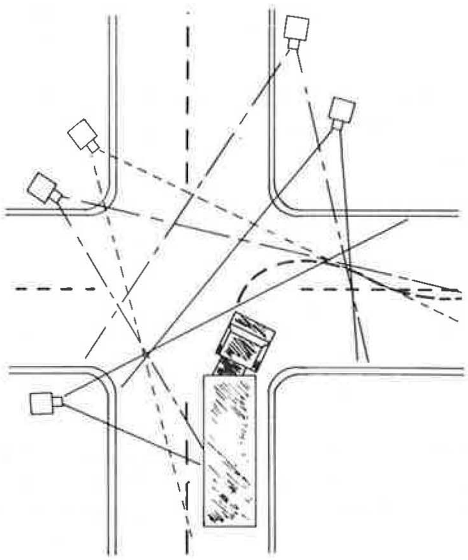


FIGURE 6 Diagram of camera layouts.

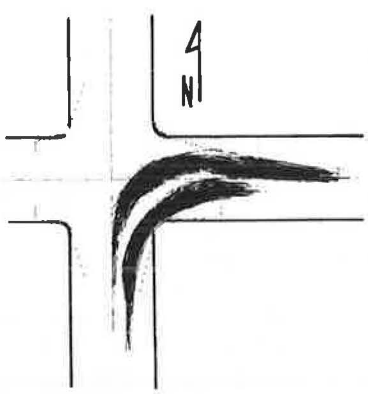


FIGURE 7 Right-turning wheelpaths.

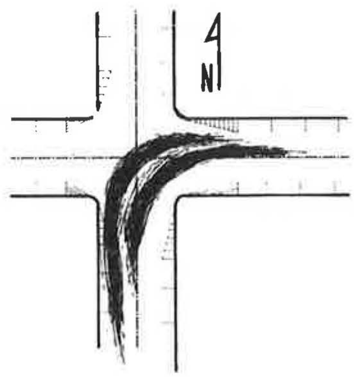


FIGURE 8 Left-turning wheelpaths.

The prevalence of gaps that allowed truckers to complete their right-turning maneuvers was important. Even in relatively high-volume situations (10,000 ADT), enough gaps were available in the traffic stream controlled by a three-way stop to accommodate all arriving trucks with only moderate queueing. Another discovery was the observed relationship between lane width and encroachment distance. For example, if lane widths are reduced from 12 to 10 ft, the minimum encroachment distance for a WB-62 truck only increases roughly 10 percent. Very few trucks ran up on the inside curb in areas where there were sidewalks. The few that did encroach did so minimally. There appeared to be much more concern on the part of truck operators about rear-wheel encroachment on the sidewalk than cross-centerline encroachment by the front of the tractor.

Figures 9 through 12 show the actual wheelpaths of right-turning trucks for the four urban intersections. Figure 13 shows the composite mean, inner, and outer envelopes of truck turning paths for the four intersections superimposed. These dia-

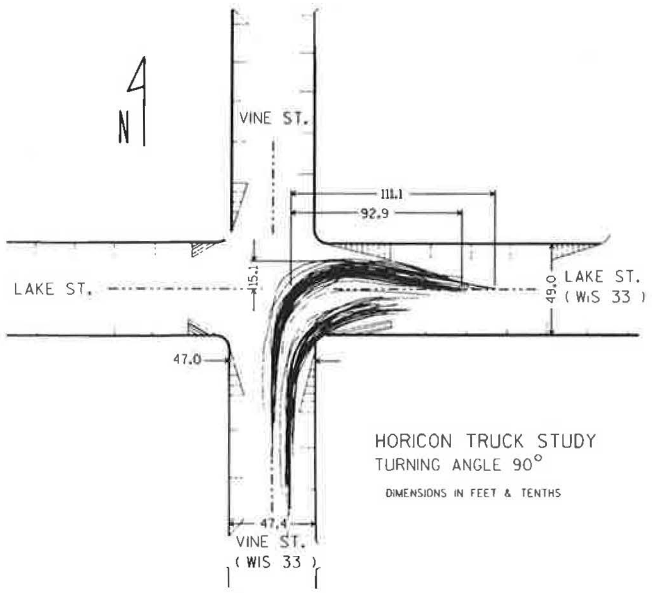


FIGURE 9 Actual wheelpaths, Horicon, Wisconsin.

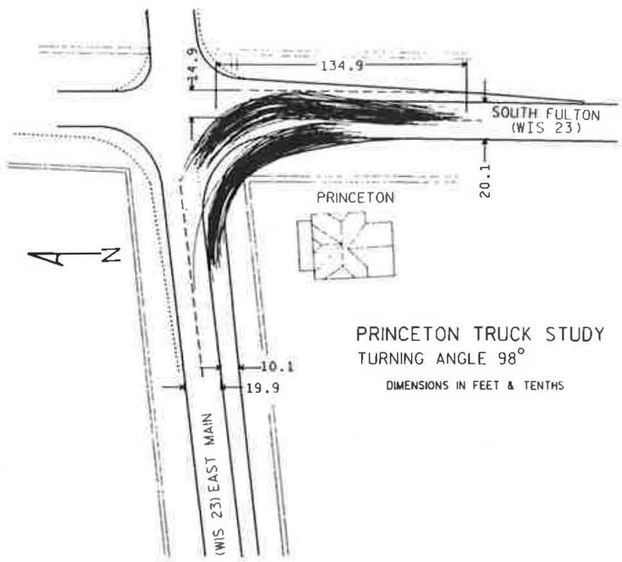


FIGURE 11 Actual wheelpaths, Princeton, Wisconsin.

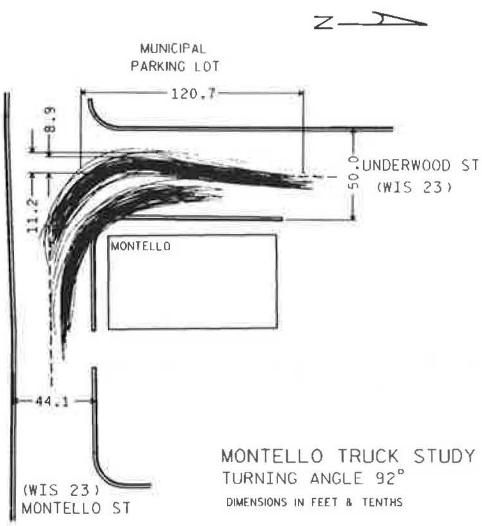


FIGURE 10 Actual wheelpaths, Montello, Wisconsin.

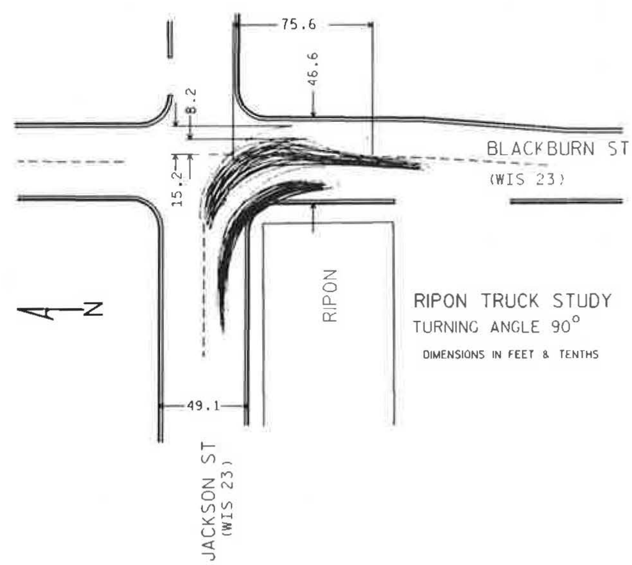


FIGURE 12 Actual wheelpaths, Ripon, Wisconsin.

grams clearly show that right-turning encroachment into lanes with moving traffic is a constant occurrence. However, most moderate-volume intersection approaches will tolerate a reasonable number of such movements because gaps of sufficient length are available.

MATHEMATICAL MODELING METHOD

By utilizing these field observations and integrating them with theoretical mathematical representations derived by the Institute of Transportation Engineers (*1*) and others, the researchers found that they could generalize the results and apply them to the majority of urban settings. Furthermore, graphical templates generated by computer-aided design and drafting (CADD) can be developed with the measurements taken from the precision photographs. A gap acceptance model was

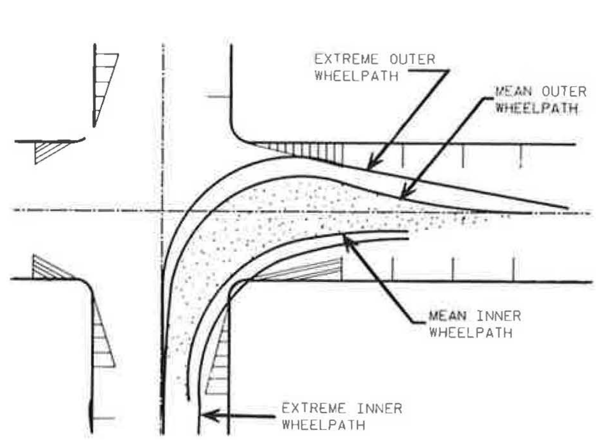


FIGURE 13 Composite mean, inner, and outer wheelpaths, all right-turning trucks.

developed to replicate the cross-traffic stream in five different general stop sign control conditions:

1. Case 1 (three-way stop, right turn no-stop for the truck approach): The observed upper-bound time gap that truck operators accepted in a "roll-through" stop with limited sight distance was 10 sec.

2. Case 2 (three way stop, right turn free flow, all other approaches required to stop): The acceptable gap was increased to 19 sec to account for the additional time for oncoming traffic to decelerate and stop (6 sec average time loss) and clear the stop bar upon reaccelerating (3 sec). This gap time was assumed to be relatively inelastic regardless of approach speed because of the approximate linear relationship between gap time and gap space. The operator must have a minimum time to accomplish the turning maneuver. As approach speeds vary in the most likely operating range of 25 to 55 mph, the space gap to provide acceptable time lengthens in linear fashion.

3. Case 3 (standard two-way stop): The acceptable time gap assumed was 14 sec, the minimum acceptable gap of 10 sec plus an acceleration time gap of 4 sec. The acceleration time to cross the near lane was considered the default value because this is the approximate time (in seconds) that it takes for a normal semitrailer to traverse a 12-ft lane according to the 1984 AASHTO policy (*2*). In addition, during the periods of peak flow it was assumed that a right-turning truck operator would move aggressively to accept a gap in opposing traffic of any reasonable duration, to the point of forcing any gap in traffic from the left that exceeded 4 sec.

4. Case 4 (three-way stop, trucks must stop, free-flow traffic from right): For the same reasons as in Case 3, a 14-sec gap was considered acceptable for a right-turning truck. In this case, traffic from the left would be metered by the stop sign to the trucker's left, thereby creating an acceptable gap from the left after every arrival.

5. Case 5 (four-way stop): Interposing a four-way stop condition was assumed to add all deceleration, acceleration, and reaction times to the observed 10-sec minimum gap. Thus, it would expand the required gap to 23 sec between the arrivals of Car 1 and Car 2 at the stop sign on the right approach. This case was regarded as the most restrictive of all stop-sign controlled configurations.

The graphs in Figures 14 to 17, inclusive, show ranges of ADTs that will provide acceptable gaps for right-turning vehi-

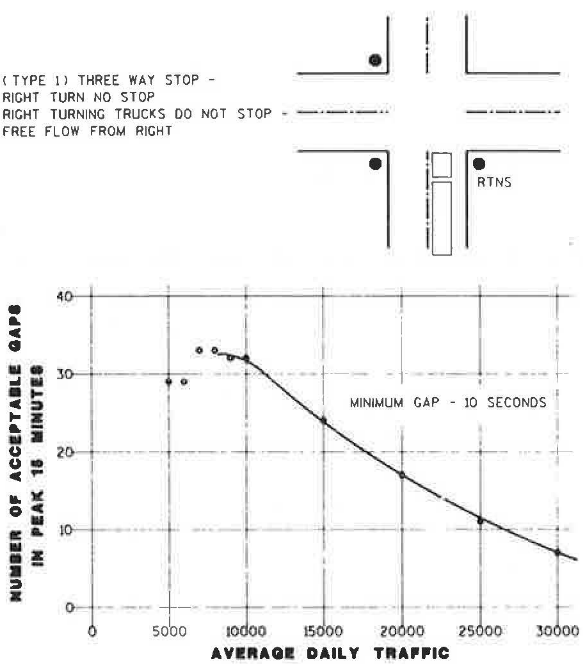


FIGURE 14 Crossroad gap availability curve for peak 15-min flow—Case 1.

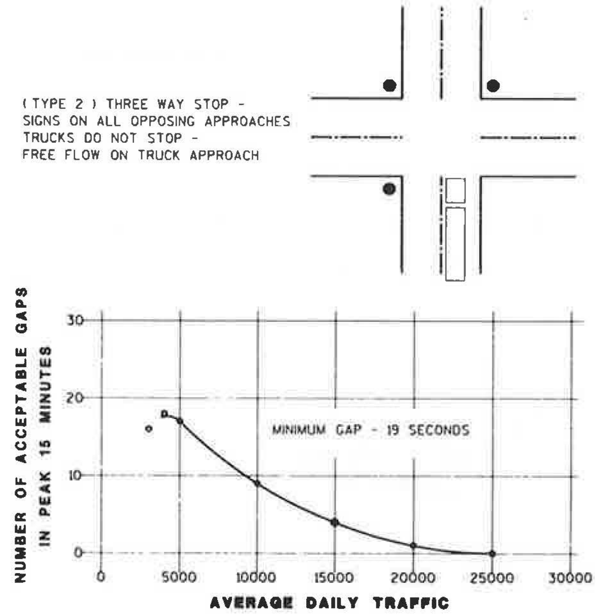


FIGURE 15 Crossroad gap availability curve for peak 15-min flow—Case 2.

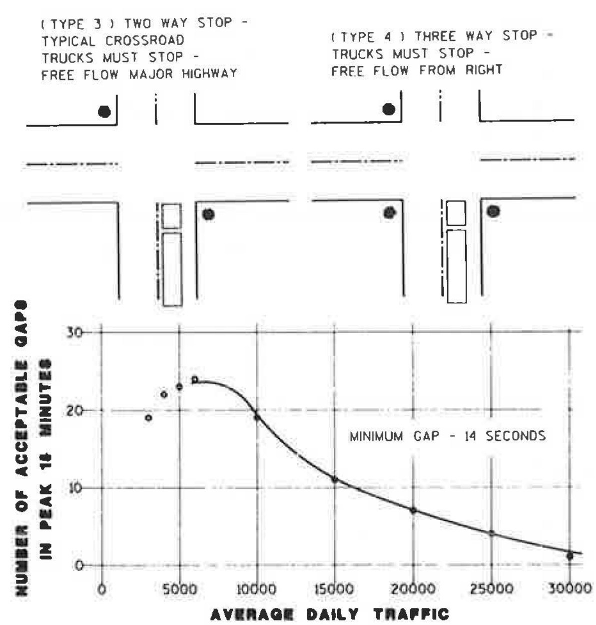


FIGURE 16 Crossroad gap availability curve for peak 15-min flow—Cases 3 and 4.

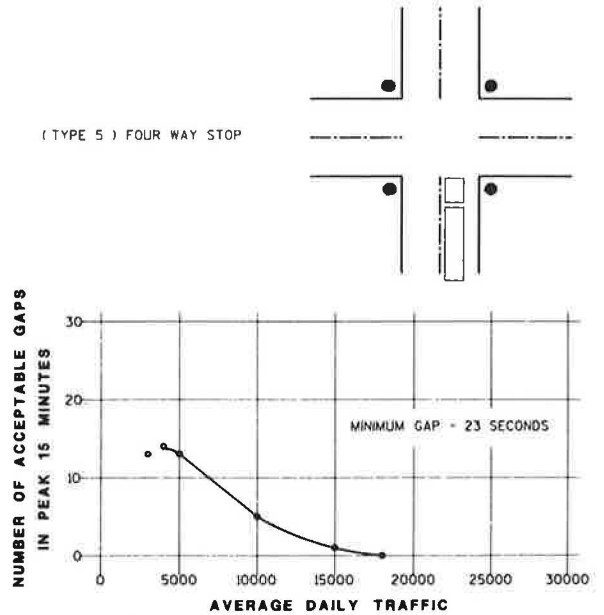


FIGURE 17 Crossroad gap availability curve for peak 15-min flow—Case 5.

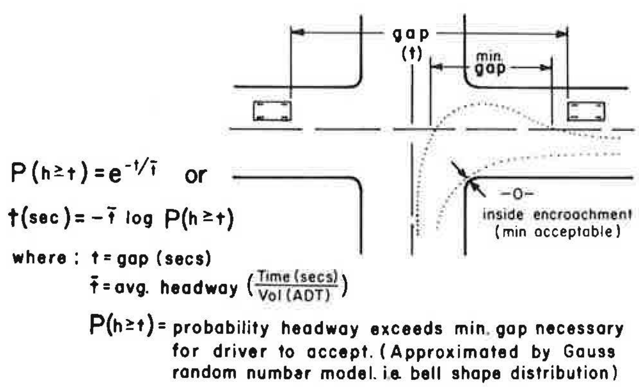


FIGURE 18 Development of negative exponential model.

cles for the time duration noted. The curves shown in these figures utilized the negative exponential distribution function to simulate intervals in the cross-traffic streams from 3,000 ADT to 35,000 ADT. Starting from the assumption that if there is no vehicle arrival in a time interval t (*3*), there will be a headway h of at least 10 sec between the last previous arrival and the next arrival (Figure 18),

$$P(0) = P(h \geq t) = e^{(-1/\bar{t})t}$$

where $\bar{t}$ is the mean headway and $P(h \geq t)$ is the probability that the headway exceeds the minimum gap necessary for the driver to accept. Then

$$P(h \geq t) = e^{-t/\bar{t}}$$

Transforming the equation,

$$\log P(h \geq t) = -t/\bar{t}$$

$$\bar{t} \log P(h \geq t) = -t$$

$$t = -\bar{t} \log P(h \geq t)$$

Traffic interval distributions were simulated by using a standard Gaussian random number generator to provide normally distributed decimal probabilities between 0.000 and 1.000 to replace $P(h \geq t)$ in the function.

By comparing the calculated or assumed input value for an acceptable gap, the researchers were able to simulate conditions in which truckers would respond to gaps as low as 4 sec. A minimum time study (15 to 30 min) during peak traffic flow could quickly refine the ability to estimate whether an intersection could function (albeit at reduced service levels) or whether arriving volumes were at or above breakdown conditions. These could also be used as design and planning tools to determine whether anticipated volumes and truck percentages would overload an intersection to the point at which it would have to be rebuilt. Another feature of the model is that it provides a method to determine optimal conditions based on assumed or measured gaps in traffic, which relate directly to observed encroachment patterns. Obviously, the longer a truck remains in or across a traffic lane, the greater the duration of the required gap to accommodate that movement. In addition, if sight distances are restricted, required reaction times will increase, causing a consequent reduction in numbers of acceptable gaps.

Figure 19 shows curves for the calculated number of acceptable gaps in the peak 15-min period for time intervals ranging from 4 to 25 sec. The model contrasts crossroad ADT with

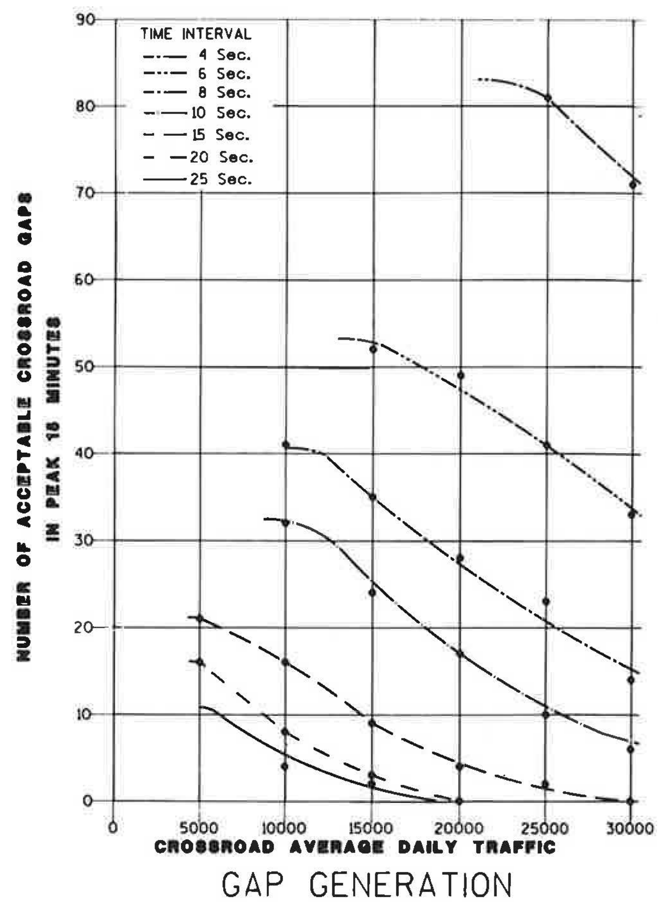


FIGURE 19 Gap availability curves for time intervals ranging from 4 to 25 seconds.

gaps of at least the time intervals specified for the peak 15 min.

PRACTICAL APPLICATIONS

The large number of potentially substandard intersections on the designated system highlights the need for a tool to aid in decision making. A study by the gap acceptance model can now be reviewed in the office. If entering ADTs and truck percentages can be determined, intersections can be evaluated on a standard personal computer or by using the curves in Figure 19. For example, if all trucks arriving on any approach are assumed to turn right (the worst-case condition), a quick assessment can be made as to the maximum crossroad ADT that can accommodate these movements, depending on the type of intersection control. If the number of cross-traffic gaps available substantially exceeds the calculated number of arriving trucks, the analyst can assume that the intersection will function within reasonable tolerances. If the number of available gaps is marginal (that is, at or below the calculated number of truck arrivals), field personnel can be assigned to perform a more in-depth study. This need not be more than a rush-hour study to determine

1. The average number of long-truck arrivals on all approaches;
2. The average number turning right, left, and proceeding straight through;
3. The approximate average time gap required for the right-turning long trucks;
4. The approximate percent of trucks on the critical approach(es);
5. The approximate vehicular counts on the approaches opposing the right-turning trucks;
6. The number of off-pavement encroachments (near-side and opposite side); and
7. The widths of approaches and approximate angles of intersection or right triangle measurement to allow the computation.

Figure 20 shows the optimum number of traffic-stream time gaps of a given duration for the peak 15-min period. Note that the curve drops steeply to a point of flexure as required gap times decrease from 4 to 10 sec. Optimum ADT declines rapidly as required gap times increase above 10 sec. The peak 15-min period was considered as the worst-case condition for cross-traffic flow. An analysis of Wisconsin's automatic traffic recording data showed average peaking characteristics somewhat higher than 9 percent of aggregated ADT. This was the peaking factor used in modeling the traffic stream.

Predictably, signalization of intersections with more than minimal right-turning trucks would create serious operational problems. Normally available gaps would disappear as opposing traffic queued up at the red signal. Trucks waiting to turn at the signal from the right-angle approach would be gridlocked. No possibility for encroachment on the outside of the turning path or offtracking inside would exist because of vehicular and building constrictions. Figure 21 illustrates this problem.

A second conclusion also emerges from the data. Even though sufficient gaps for right-turning trucks exist in the traffic stream, there is a lower-bound street dimension that

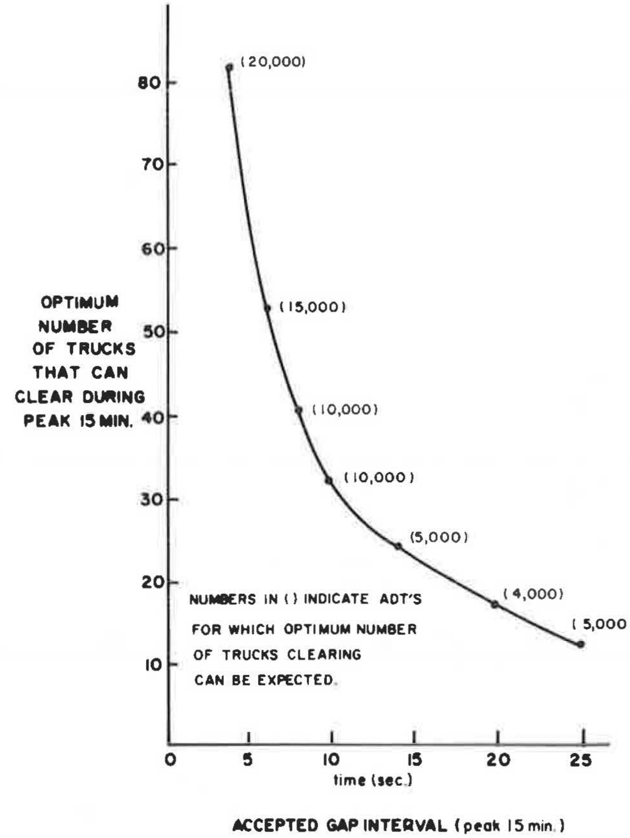


FIGURE 20 Optimum number of trucks that can turn right for a given gap time.

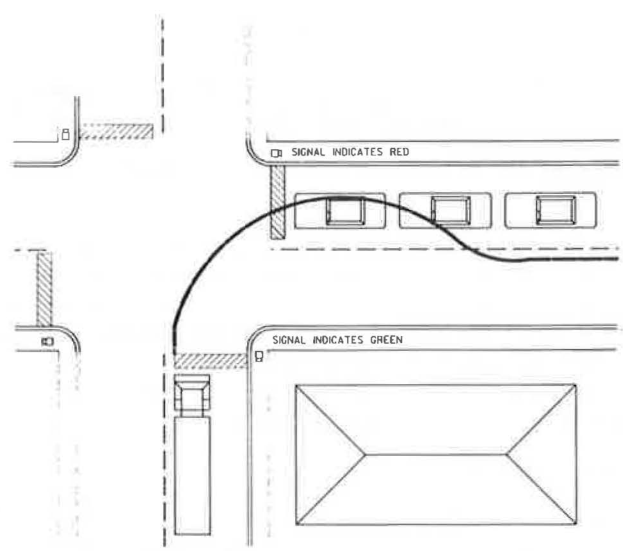


FIGURE 21 Illustration of effect of gap closure at red signal indication on cross street.

will foreclose such maneuvers for all practical purposes. It appears from the data that if curb-to-curb street widths on the major approaches are 37 ft or less (including the parking lanes), the route should not be designated for long-truck operation without significant intersection alterations. This is for a current mix of trailer lengths that seldom exceeds 39 ft (overall semitrailer wheelbases of 57 ft or less). The researchers believe that it will take about 5 years for the shorter trailers to be replaced by longer ones. Observed offtracking increases of 0.75 ft per foot of increased trailer wheelbase length indicate that the lower-bound street width dimension would increase to approximatley 40 ft by the time this turnover has taken place. This would maintain the approximate 9- to 10-ft average opposite-lane encroachment currently being experienced and would allow a bypass lane of similar width. Figures 22 through 25 illustrate the varying degrees of observable offtracking and encroachment severity as intersection approach widths decrease from 50 to 28.5 ft.

Using the nomographs constructed from the observed results and shown in Figures 26 and 27, the planning, design, or traffic engineer can now make several determinations.

1. The approximate average gap lengths in the opposing traffic streams required to accommodate right-turning trucks can be determined. This will also assist in determining how far to restrict parking to allow for a bypass lane.
2. The approximate average lateral encroachment that must be regularly available if a route is to be designated for right-turning trucks can be found. This will help determine whether the street width at the intersection is adequate for turning trucks under any circumstances. (The nomographs assume that the centerline equally divides the curb-to-curb dimension. Appropriate conversions should be made if the centerline is offset.) Using the curves for the gaps versus crossroad ADT (Figures 14–17), the number of gaps of a given time duration that will probably occur in the cross-traffic stream opposing right-turning trucks can be determined. The various traffic control configurations show the gap expectancies.
3. The probability that permitted overwide loads will be accommodated can also be estimated.
4. Finally, Figure 28 and Table 2 show the relationship between street width and stop bar location for left-turning trucks. This graphical solution, based on the actual measured observations of the left-turning truck population, allows the

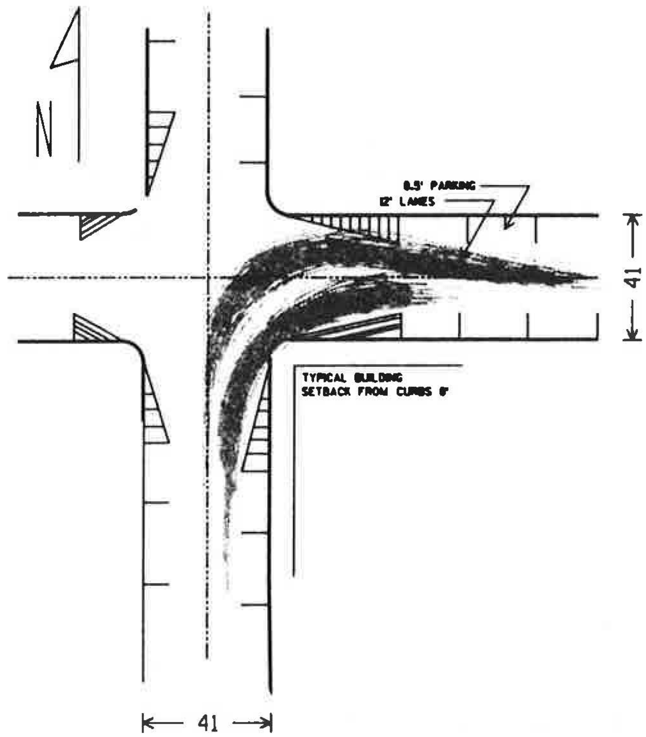


FIGURE 22 Offtracking/encroachment for 50-ft width approaches (note room available for opposing traffic to bypass encroaching trucks).

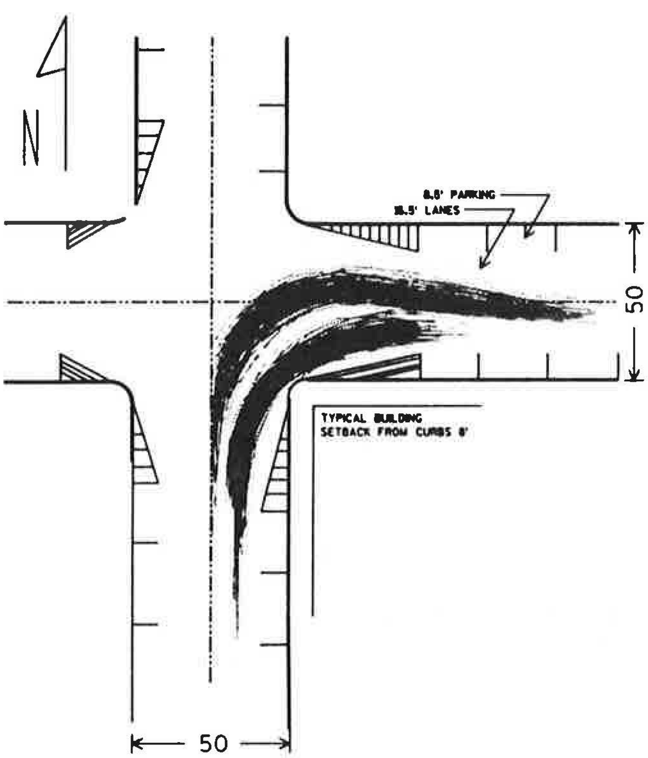


FIGURE 23 Offtracking/encroachment for 41-ft width approaches: trucks must ride up on inside curb or use full approach width to complete turns.

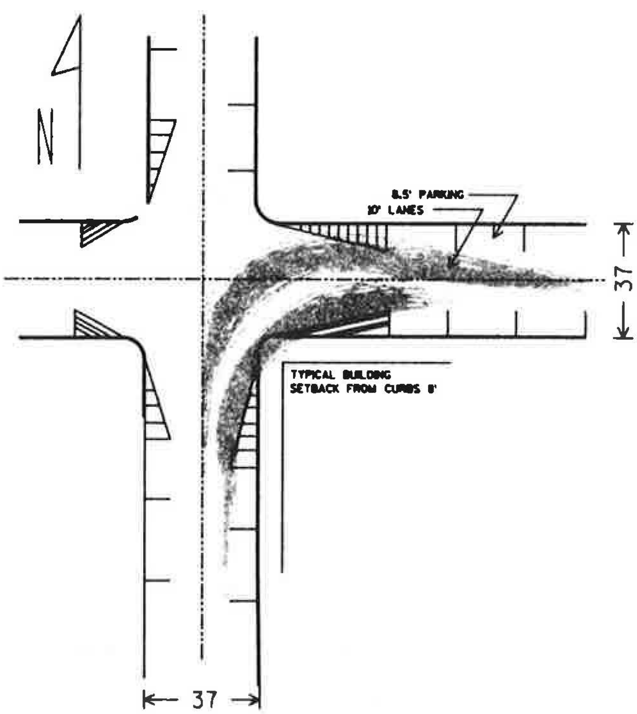


FIGURE 24 Offtracking/encroachment for 37-ft width approaches: entire approach width used; most trucks will ride over inside curb.

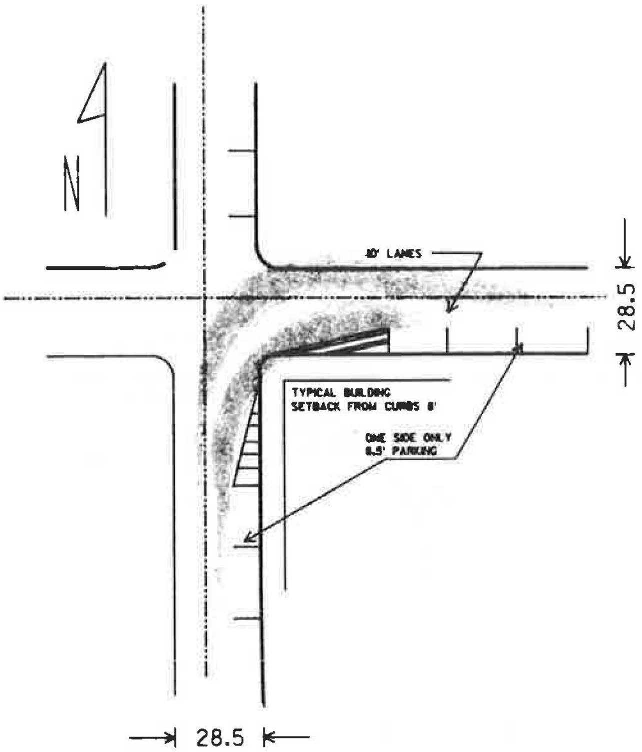


FIGURE 25 Offtracking/encroachment for 28.5-ft width approaches: truck turning movements severely restricted (note distance that trucks traverse behind curbs).

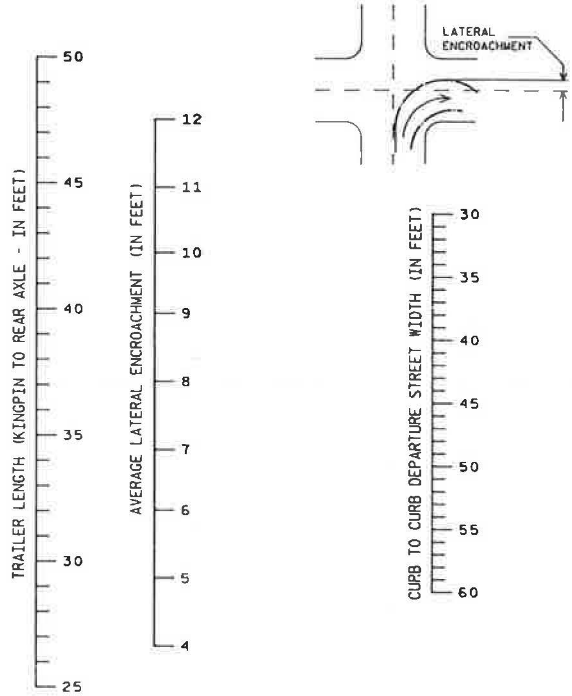


FIGURE 27 Nomograph of lateral encroachment.

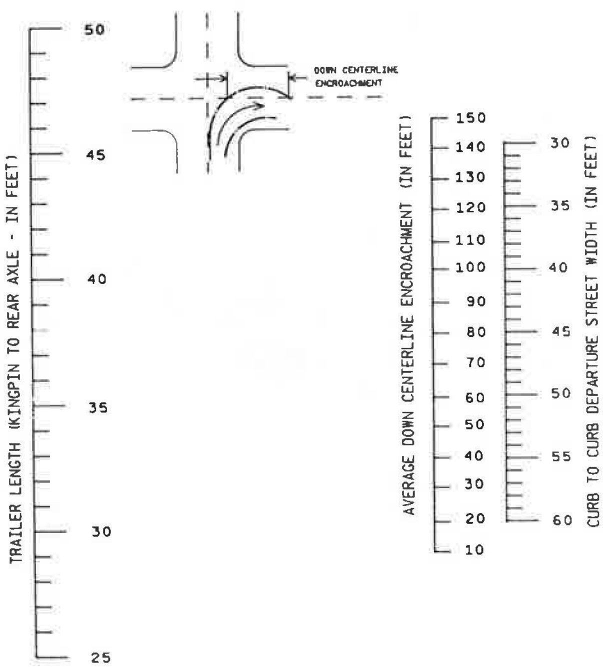


FIGURE 26 Nomograph of sown-centerline encroachment.

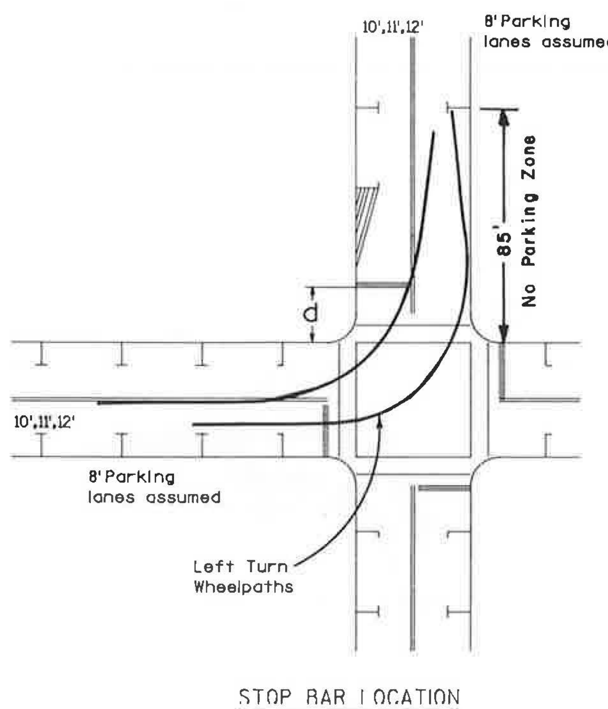


FIGURE 28 Left turn effects on stop bar and parking stall location.

TABLE 2 STOP BAR LOCATION AS A FUNCTION OF STREET WIDTH

Driving Lane Widths (ft)		STOP Bar Distance from back of curb
Turning from	Turning Into	d (ft)
10	10	32
11	10	28
12	10	27
10	11	25
11	11	25
12	11	23
10	12	22
11	12	21
12	12	19

engineer to accurately locate signals, signs, parking zones, and other street furniture to help prevent traffic conflicts and accidents. It should be noted, however, that sight distance requirements increase markedly as streets narrow. Therefore engineers should consider removing parking downstream from the stop bar when existing sight restrictions cannot be removed. This would allow the opportunity to shift arriving traffic into the parking lane, reducing the conflict area and allowing stop bar placement much closer to the center of the intersection.

CONCLUSIONS AND RECOMMENDATIONS

1. Critical maneuvers on the designated highway system are right turns in downtown areas.
2. Highways on downtown two-lane streets that are 37 ft wide or less and have right-angle turns at one or more intersections should not be included in a designated highway system if there are large numbers of long trucks in the traffic stream.
3. Installing signals at downtown intersections on the designated highway system can cause serious operational problems for both left- and right-turning long trucks.
4. The best apparent traffic control configuration for downtown intersections is one that maximizes free traffic flow on the heavy-volume approaches and minimizes pedestrian conflicts by placing crosswalks on minor-volume approaches.
5. The optimum traffic volume that will accommodate the largest number of long trucks during rush hours is approximately 10,000 ADT on two-lane cross streets.
6. Parking along the first 100 ft of the critical lanes (the left-turning truck's passenger side and the right-turning truck's driver side) hinders efficient traffic operation if there are high percentages of left- or right-turning trucks during peak hours.
7. Before resorting to full-scale intersection revision or signalization, numerous well-known measures should be tried, namely,

- Removing parking,
- Offsetting (shifting) the location of the centerline,
- Prohibiting rush-hour parking,
- Reducing restrictive traffic control measures,
- Increasing sight distances,
- Minimal widening (if possible),
- Diverting traffic,
- Metering cross-traffic flow through installation of upstream signals,
- Prohibiting long-truck operation during rush hours,
- Restricting right turns, and
- Restricting operation to vehicles with special equipment (such as steerable rear axles).

ACKNOWLEDGMENTS

The software for the gap acceptance model is available from the Wisconsin Department of Transportation, Applied Research Section, Madison, Wisconsin.

This study was undertaken as a joint venture between the Traffic and Design staffs of the Wisconsin Department of Transportation (WisDOT), Materials and Applied Research Section, and the University of Wisconsin. Financing was provided under the auspices of the Highway Planning and Research Program, Federal Highway Administration. Staff from the WisDOT Technical Services, Planning, Madison, and Waukesha Transportation District offices; all participating cities; Dawes Rigging, Inc.; and Hansen Trucking, Inc., also provided valuable technical, law enforcement, and equipment rigging and operational assistance.

REFERENCES

1. W. S. Homburger, L. E. Keefer, and W. R. McGrath. *Transportation and Traffic Engineering Handbook*, 2nd ed. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1982, pp. 437–469.
2. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington, D.C., 1984, pp. 28–35 and 159–162.
3. K. C. Sinha and P. H. DeCabooter. A Computer Simulation Model of the Driver Visual Part Task. *Traffic Quarterly*, 1972, pp. 589–613.

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

Methodology for Evaluation of Truck Weight Regulation Enforcement Programs

B. G. BISSON AND D. J. GOULD

Highway agencies all over the world recognize that overweight trucks are a major cause of premature pavement deterioration. Compliance with truck weight regulations in each jurisdiction varies because of differences in enforcement levels, tolerances, fine schedules for violations, and other punitive actions. The object of this research was to develop a methodology for assessing the effectiveness of a truck weight enforcement program. Truck weight regulations and trucking activity in the Province of New Brunswick, Canada, were used as a case study. The methodology essentially compares incremental revenues that can be earned by overloading a particular truck configuration with the expected cost of getting caught, taking into account the fine regime and the level of enforcement. The results of the research demonstrated that fines are not structured in New Brunswick to be an effective deterrent for would-be violators. Alternative enforcement programs were postulated and the deterrent effect was evaluated.

Highway agencies all over the world recognize that overweight trucks are a major cause of premature pavement deterioration. Truck-weighing programs are the cornerstone of weight enforcement, but differences exist among agency programs in almost all aspects of enforcement. The differences include levels of enforcement activity, tolerance, fine schedules for violations, and other punitive actions taken against violators. All of these differences represent factors that go into determining the effectiveness of enforcement of truck weight limits. A change in any one of the factors alters the effectiveness of any program.

This study develops a methodology for assessing the effectiveness of one of the most important aspects of a weighing program, the schedule of fines. A case-study approach utilizing pertinent data for the Province of New Brunswick, Canada, was employed.

Case Study: New Brunswick Truck-Weighing Program

A recent paper presented to the Canadian Transportation Research Forum (CTRF) by members of the University of New Brunswick Transportation Group on the degree of enforcement of the New Brunswick Motor Vehicle Act presented evidence that the current fine schedule for overweight vehicles on New Brunswick highways does not present a deterrent to overweight loads (*1*). The observations were based on a 1 percent random sample of 1986 violations in which the cost of the fine from the point of view of the truck operator was estimated to be an average of \$0.03/kg of incremental payload attributable to the overload. This cost, however, represents 100 percent probability of being caught, which is not the case. Permanent weigh scales can be avoided, and scales are not open at all times. Therefore, the violator has an expected cost of \$0.03/kg multiplied by the perceived probability of getting caught. If the fine does not increase with each subsequent violation and if the trucker can earn incremental revenue that exceeds the amount of the fine by operating overweight, the expected return will exceed the expected cost; thus, many truckers are tempted to operate overweight.

RESEARCH OBJECTIVES AND SCOPE

The purpose of this study was to develop a means of assessing the New Brunswick Department of Transportation (NBDOT) truck schedule of fines in terms of deterring overweight operations. The study also developed alternative fine schedules based on current levels of enforcement, tolerance, and actions against violators.

At this point, the manner in which the deterrent effect is to be accomplished must be clarified. If an agency desires to effectively reduce the number of overweight vehicles, it might do so in a number of ways.

1. It might increase the likelihood that violators will be apprehended by increasing the level of enforcement.
2. The cost of violations to truckers once they have been apprehended might also be increased.
3. The cost of violations might be in the form of fines or actions taken against the violator. For example, violators may be required to unload the excess weight. In fact, NBDOT is contemplating the incorporation of a point system in which a computer would be used at the scale to record points lost. After the loss of a certain number of points, the violator's license would be revoked.

In order to limit the scope of this study to a manageable size, deterrence was assessed by altering the fine schedule, keeping all other factors contributing to the expected cost of the trucker constant (i.e., level of enforcement, tolerance, etc.). In effect the study assumes that NBDOT is operating its truck-weighing program at the highest level of justifiable enforcement and at levels of tolerance and punitive actions against truckers that the public will support.

UNB Transportation Group, Civil Engineering Department, University of New Brunswick, Fredericton, New Brunswick E3B 5A3, Canada.

METHODOLOGY

The first step in the analysis involved selecting a representative sample of commodity movements. It was determined from a 1984 truck origin-destination (O-D) survey (*2*) that the top 25 commodities accounted for 68 percent of all intra- and interprovincial movements. Hence, to make the study more manageable, the analysis was restricted to the top 25 commodities.

Data from Statistics Canada (*3*) were used to determine average freight rates for the selected commodities. Representative freight rates were estimated for short-, medium-, and long-haul distances for each commodity.

In order to estimate legal payloads for each commodity, it was then necessary to select specific truck types and axle configurations. Again, it was determined from the 1984 truck O-D survey that four truck types (two- and three-axle straight trucks and five- and six-axle tractor-semitrailers) accounted for 93 percent of truck movements. It was assumed that each truck type would operate with an axle configuration that permitted the maximum allowable gross vehicle weight. (Inspection of the O-D data confirmed the validity of this assumption.)

A range of HD overweight scenarios was then developed for each truck type, taking into account the weight limit regulations that apply to each of three classes of highway in New Brunswick. The overweight scenarios included both axle group and gross vehicle weight violations.

The next step in the analysis involved estimating the probability of detection. Data on number of vehicles checked were available for each weigh scale for 1984, 1985, and 1986. The ratio of vehicles checked to average annual truck traffic (AATT) was calculated for each weigh scale. The probability of detection was estimated to be 42 ± 12 percent. It should be noted that this is the actual probability of detection. The would-be violator may perceive the probability to be higher or lower at certain periods of time, the perception being influenced by a number of factors.

Using the actual probability of detection as a proxy for the perceived probability of detection by the violator, the expected cost of detection was estimated by multiplying the fine that would be levied for a given overweight scenario by the probability of detection. The expected cost of detection was then compared with the marginal revenue that would be earned from the excess payload above the legal limit for each scenario.

FINDINGS

Of the 40 overweight scenarios that were analyzed for each truck types, the results indicated that in most cases the marginal revenue attributable to excess payload exceeded the expected cost of detection by a substantial margin. In some cases, the margin reached as high as a factor of 10. The fines appear to be a deterrent for low-value commodities such as sand and gravel. However, in general it was concluded that effectiveness of the fine regime in deterring overweight violations was minimal.

To demonstrate the extent to which the fine would have to be modified in order to deter the tractor-semitrailer configurations, a number of computer runs were made in which the fine structure was increased by

1. Increasing the basic fine amount;
2. Increasing the graduation structure,
3. Changing the policy of penalizing the most overweight axle, and
4. Combinations of all of the above.

The alternative that produces a deterrent to a reasonable portion of commodity movements consists of increasing the basic fine to $200, penalizing all overweight axles by adding the overweight amounts on each axle group and using this sum to determine the fine, and doubling the graduation scheme. The increased basic fine compensates for the loss in deterrence from the perceived probability of getting caught. Increasing the graduation scheme increases the fine with increasing overweight amounts reflecting a greater deterrence of severe violations. By penalizing all overweight axle groups, the violator who distributes the overweight load to all axle groups, thus lowering the weight on the critical axle and therefore minimizing the fine, is not rewarded for his ingenuity. This phenomenon is evident from the current fine structure and policy.

CONCLUSION

The development of an effective enforcement regime for vehicle weight and dimension regulation involves a difficult tradeoff between the level of enforcement (probability of detection) and the severity of punishment for violations (the fine regime). The costs of incremental enforcement are high and the resultant benefits will be minimal if the fine regime does not impose a sufficient financial penalty on violators. On the other hand, it is generally accepted that the "punishment should fit the crime." This research demonstrates that fines would have to be increased substantially, given the probability of detection, to produce an adequate deterrent effect.

It is important to recognize that many violations are beyond the control of the operator; for example, load distribution on axles, overloading by shippers, and variabilities in commodity weight density due to such factors as moisture content. Furthermore, some commodity movements that have a high risk of being overweight, such as forest products in New Brunswick, enjoy a high level of political sensitivity. The imposition of a severe punishment regime would therefore not be politically feasible.

In conclusion, it is by no means a simple task to strike an appropriate balance between the level of enforcement and the severity of punishment. However, if the case study presented in this paper is typical of weight and dimension enforcement regimes, it is evident that the severity of punishment should be increased.

REFERENCES

1. B. G. Bisson, F. R. Wilson, and D. C. Good. Enforcement of Vehicle Weights and Dimension Regulations. In *Proceedings, 22nd Annual Meeting of the Canadian Transportation Research Forum*, St. John's, Newfoundland, June 1987, pp. 465–481.
2. *The Atlantic Provinces Primary Highway Strengthening/Improvement Program Motor Carrier Benefit Study*. Fiander-Good Assoc. Ltd., Fredericton, New Brunswick, June 1985.
3. *Trucking in Canada—1985*. Catalogue 53-222. Statistics Canada, Ottawa, Ontario, 1986.

Publication of this paper sponsored by Committee on Traffic Law Enforcement.

Comparison of Accident Rates for Two Truck Configurations

PAUL P. JOVANIS, HSIN-LI CHANG, AND IBRAHIM ZABANEH

Industry-supplied data allowed a structured statistical comparison of the safety performance of tractor-semitrailers (singles) and doubles by comparing their accident experience on the same routes for 3 years. This paired structure essentially controls for roadway, environment and traffic conditions. Separate comparisons of vehicle safety performance were conducted for access- and non-access-controlled highways, local streets, and parking lots. In general, doubles experienced lower accident rates than singles in 1983 and 1985, but higher accident rates in 1984, which was a year of greatly expanding doubles operation. Doubles' accident rates are significantly lower than singles' accident rates for all types of operating environments over the entire period from 1983 to 1985. For the types of carriers represented in the data and for the conditions characterized by the routes in the sample, the consistent evidence is that doubles had better safety performance than singles except for the transition year 1984. The generalization derived from the study is that doubles are generally as safe or safer than singles, even when specifically controlling for roadway, traffic, and environmental conditions. This study was conducted on routes that are approved for doubles' operation. It is, therefore, not appropriate to extrapolate these findings to any specific route.

Motor carriage was a major area of governmental policy and legislative activity during the 1980s. The decade began with the partial economic deregulation of interstate carriage in 1980. Barriers to entry into the business and in selected markets were significantly lessened; pricing was also liberalized. The Surface Transportation Assistance Act (STAA) of 1982 revised highway user fees and initiated steps to standardize interstate size, weight, and vehicle configuration restrictions. One of the many changes brought about by this significant legislation was the more uniform legalization of the use of double combination tractor-trailers on Interstates and designated state and local roads. This expanded role for doubles overlapped with the passage of additional safety-related legislation in 1984 and 1986. The latter, the Commercial Motor Vehicle Safety Act of 1986, initiated a process that will likely culminate in more consistent examinations and procedures for licensing commercial drivers. The 1986 legislation also proposed strict penalties for drug and alcohol use during operation of a commercial motor vehicle.

Throughout all this legislative activity, the safety performance of the trucking industry has been a continuing point of debate and discussion. This is a legitimate concern when major changes occur in industry economic structure (as a result, for example, of economic deregulation), user fees, or operating regulations. Safety concerns are heightened by the continuing pressure to allow greater use of still larger trucks that must share the road with smaller automobiles. As truck and automobile mileage continues to grow year by year, these different types of vehicles are even more likely to confront each other on a roadway infrastructure that has had nearly fixed capacity for the past decade. The challenges posed by the confluence of these forces should be clear to all who seek to manage safety effectively.

The safety performance of doubles has been of particular interest because of their greatly expanded use following passage of the 1982 STAA. National less-than-truckload (LTL) carriers in particular (but not exclusively) have used doubles to increase their productivity and provide better customer service. Although the act was passed many years ago, battles continue to be fought concerning the access of doubles to state (and some Interstate) highways. The principal argument used to restrict access is the safety performance of the vehicle configuration.

There is a clear need to objectively assess the safety performance of doubles in a broad range of operating conditions. There have been numerous such studies, but they have often led to conflicting findings. This paper attempts to respond to the need for this safety assessment by reviewing the most recent literature assessing doubles' safety performance and presenting findings from new studies undertaken for this specific purpose.

OBJECTIVES

There is a need to better understand the safety performance of double combination tractor-trailers, particularly in comparison with the most likely alternative, a single combination (tractor-semitrailer). The authors seek to contribute to this understanding in two ways:

1. By briefly reviewing the literature concerning doubles' safety performance. This review focuses on the literature that has appeared since TRB Special Report 211 (*1*), which contains an excellent summary of safety studies up to that time. Particular attention is paid to data sources and methodology, because these are likely to have a strong influence on the interpretation of each study's findings.
2. By describing the results of studies conducted during the last few years at Northwestern University that were directed at obtaining a better understanding of doubles' safety performance. These studies have differed from those generally

P. P. Jovanis, Department of Civil Engineering and Transportation Research Group, University of California, Davis, Davis, Calif. 95616. H.-L. Chang, Department of Transportation Engineering and Management, National Chiao Tung University, Hsinchu, Taiwan, Republic of China. I. Zabaneh, Transportation Center, Northwestern University, Evanston, Ill. 60208.

reported in that they use industry-supplied data sets, which provide much greater detail concerning both accidents and exposure.

The safety and operations data used in the Northwestern studies were from carriers with well-established safety programs and close monitoring of on-road driver performance. The analyses are not intended to typify the safety performance of all doubles operations. Rather, they are intended to respond to the following research questions:

1. If a carrier has a well-established safety program and generally makes a good-faith effort to adhere to federal safety regulations, are doubles inherently less safe than singles?
2. Does the safety performance change for different roadway types?

Given the acrimony and mysticism concerning doubles' and singles' safety performance, the authors believe that an answer to these questions would be a significant contribution.

STRUCTURE OF PAPER

The literature review describes three of the major doubles safety studies that have been conducted since 1986 as well as an overview of other relevant research. Next the structure of the empirical analysis is described, including data sources. The empirical analyses are presented, and the paper concludes with a summary and recommendations for future research.

LITERATURE REVIEW

Any review of doubles' safety performance must consider the findings of the major TRB doubles study completed in 1986 (*1*). Although the TRB study went well beyond safety to include issues such as pavement damage and user fees, it contained a comprehensive review of the existing safety literature, which included comparisons of doubles' and singles' handling characteristics as well as accident experience. The TRB report concluded that doubles were more likely to encroach on adjacent lanes in high-speed turns, to roll over (particularly the rear trailer), and to generally provide poorer sensory feedback to the driver. Doubles are more maneuverable in low-speed turns, however, so they are likely to perform better at intersections. After a summary of more than 15 studies concerning doubles' safety performance, the report concludes the following: the three most reliable comparisons of accident rates show that doubles have 2 percent lower, 6 percent higher, and 12 percent higher rates than singles, respectively. A comparison of the three most reliable fatal accident rate studies show that doubles have 7 percent lower, 5 percent higher, and 20 percent higher fatality rates than singles.

The review by the TRB study committee determined that there had been no definitive study of doubles' safety performance at that time. Special Report (SR) 211 concludes that doubles' accident rates are equal to or slightly higher than those of singles per vehicle mile and generally lower than those of singles per ton-mile.

Since publication of SR 211, there have been three research studies that focused on safety comparisons of doubles versus singles. Studies by the University of Michigan Transportation Research Institute (UMTRI) (*2*), the Insurance Institute for Highway Safety (*3*), and the University of Saskatchewan (*5*) differ greatly in data sources and method and are reviewed in the following three subsections.

UMTRI Study

Carsten describes a study to assess doubles' safety performance conducted by UMTRI in 1986 (*2*). A number of comparisons of singles' and doubles' safety performance were conducted using data from a variety of sources, including the National Accident Sampling System (NASS), accidents reported to U.S. Department of Transportation Office of Motor Carriers (formerly the Bureau of Motor Carrier Safety), Trucks Involved in Fatal Accidents (TIFA) and exposure data from the Truck Inventory and Use Survey (TIUS) compiled by UMTRI. The paper includes a discussion of operating difficulties with doubles (including rearward amplification) that may contribute to accident risk.

Carsten showed that there is no conclusive evidence of an overall difference in fatal or injury involvement rates for singles compared with doubles. This conclusion is tempered by the generally safer operating environment that characterizes doubles operations. Carsten further concludes that differences in truck handling characteristics are reflected in the differing accident experience of the two truck configurations.

Insurance Institute for Highway Safety Study

In a recent study by the Insurance Institute for Highway Safety (IIHS), Stein and Jones used a novel case-control methodology to compare accident involvements of doubles and singles (*3*). Accident data were obtained from 676 truck-involved crashes that occurred along Interstate 5 or Interstate 90 in the state of Washington from June 1985 through July 1986. Accidents were included in the data base if the truck weight exceeded 10,000 lb and the crash resulted in personal injury or property damage exceeding \$1,500. The location, day of week, and time of day of the accidents provided the information needed to select a control sample for comparison with the accident cases. For each large truck involved in a crash, three trucks were selected for inspection from the traffic stream at the same time and place as the crash, but 1 week later. A comparison of relative involvement in accidents compared with relative involvement (occurrence) in the control sample was used to calculate overinvolvement ratios. The control sample can thus be thought of as a pseudo exposure measure. An advantage of the methodology is that it allows for direct comparison of a large number of attributes of accident involvements with a similar set of nonaccident involvements. This disaggregate structure facilitates comparisons of a range of potential contributing factors such as vehicle configuration (principally), driver age, hours driving, cargo weight, and fleet size.

Stein and Jones found that doubles were consistently overinvolved in accidents by a factor of 2 or 3. The overinvolvement of doubles was found regardless of driver age, hours of driving, cargo weight, or type of fleet. The authors conclude that increasing use of doubles will produce more large truck crashes, despite their increased load-carrying capacity. The authors correctly point out that their findings cannot be directly converted to an accident rate per vehicle mile, but it is clear that the IIHS finding of 2- or 3-times greater accident risk for doubles compared with singles is a much larger difference in safety performance than has been identified in any previous study. The authors further state that previous studies using conventional accident and exposure data to estimate accident risk are unable to control for possible differences in operating conditions between the two vehicle configurations.

Although the study is creative in its use of methodology, the novelty of the approach and the apparent inconsistency (in scale at least) with previous research findings argue for a closer examination of the case-control technique as used in this application. The principal area for additional discussion is the method used to obtain the control sample and any generalization that can be derived from a study using this technique.

The seminal research in the application of this technique to road safety was a study by Haddon investigating 50 fatal pedestrian accidents in Manhattan (*4*). Haddon carefully describes the technique used to collect the control sample and, in particular, discusses the characteristics of individuals who refused to participate as controls. Although the study used three slightly different techniques to obtain the control data (they varied somewhat by neighborhood and time of day), they shared the common objective of limiting investigator bias by stopping pedestrians at the accident scene immediately after the accident. By simply taking the first four pedestrians at the site (with some very limited restrictions), Haddon directly acknowledges an effort to restrict investigator bias. Haddon also qualitatively describes the characteristics of the 12 pedestrians that refused, at some stage, to participate and argues that 12 out of 200 individuals are unlikely to alter the study findings. Further, the refusals were widely distributed across study sites (38 of 49 sites had no refusals), strengthening arguments against bias.

The large-truck study by Stein and Jones is much less clear concerning experiences during collection of the control sample and any potential effects regarding bias. Rather than collect the control data on the first set of trucks passing a site, at the same time of day and day of the week but 1 week later, Stein and Jones staggered their control data collection to one-half hour before and after the time of the crash as well as at the time of the crash. Despite the most well-intentioned investigator, this staggering in time could allow for investigator bias to manifest itself.

Stein and Jones do discuss difficulties in obtaining control data at some sites because of high roadway volume, lack of space, and other safety considerations. Unfortunately, there is no discussion of the frequency with which these events occurred and what effect, if any, they might have on the findings. Although the authors state that 85 percent of the accidents were matched with control data, it is unclear how strictly the matching criteria were followed and whether stricter criteria should not have been used. In keeping with the concern that the study be representative, all trucks passing each site for the hour bracketing the accident time could have been counted. Although only three trucks would have been stopped for further investigation, a more thorough understanding of configuration flow rates would have resulted. The additional counts would have provided an even more accurate description of the exposure to risk at the sites for the two configurations.

The final, but in many respects the most important, point is the ability to generalize the findings to other Interstates in Washington or elsewhere in the United States. In the seminal research, Haddon cautions several times against the extrapolation of findings to a broader population. First he cautions that site bias may affect the presence of potential contributing factors (in this case blood alcohol concentration) in accident victims and the control group (*4*, p. 671). He specifically argues that the sites chosen through the method may not be typical of all Manhattan. He later goes on to caution concerning extrapolation to other cities (*4*, p. 675). He does present qualitative arguments using supporting data but goes on to say that similar research is needed in other cities before more generalizable conclusions may be drawn.

In contrast, the truck safety research seems to imply findings generalizable not only to the rest of Washington but to the remainder of the United States as well. There is virtually no discussion of the attributes of the two Washington Interstates and their generalizability to other Interstate segments in the state or across the United States. Because sites involving heavy trucks were selected, they may represent a selection bias (i.e., sites with an unusually high risk of truck crashes). The possible selection bias raises questions about whether the IIHS results could be replicated at randomly selected sites or at a broader sample of national sites.

University of Saskatchewan Study

In a recent paper from an OECD conference concerning heavy trucks (*5*), Sparks and Bielka described a comparison of doubles' and singles' accident rates in Saskatchewan. The study was conducted at two levels: a provincewide analysis of accident rates using data from police accident reports, average daily traffic (ADT) counts, and vehicle classification counts; and a comparison of accident rates using data from two large fleets.

In the regional analysis the authors paid particular attention to the implication of measurement errors on the final estimated accident rates. They found that uncertainties in the estimation of the percentage of trucks and the percentage of doubles within the truck fleet have the greatest influence on the estimated accident rates. The general conclusion of both the regional and fleet-specific analyses was that there was no apparent difference in accident rates.

This is a thoughtful and carefully conducted study that is important for two reasons.

1. It clearly demonstrates the uncertainty in using regional data to conduct these types of comparative safety studies, one of the few studies to address this topic.
2. It introduces the feasibility of using carrier-specific data to improve the understanding of doubles' safety performance.

Summary

The conclusion in two of three studies is that doubles' rates are indistinguishable from rates of singles. None of the reported studies, however, has been able to control for differences in how and where doubles operate. The research reported in this paper attempts to respond to the need for this type of carefully controlled study.

STRUCTURE OF THE ANALYSIS

Overview

Much of the uncertainty regarding comparative studies of the safety performance of doubles and singles results from two interrelated issues: first, exposure data are not generally available to conduct accurate comparisons of accident rates and, second, the accident comparisons do not control for the effect of other variables such as weather and road design on safety performance.

To overcome these difficulties, the following approach is adopted. Accident data and measured dispatch (exposure) data are obtained for randomly selected origin-destination terminal pairs used for national LTL carriage. The only condition for inclusion in the sample is that the route actually contain both singles' and doubles' operations over precisely the same highway segments. This approach allows the use of very accurate exposure data for both types of trucks. Further, by using routes that contain operations of both vehicle types, it is possible to control for differences in road design, traffic level, and, generally, weather conditions.

There are additional advantages of conducting the comparison with carrier-supplied data such as these. The statistical test more directly compares the vehicle configurations that are the actual options along a route. If an individual carrier is restricted from using doubles, the single combination vehicle is the most likely alternative. Within a firm, that alternative vehicle will be subject to the same level of maintenance and the driver to the same level of management as the double combination that they replaced. The paired structure thus avoids inaccuracies that may occur in conducting cross-sectional studies that obtain doubles data from carriers in the LTL industry but include singles data from private and truckload carriers. The argument is not that these other types of carriage are less safe than LTL. Rather, it is that restrictions on doubles' travel should be based on an assessment of the safety performance of the vehicle configuration itself, without confounding effects such as level of vehicle maintenance and driver management.

Analysis Method

In order to conduct a statistical comparison of doubles' and singles' safety performance controlling for roadway design, traffic, and environmental conditions, it is necessary to test hypotheses concerning the mean difference in the accident rates of doubles and singles. The unit of observation is therefore the accident rate difference for each terminal pair in the data. The test statistic is the paired-T-test (*6*), given as

$$T = \frac{\overline{D} - d_0}{S_d/(n)^{1/2}} \tag{1}$$

where

$\overline{D}$ = mean of the differences between the paired observations,
d_0 = difference to be tested for,
S_d = standard deviation of the differences, and
n = number of observations.

The degrees of freedom for the test equals $n - 1$.

The random variable D is calculated as the difference between the accident rates of doubles and singles on a terminal pair and $\overline{D}$ is the mean for these route-level differences:

$$D_i = \mathrm{ARD}_i - \mathrm{ARS}_i \tag{2}$$

$$\overline{D} = \left(\sum_{i=1}^{n} D_i\right) \Big/ n \tag{3}$$

where

ARD_i = accident rate per million truck miles for doubles on terminal pair i,
ARS_i = accident rate per million truck miles for singles on terminal pair i, and
n = number of terminal pairs.

The value for d_0 for these comparisons is zero. The other variables are as commonly defined.

It is important to emphasize that the statistical tests are conducted using the mean (and standard deviation) of the difference in accident rates for each vehicle configuration on all the routes. This mean is then tested against the distribution of mean differences that would occur under the null hypothesis. By the central limit theorem, no matter what the distribution of the random variable is, the sampling distribution of its mean is normally distributed and can thus be characterized by the standard normal distribution (for sufficiently large samples). It is therefore unnecessary to test for a specifically normal distribution in the data; the statistical theory is sufficient to support the validity of the method.

In addition to comparisons of the accident rates of the two configurations on each type of route, accident rates are compared for parking lots (both at terminals and at stops) used while en route. Because the etiology of accidents is likely to be different in these different environments, separate comparison of the rates is useful.

This methodology allows a direct comparison between the truck configurations. The means for each configuration are also reported in order to provide the reader with a frame of reference, even though the vehicle-specific means are not used in the test statistic (the differences in route-level means are used instead). Findings for each year are also reported, as are findings for the data as a whole. Some variation is expected from year to year because of exogenous factors. Further, as described earlier, passage of the 1982 STAA allowed more uniform use of doubles. It took the industry 2 to 3 years to respond, but the effect was greatly expanded doubles operations during 1984 and 1985. The accident data may reflect this "learning curve" as drivers familiar with singles more frequently drive doubles.

Data Description

Accident data include all accidents reported during the processing of internal company claims, those meeting U.S. Department of Transportation reportability thresholds as well as minor property damage accidents. In addition to obtaining the vehicle configuration involved in the accident, the location (access-controlled and non-access-controlled highway, local street, or parking lot) and origin-destination terminals are determined from accident reports.

For each of the randomly selected terminal pairs, exposure data included the total mileage for each vehicle configuration between each terminal pair for each year. In addition, precise vehicle routings were obtained from carriers and verified using highway maps. The routing information was used to calculate the proportion of each route's mileage that occurred on the three roadway types. Applying these proportions to the annual mileage provided an estimate of the annual truck mileage for each type of highway on each route. Combining these data with location-specific accident data allowed the computation of an accident rate for each type of highway along each route. Figure 1 shows the geographic distribution of the terminal pairs used in the study. The routes are fairly distributed among western, midwestern, and eastern states. It should be remembered that these routes resulted from a random sample of terminal pairs with both doubles' and singles' operations.

Initial screening of the randomly selected routes revealed the presence of some routes with an extremely low number of dispatches and thus vehicle miles. A complete comparison of configuration safety performance was conducted for this full data set as well as for a data set containing only higher-volume O-D pairs for the following reason. If an accident happened to occur on a low-volume route, the rate (per million vehicle miles) would be greatly and artificially inflated. These greatly inflated rates would be treated in the statistical analysis with the same weight as a very heavily traveled route with high exposure (e.g., 6,000 dispatches or more) because the analysis is conducted at the route level. In order to ensure that all O-D pairs had some minimum exposure magnitudes, it was decided to include in the analysis only O-D pairs with at least 100 dispatches per year for each vehicle configuration. Although the restriction alters somewhat the randomness of the sample, the concept of comparing roughly comparable O-D volumes seemed a reasonable one.

Table 1 is a summary of descriptive statistics for the sample used in this research. The data set includes nearly 900 accidents (376 involving singles and 507, doubles) and over 300 million vehicle-mi of operation (127 million by singles and 209 million by doubles). Included for the reader's information is the total number of accidents, total truck miles, and resulting accident rate (total accidents divided by total miles). This indicates that the accident rates are in the range previously reported in the literature (*2,5*).

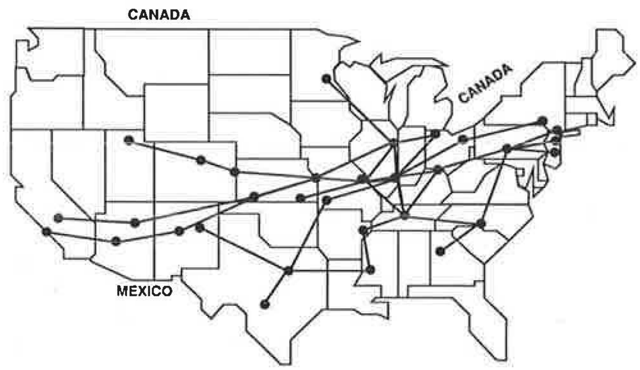


FIGURE 1 Geographic distribution of roadway segments.

TABLE 1 DESCRIPTIVE STATISTICS FOR TRUCK SAFETY AND OPERATIONS

ITEM	1983	1984	1985	TOTAL
Number of O-D Pairs	111	130	114	355
Average O-D Distance (Miles)	282	262	265	269
Number of Singles Trip (Million)	0.18	0.20	0.10	0.48
Singles Mileage (Million Veh-Miles)	50.0	51.0	26.6	127.6
Number of Singles Accidents	160	127	89	376
Singles Accident Rate*	3.20	2.49	3.34	2.95
Number of Doubles Trips (Million)	0.14	0.29	0.35	0.78
Doubles Mileage (Million Veh-Miles)	39.5	76.8	92.8	209.1
Number of Doubles Accidents	107	162	238	507
Doubles Accident Rate*	2.71	2.11	2.56	2.42

* Accident Rate = Accidents/Million Vehicle-Miles.

Clearly apparent in the data regarding both number of trips and number of vehicle miles per year is a strong shift toward doubles and away from singles during 1984 and 1985. Although singles' trips and mileage increased slightly from 1983 to 1984, doubles' trips and mileage increased by nearly a factor of 2. These data suggest that the increase in freight traffic accompanying the economic expansion during 1984 was taken up almost entirely by expanded doubles' use. Doubles' trips and miles continued to expand during 1985, whereas singles' operations on the terminal pairs were greatly reduced. These changes in the pattern of exposure to risk are reflected by changes in the annual number of doubles' and singles' accidents.

The data in Table 1 are intended to be purely descriptive. In particular, the accident rates that appear in rows 6 (for singles) and 10 (for doubles) are simply numbers obtained by dividing yearly accidents by yearly vehicle miles. Although this is informative, it is subject to the criticism that doubles may be operating on different roads and under different conditions than singles. It is only by conducting detailed route-level comparisons that differences in roadway and environmental conditions can be controlled and valid hypothesis tests concerning accident rate differences can be conducted.

FINDINGS

Overview

Tables 2 through 5 summarize the safety performance of the two vehicle configurations in each of the four operating environments. In computing the accident rate differences for doubles and singles, only the accidents occurring in each operating environment (access-controlled highways, non-access-controlled highways, local streets, and parking lots) are included. The "difference" is defined as the mean of the differences in accident rates between doubles and singles for each route. It must be remembered that statistical tests are conducted only using the data under the column titled "Difference," with variables as defined in Equations 1–3. The yearly mean accident rates for each vehicle type are included, along with their standard deviations, for informational purposes. A parallel set of tables was constructed using the entire data set; there were some differences in values for the full data set, but the interpretations derived from the tables are identical, so the tables are not replicated here.

The general expectation, given the data in Table 1, is that 1983 would reflect conditions as experienced before the 1982 STAA, owing to time lags to purchase and operate new equipment and the bare beginning of the economic recovery. The accident rate for doubles could be expected to increase in 1984 because of the rapid expansion of doubles operations and the requisite use of drivers in a vehicle to which they were unaccustomed. The rate was expected to drop somewhat in 1985 because the drivers were getting more familiar with doubles. Although these may be plausible hypotheses, it must be remembered that the firms participating in the study are conducting a variety of training programs to acquaint drivers with doubles operation. Given their generally high level of driving experience, drivers should have accomplished the transition to doubles relatively smoothly.

Safety Performance

Travel on Access-controlled Highways

With high geometric design standards and full access control, these highways should be more suitable to large-truck doubles operation than other types of roadways. If this assumption is true, the difference in accident rates for travel on access-controlled highways between doubles and singles should be much less than for travel on other roadways.

According to the statistics in Table 2, doubles experienced a lower accident rate per million miles than singles in 1985. Singles had a lower rate than doubles in 1984, but doubles had a lower rate again in 1985. Each of these yearly differences is statistically significant. The trend of safety performance by doubles followed by safer performance by singles may be explainable as part of a "learning curve" for doubles operation. This does not explain the increase in accident rates for

TABLE 2 ACCIDENT RATE DIFFERENCES FOR DOUBLE AND SINGLE COMBINATIONS ON ACCESS-CONTROLLED HIGHWAYS*

Year	Interstate Highways			No of Pairs	Paired-T Statistic
	Double	Single	Difference		
1983	2.79 (0.91)**	3.20 (0.94)	-0.41 (1.35)	110	-3.17
1984	4.59 (2.36)	4.26 (1.68)	0.33 (1.48)	127	2.50
1985	3.03 (0.83)	3.97 (1.84)	-0.95 (2.05)	112	-4.88
1983-5	3.52 (0.94)	3.83 (0.90)	-0.31 (0.95)	349	-6.09

* Accident Rate = Accidents / Million Vehicle-Miles.

**The term in parentheses is the standard deviation, S_d in Equation 1.

TABLE 3 ACCIDENT RATE DIFFERENCES FOR DOUBLE AND SINGLE COMBINATIONS ON NON-ACCESS-CONTROLLED HIGHWAYS*

Year	State Highways			No of Pairs	Paired-T Statistic
	Double	Single	Difference		
1983	15.21 (8.89)**	34.55 (18.16)	-19.34 (20.42)	41	-5.99
1984	22.48 (17.80)	8.43 (5.30)	14.05 (18.71)	47	5.09
1985	18.16 (9.26)	45.29 (23.52)	-27.13 (20.87)	41	-8.22
1983-5	18.80 (7.61)	28.45 (9.66)	-9.65 (11.54)	129	-9.46

* Accident Rate = Accidents / Million Vehicle-Miles.

**The term in parentheses is the standard deviation, S_d in Equation 1.

TABLE 4 ACCIDENT RATE DIFFERENCES FOR DOUBLE AND SINGLE COMBINATIONS ON LOCAL STREETS*

Year	Local Streets			No of Pairs	Paired-T Statistic
	Double	Single	Difference		
1983	9.19 (5.44)**	32.41 (12.58)	-23.23 (13.89)	108	-17.30
1984	13.49 (10.73)	9.39 (5.34)	4.10 (12.07)	126	3.80
1985	6.68 (3.20)	6.36 (2.96)	0.32 (4.45)	110	0.75
1983-5	9.96 (4.39)	15.65 (4.54)	-5.69 (6.38)	344	-16.52

* Accident Rate = Accidents / Million Vehicle-Miles.

**The term in parentheses is the standard deviation, S_d in Equation 1.

singles during the same time period. Because the pattern is so similar, one wonders if some common but exogenous factors such as weather conditions during a year or changes in automobile travel are affecting the results. When data for all 3 years are combined, doubles have an accident rate that is approximately 10 percent lower than that of singles (again the difference is statistically significant).

These statistics show that doubles experienced generally safer operations except for the transition to expanded use in 1984. This result runs counter to an assumption that doubles have a higher operating risk on access-controlled highways than singles.

Travel on Non-Access-controlled Highways

Non-access-controlled highways are designed to lower geometric standards than Interstate highways. Although speed limits are generally lower, one might expect the accident rates for both singles and doubles to be higher than on Interstate highways. The lower geometric design standards are generally perceived to increase the difficulty of operating doubles, hence the hypothesis that doubles have a higher accident rate than singles on state highways.

The accident rates shown in Table 3 are derived directly from the accidents and exposure on non-access-controlled highways alone. Doubles had a lower accident rate than singles by 19.34 accidents per million miles in 1983. Singles were lower by 14.05 in 1984, but doubles were lower by 27.13 in 1985. Again, all findings are statistically significant. The up-and-down pattern of accident rates seems to again indicate a learning curve for doubles' highway travel on non-access-controlled facilities.

On the basis of a statistical comparison between mean accident rates, large trucks traveling on non-access-controlled highways have consistently higher accident rates than those on access-controlled highways. These findings are consistent

TABLE 5 ACCIDENT RATE DIFFERENCES FOR DOUBLE AND SINGLE COMBINATIONS IN PARKING LOTS*

Year	Double	Single	Difference	No of Pairs	Paired-T Statistic
1983	0.30 (0.22)**	1.29 (0.87)	- 0.99 (0.90)	111	-11.54
1984	0.28 (0.07)	0.45 (0.30)	-0.17 (0.32)	130	- 6.03
1985	0.14 (0.07)	0.40 (0.21)	-0.26 (0.22)	114	-12.56
1983-5	0.24 (0.09)	0.70 (0.30)	-0.46 (0.31)	355	-27.92

* Accident Rate = Accidents / Million Vehicle-Miles.

**The term in parentheses is the standard deviation, S_d in Equation 1.

with the general position that Interstates are much safer than state highways for large-truck operation. The yearly pattern in accident rate differences was very similar to the pattern for Interstates: doubles had significantly lower rates in 1983, 1985, and all 3 years combined, whereas singles had lower rates than doubles in the transition year 1984.

Travel on Local Streets

Local streets have lower geometric design standards than Interstates and state highways and a generally higher level of conflicting traffic. However, both trucks and automobiles operate more slowly on local streets, and this allows drivers a longer time to react to unexpected events. As stated in SR 211, doubles' superior low-speed turning performance may result in this configuration's having a lower accident rate than singles on this type of road.

Table 4 shows the accident rates for travel on local streets for both doubles and singles. Doubles experienced 23.23 fewer accidents per million local street truck miles in 1983. The difference was 4.10 in favor of singles and was an insignificant 0.32 in 1985. Again, the trends in the doubles' accident rate differences are consistent with a driver learning process.

According to the mean accident rates over the 3-year study period, travel on local streets seems to have a higher risk than travel on Interstate highways, but a lower risk than travel on non-access-controlled highways. The doubles had a lower mean accident rate than singles in 1983 but a higher mean accident rate in 1984 and 1985. Over the entire 3-year period, doubles experienced a significantly lower accident rate than singles.

In Parking Lots

Accident occurrence in parking lots is not normally included in safety assessments of doubles. Perhaps it is because these accidents are generally of low severity and may represent minimal risk to the motoring public. However, such accidents are a source of cost to motor carriers and a source of delay and inconvenience to shippers. For these reasons, a comparison of doubles' and singles' accident risk in this environment is included here.

The most difficult decision in comparing parking lot accidents is to decide on an appropriate exposure measure. The exposure measure should be able to describe the number of opportunities for an accident in a parking lot for each trip. It was assumed that longer truck trips would result in a greater number of parking lot arrivals and departures. For this reason, truck miles was chosen instead of vehicle trips as the exposure measure for involvement in parking lot accidents. Table 5 shows the accident rates occurring in parking lots for doubles and singles. The parking lot accident rates decrease year by year for both doubles and singles, but singles experienced consistently higher parking lot accident rates than doubles for each study year. The difference is significantly different from zero for each year's comparison. This result contradicts the authors' intuitive assumption that doubles are more difficult to operate in parking lots than singles and result in higher parking lot accident rates than singles.

CONCLUSIONS AND RECOMMENDATIONS

The comparisons of doubles' and singles' safety performance have found significant differences in the accident rates of the two configurations. In general, doubles experienced lower accident rates than singles in 1983 and 1985, but higher accident rates than singles in 1984, which was the transition year for expanding doubles operation following the 1982 STAA. Doubles' accident rates are significantly lower than singles' accident rates for all types of operating environments over the whole period from 1983 to 1985. For the types of carriers represented in these data and for the conditions characterized by the routes in this sample, the consistent evidence is that doubles had better safety performance than singles except during the transition year 1984.

By separately analyzing safety performance on access-controlled highways, non-access-controlled highways, and local streets (also in parking lots), it was possible to compare the relative safety performance of each configuration in each operational environment. Truck accident rates on access-controlled highways were 5 to 7 times those on non-access-controlled roads. The safety performance on local streets was, somewhat surprisingly, in between the rates for Interstates and state highways. It should be remembered, however, that the paired comparison conducted in this research allowed more efficient detection of significant differences. Some may argue, therefore, that the approximate 9 percent difference between doubles' and singles' accident rates on access-controlled facilities may be statistically significant but practically irrelevant. It is not the authors' position to make judgments about how large a safety difference is required to be for it to be important. It is sufficient to say that the doubles rates are consistently less than those of singles.

There appears to be strong evidence of a learning curve that occurred during expansion of doubles operations in 1984. This evidence is particularly strong on state and local roads where doubles rates increased from 1983 to 1984 and then dropped in 1985 to nearly 1983 levels. No such consistent trend was observed for singles in these two operating environments.

The generalization derived from the study is that the double configuration itself is generally as safe or safer than the single configuration, even when roadway, traffic, and environmental conditions are specifically controlled for. One must remember, however, that these doubles operations occurred on routes that, de facto, were approved for doubles operation. It is therefore not appropriate to extrapolate these findings to any specific route. The authors believe that these findings, along with those of Sparks and Bielka and Carsten, generally support the widespread use of doubles unless specific data on their safety performance indicate conditions that differentially affect them.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Gar Foundation, United Parcel Service Foundation, Yellow Freight System, Inc., and the Office of Technology Assessment of the U.S. Congress. The study was conducted while the authors were affiliated with the Northwestern University Transportation Center.

REFERENCES

1. *Special Report 211: Twin-Trailer Trucks: Effects on Highways and Highway Safety.* TRB, National Research Council, Washington, D.C., 1986.
2. O. Carsten. Safety Implications of Truck Configuration. In *Transportation Research Record 1111*, TRB, National Research Council, Washington, D.C., 1987, pp. 17–26.
3. H. S. Stein and I. S. Jones. *Crash Involvement of Large Trucks by Configuration: A Case-Control Study.* Insurance Institute for Highway Safety, Washington, D.C., Jan. 1987.
4. W. Haddon et al. A Controlled Investigation of the Characteristics of Adult Pedestrians Fatally Injured by Motor Vehicles in Manhattan. *Journal of Chronic Disease*, Vol. 14, No. 6, Dec. 1961.
5. G. A. Sparks and J. Bielka. Large Truck Accident Experience in Western Canada. Presented at Symposium on the Role of Heavy Freight Vehicles in Traffic Accidents, Roads and Transportation Association of Canada, Ottawa, Ontario, 1987.
6. R. E. Walpole and R. H. Meyers. *Probability and Statistics for Engineers and Scientists.* Macmillan Company, New York, 1972, 506 pp.

DISCUSSION

ROBIN HERTZ AND PAUL L. ZADOR
Insurance Institute for Highway Safety, 1005 N. Glebe Road, Arlington, Va. 22201.

To assess the safety of double trailer trucks, Jovanis et al. used carrier-supplied data sets containing both crash and exposure data. The crash data included all crashes reported during the processing of internal company claims; the exposure data consisted of route-specific mileage by vehicle configuration. Although the authors acknowledge that all participating carriers had "well-established safety programs" and made "a good faith effort to adhere to federal safety regulations," they nevertheless conclude that their study findings can be generalized, not to specific routes or to specific carriers, but to the trucking industry as a whole. However, such carriers do not represent the whole of the trucking industry, and the findings of this study cannot be generalized beyond the safety-conscious study participants.

The authors compared crash rates of paired groups of doubles and singles operating between the same origin and destination terminals. These "terminal pairs" consisted of at least 100 dispatches/year of each of the two truck configurations. Crash rates were calculated separately for Interstate highways, state highways, local streets, and parking lots. The rates were calculated separately for 1983 through 1985 and for all 3 years combined.

Unlike other studies of crash rates of trucks of various configurations, the authors controlled for roadway of exposure by selecting origin and destination terminal pairs and maintaining this pairing in the data analysis. Beyond this one important factor, however, no attempt was made to eliminate or even to recognize other potential sources of bias. Important mechanisms for bias include, for example, the possibility that driver safety records and tractor maintenance records routinely influence the configuration choice. Had the companies in the study typically assigned doubles to the drivers who have better safety records and more experience, the results of this study would reflect the success of such assignment policies rather than the performance of doubles. Controlling for the age of drivers, the time and the day when the crash occurred, and the type and weight of the cargo carried could have provided some assurance that the results were not confounded with a crude selection bias.

It was not necessary for the authors to discard data for the less-traveled routes; with the appropriate statistical technique, all data could have been retained and included in a weighted analysis. The crash rate comparison specified by Equations 1–3 accords equal weight to rates based on small and large traffic volumes and results in unnecessarily unreliable estimates. Moreover, it is puzzling that in Tables 2–4 most of the differences between the doubles' and singles' crash rates are statistically significant on the basis of the paired-T-tests, yet the standard error estimates typically exceed the difference estimates, a situation that normally indicates the absence of statistical significance. The lack of consistency in the direction of the difference is also puzzling. It is not easy to understand how it is possible for doubles to be significantly superior to singles with regard to safety in 1983 and 1985, and significantly inferior to them in the intervening year, 1984.

In contrast, in their study, Stein and Jones (*1*), rather than determining crash rates by configuration, studied risk factors for crash involvement using the case-control method. Contrary to the criticism by Jovanis et al. of the "novelty of the approach," modern case-control studies have been used in medicine, public health, and sociology since the 1920s.

In the Schlesselman (*2*) design, the unit of analysis is the individual rather than the group, making it possible to study many factors relating to the crash. Each crash-involved truck and truck driver (case) was matched to and compared with three trucks and truck drivers who were not crash involved (control). By matching on roadway, time of day, and day of the week, the cases and controls were comparable with respect to these attributes and the hazards associated with them. Control trucks were selected by Washington State Patrol commercial vehicle enforcement officers according to a specific and rigorous research protocol. Controls were selected one week after each crash. The first control truck was stopped for inspection 30 min before the time of the crash, the second was stopped at the time of the crash, and the third was stopped 30 min after the crash. The officers were instructed to select the first truck going through the crash site at the sampling time. Although the officers could not be blinded to the case or control status of the truck entering the study sample, they were not aware that one objective of the study was to determine the association between configuration and crash risk. Thus, there is no reason to believe that the study objective would have influenced the selection of control trucks.

Both case and control trucks were subjected to a rigorous vehicle inspection. Case and control drivers were interviewed regarding their age, experience, and hours of service. After adjusting for truck and driver characteristics, Stein and Jones found that double trailer trucks were consistently overinvolved in crashes by a factor of 2 to 3. The strength of the finding lies in the fact that the study compared different truck configurations operating in the same environment, analyzed the confounding effects of other truck and driver characteristics, relied on data collected by state patrol officers rather than motor carriers, and sampled from the population of trucks traveling on the Interstate system rather than the limited population of trucks operated by a nonrepresentative segment of the trucking industry.

REFERENCES

1. H. S. Stein and I. S. Jones. Crash Involvement of Large Trucks by Configuration: A Case-Control Study. *American Journal of Public Health*, Vol. 78, 1988, pp. 491–498.
2. J. J. Schlesselman. *Case-Control Studies: Design, Conduct, Analysis*. Oxford University Press, New York, 1982.

AUTHORS' CLOSURE

We appreciate the time and effort contributed by Hertz and Zador in their formal comments concerning this research. In addition to a recapitulation of the IIHS study method and findings, their comments focus on three major areas: the design of the experiment and structure of the analysis, the treatment of data and reporting of findings, and the generalizability of the study findings and their implications for policy. We are happy to share our response in each of these areas.

IIHS STUDY

There has never been, nor is there ever likely to be, a definitive study of doubles' safety performance. Our research was not developed in response to specific IIHS findings, so a point-by-point comparison serves no purpose. Although we stand by our comments in the text of our paper, one point needs to be reemphasized: It is not the novelty of the case-control method per se that is at issue; it is the soundness of its execution and the interpretation of the findings. The discussants and the authors of the IIHS study imply that their findings are an accurate assessment of doubles' accident risk across the United States in broad highway operation. We simply disagree with that generalization for all the reasons stated in the text.

We understand the value of the disaggregate analyses conducted with the case-control methodology. Jovanis and Chang have adapted another method from biostatistics, survival theory, to construct a disaggregate model of accident occurrence (*1,2*). We fully support the concept of disaggregate analyses; it is the interpretation given to the IIHS data that we find unacceptable.

TREATMENT OF DATA AND REPORTING OF FINDINGS

The discussants suggest that weights be applied to the accident rate data as an alternative to eliminating low-volume O-D pairs. Beyond this general recommendation, the discussants offer no specifics on how the weights are to be determined. Vehicle miles of doubles and singles differ greatly at individual O-D pairs. If one wishes to retain the paired structure, the difficult decision is how to assign a weight to the accident rate difference when it is composed of vehicle configurations with two different levels of exposure. Rather than develop an ad hoc rule or forego the increase in statistical power associated with the paired structure, we chose the approach of parallel analyses—one with all data and one with higher-volume O-D pairs only.

The discussants are correct in their identification of an inconsistency concerning the standard errors that appeared in Tables 2–5 of the earlier version of the paper. The numbers in parentheses in Table 2–5 are now correctly labeled as the sample standard deviation of the random variable in question. The standard error is obtained by dividing this value by $(n)^{1/2}$. The variables are now correctly labeled and defined in the text; there is no change in the analysis or interpretation of the data.

The discussants indicate that the change in the direction of statistical significance from year to year is "puzzling" and shows a "lack of consistency." We speculated that the reversal in statistical significance in 1984 was due to a driver learning curve and other exogenous phenomena (an increase in automobile VMT). There are many other hypotheses for the reversal in statistical significance, but none can be tested with our data. There is a very clear and consistent pattern for each of the 3 years and for each operating environment; it is this consistency that is the strength of the analyses.

DESIGN OF EXPERIMENT AND STRUCTURE OF ANALYSIS

The discussants argue that the research controls for only type of roadway and does not seek to eliminate or recognize other sources of "bias." Clarification is needed on both points.

The paired structure of the analysis does much more than control for the type of highway exposure. By studying the O-D pairs throughout each year for 3 years, the research implicitly controls for the volume of automobile traffic on each route. As singles and doubles are dispatched throughout the day, they experience generally the same level of automobile traffic. Increases in automobile traffic increase the risk of multiple-vehicle accidents; therefore the paired structure more explicitly controls for traffic level than would a cross-sectional design that compared configurations on similar but not identical routes. Similar arguments can be made for weather conditions.

The discussants argue that time of day is not controlled for, but this is only an issue if doubles are dispatched at consistently different times than singles (and thus exposed to a different level of risk). Carriers do not dispatch vehicles with this differential policy applied to vehicle configurations. They generally dispatch many trips for both vehicle configurations late at night and early in the morning. An independent analysis of accidents occurring on a broader set of O-D pairs reveals no difference in the time of day of accident occurrence for doubles and singles.

Driver experience may be a differential factor for doubles and singles but not for the reasons posed by the discussants. Drivers are not assigned to a vehicle by the firm but by an elaborate process using a bidding system that combines the time at which a driver becomes available for a load and his seniority. It is not possible to examine this hypothesis for the O-D pairs in the study, but for a broader set of routes, the experience of randomly selected drivers is displayed in Table 6. The distribution of driver experience is statistically independent of configuration at the .05 significance level. Although this is not as direct as considering the study O-D pairs alone, the finding, along with knowledge of how drivers are assigned to trucks, gives confidence that driver experience is essentially controlled for in the experiment. Furthermore, the discussants fail to recognize that a firm will manage its drivers in a consistent way, independent of which configuration they drive on a particular day. By conducting the paired comparison for doubles and singles operated by the same firm, even more general driver attributes than experience are controlled for. Differences in safety performance are thus more directly associated with the vehicle configuration, not confounding effects.

Other comments made by the discussants concerning driver and vehicle records presuppose what is at issue. Companies do not routinely "assign" their safest drivers to doubles (even if they could) because they do not believe that doubles are inherently less safe. Although it would have been advantageous to explicitly control for cargo weight and driver age, we believed it more important to control for highway type, traffic level, and weather conditions, because we believe that these are more important contributing factors to accidents than are cargo weight and driver age.

GENERALIZABILITY

The discussants argue quite strongly that the study findings are not generalizable to the industry as a whole. This is a complex issue, which is perhaps best discussed in the context of the original research question; that is, if a carrier has a well-established safety program and generally makes a good-faith effort to comply with federal safety regulations, are doubles inherently less safe than singles? Further, does safety performance change for different roadway types? The direct short answers to these questions based upon this research are that doubles are not inherently less safe than singles and that this finding applies across all highway types included in the study. We believe that this is an important finding that is a research contribution.

Do the data in this study characterize practices throughout the LTL industry? We don't think anyone knows, or can hope to know, the answer to this question, given the questionable accuracy of publicly available accident and operations data for firms (*3*). Any discussion of generalizability that is argued on the basis of characterizing motor carriers' concerns for safety management is thus more likely to be based upon belief or supposition rather than scientific evidence. The alternative is to consider the findings in the context of the extant literature on doubles' and singles' safety performance.

Given the documented evidence regarding differences in configuration handling characteristics (*4*) and related accident outcomes (*5*), it is clear that configuration plays a role in accident causality. The findings here suggest that the differences in causal mechanisms do not result in differences in broad accident risk (i.e., accidents per million miles). The weight of recent evidence from this study, the study by Sparks and Bielka and the study by Carsten suggest, as a composite, that doubles are at least as safe as singles. Safety regulation should thus focus on broad oversight of driver hours, training,

TABLE 6 RANDOM SAMPLE OF DRIVER EXPERIENCE FOR TWO VEHICLE CONFIGURATIONS

	Level of Experience					
	<1	1-3	3-5	5-10	>10	TOTAL
Drivers of Singles	78	49	57	326	407	917
Drivers of Doubles	87	38	36	291	359	811
Total	165	87	93	617	766	1728

substance abuse, and vehicle operation (for all configurations), not on regulations that restrict doubles in particular.

REFERENCES

1. P. P. Jovanis and H. Chang. Disaggregate Model of Highway Accident Occurrence Using Survival Theory. *Accident Analysis and Prevention*, Vol. 21, No. 5, Oct. 1989.
2. H. Chang. A Disaggregate Survival Model of Motor Carrier Accident Occurrence. Ph.D. dissertation. Department of Civil Engineering, Northwestern University, Evanston, Ill., 1987.
3. *Gearing Up for Safety: Motor Carrier Safety in a Competitive Environment.* Report OTA-SET-382. Office of Technology Assessment, U.S. Congress, Sept. 1988.
4. *Special Report 211: Twin-Trailer Trucks.* TRB, National Research Council, Washington, D.C., 1986.
5. O. Carsten. Safety Implications of Truck Configuration. In *Transportation Research Record 1111*, TRB, National Research Council, Washington, D.C., 1987, pp. 17–26.

The findings and conclusions are strictly those of the authors, who assume all responsibility for them.

Publication of this paper sponsored by Committee on Traffic Records and Accident Analysis.

Use of Time Series Analysis to Forecast Truck Accidents

SNEHAMAY KHASNABIS AND SEUNG HWA LYOO

The purpose of this paper is to test the feasibility of using the Box-Jenkins method of time series analysis for forecasting truck accidents. Time series analysis is a technique by which the autocorrelation between sequential observations is analyzed and models are developed to produce forecasts. The authors used the Auto-Regressive Integrated Moving Average Method (ARIMA) in an effort to incorporate seasonal fluctuations in the data base to develop the model. A total of 88 data points representing monthly accidents involving large trucks in Michigan, observed between January 1978 and April 1985, was used to develop the model. Two types of checks were used to test the goodness of fit of the model. First, diagnostic checks were conducted to test the degree of correspondence between the observed data (used for model development) and the model output. This test indicated that approximately 70 percent of the autocorrelations are accounted for in the model. Second, the model was used to forecast monthly accident data for the 20-month period between May 1985 and December 1986 (data base not used in model development). The forecast data were then compared with the actual truck accidents observed during the same period. This test showed excellent correspondence between the observed data and the model output. The authors recommend further studies to test the feasibility of using time series analysis as an accident prediction tool.

A time series is a set of observations generated sequentially in time, in either a continuous or a discrete form. The values of observations at different time points are not assumed independent. Rather it is assumed that there exists a pattern of autocorrelation between these sequential observations. In real life, a great deal of data in economics, business, engineering, and the natural and social sciences is found in the form of time series in which observations are dependent and the nature of the dependence itself is of great interest to researchers (*1,2*). Time series analysis is a technique by which the autocorrelation between these sequential observations is analyzed and models or mathematical formulations are developed to fit the data, which can be used to produce forecasts of time series that might be expected under various scenarios.

MODELS TO DESCRIBE TRAFFIC EVENTS

In accident analysis, forecasting accidents under alternative hypotheses has perplexed researchers for a long time. Accidents typically are considered random events, and the current literature indicates efforts by researchers to fit different types of mathematical distributions (ranging from stochastic to deterministic) to accident data in an effort to develop predictive models (*3,4*). The use of the Poisson distribution, for example, to describe the occurrence of accidents as random events is quite common. Indeed, researchers have applied the Poisson and the negative exponential distribution (as an outgrowth of the Poisson) in describing other traffic events as well, such as arrival of vehicles at isolated intersections and distribution of vehicular headways on rural highways.

The use of the Poisson function to describe traffic events requires the implicit assumption of randomness, in which the occurrence of any of the events is not likely to be influenced by the occurrence (or nonoccurrence) of the preceding event. In real life, however, many traffic events are not to be considered independent and thus the assumption of randomness becomes questionable. For example, the arrival of vehicles at a signalized intersection on a congested urban arterial is likely to be affected by arrivals upstream of the intersection. Similarly, as traffic volume on a rural intersection increases, vehicular headways are likely to be more dependent upon one another. The transition of traffic movement from a "free flow" regime to a "constrained" flow regime (as volume increases from light to heavy) was described originally by Schuhl through mathematical models (*5*). The Schuhl model, as it has been designated in the literature, treats the total flow in two separate components: one for the random flow and the other for the constrained flow. Similar efforts to describe traffic flow on two-lane highways in Indiana and North Carolina have been described by Grecco and Sword (*6*) and Khasnabis and Heimbach (*4*).

PURPOSE OF PAPER

The purpose of this paper is to demonstrate the applicability of time series analysis technique for forecasting traffic accidents. The purpose of the earlier discussion of random versus nonrandom events was simply to provide background information on the concept of dependence or independence of observation (whether of traffic accidents or vehicular headways) and how the phenomenon of dependence has been treated by researchers for the purpose of model development.

Time series analysis techniques were used during the past decade to evaluate the effectiveness of highway safety countermeasures. Wagenaar, Arnold, and others, for example, have used this technique to evaluate the effectiveness of mandatory seat belt laws and child restraint systems and the effect of a minimum-age law on alcohol-related accidents involving young drivers (*7–9*). In a 1985 study conducted for the National Highway Traffic Safety Administration, Arnold used time series techniques to demonstrate a reduction in fatal

Civil Engineering Department, Wayne State University, Detroit, Mich., 48202.

crash involvement among drivers affected by an increase in the drinking age in 13 states (*10*). Similarly, a time series technique was used by Wagenaar et al. in 1988 to evaluate the effect of mandatory seat belt laws in eight states (*9*). Wagenaar also used the Box-Jenkins intervention analysis method to assess the long-term effects of a raised drinking age on reducing motor-vehicle crash involvement among young drivers. He used multiple levels of comparison groups and multiyear time series designs to obtain accurate estimates of the effect of raising the drinking age and to ensure that the observed effects were, in fact, caused by changes in the drinking age (*8*).

Recent increases in fatalities resulting from truck accidents have caused researchers to question the relative role of trucks (particularly heavy trucks) in the incidence of traffic accidents. In addition, the passage of the 1982 Surface Transportation Assistance Act, which made it possible for heavier, longer, and wider trucks to operate on selected national highways, has raised concerns in the minds of many safety experts. During the coming decade trucking activity is likely to increase further because of increased application of the "just-in-time" concept of delivery techniques by the manufacturing industry and because of price competition, brought about by the deregulation of the trucking industry. As such there is considerable interest among researchers to develop forecasts of truck accidents over a specific geographic area. This paper is an effort to apply time series analysis techniques to forecast truck accidents, notwithstanding the argument of dependence versus randomness presented earlier.

TIME SERIES MODEL

Time series analysis postulates that future values have a probability distribution that is conditioned by a knowledge of past values; therefore, exact predictions are impossible. Moreover, the reliability of prediction values depends on the characteristics of the data, so the data may have to be modified appropriately.

A distinction has been made in the literature on time series analysis between stationary and nonstationary models (*1*). In stationary models, an assumption is made that the process remains in equilibrium about a constant mean. In this category three broad types of models can be identified. Nonstationary models, on the other hand, exhibit a pattern in which observations do not vary about a fixed mean.

Autoregressive Models

Autoregressive (AR) models are essentially stochastic models in which the current or future value of the process is expressed as a finite linear combination of previous values of the process and a shock (error term). Mathematically, the process (X_t) of order p can be represented as

$$X_t = m_1X_{t-1} + m_2X_{t-2} + \dots + m_pX_{t-p} + A_t \quad (1)$$

where

m_1, m_2 = model parameters,
X_{t-1}, X_{t-2} = observation at time $t - 1$, $t - 2$, etc., and
A_t = random shock (error).

In Equation 1, the variable X_t is regressed on previous values of itself, hence the name "autoregressive."

Moving Average Method

In the moving average (MA) method, the current value of the process is expressed as a linear combination of previous random shock values. Mathematically, the process (X_t) of order q can be expressed as

$$X_t = A_t - n_1A_{t-1} - n_2A_{t-2} - \dots - n_qA_{t-q} \quad (2)$$

where n_1, n_2 are model parameters and A_t, A_{t-1} are random shock at time t, $t - 1$, and so on.

Mixed ARMA Method

It is sometimes advantageous to combine the AR and MA processes to achieve greater flexibility in fitting actual time series. This leads to the ARMA model, which can be expressed for the process (X_t) of order p,q, mathematically as

$$X_t = (m_1X_{t-1} + m_2X_{t-2} + \dots + m_pX_{t-p}) + (A_t - n_1A_{t-1} - n_2A_{t-2} - n_qA_{t-q}) \quad (3)$$

In real life, representation of actually occurring stationary time series can be obtained by AR, MA, or ARMA methods in which p and q are not greater than 2 and often less than 2. However, in business, engineering, industry, and economics, where forecasting has been of particular importance, time series data can be better represented as nonstationary, having no natural mean yet exhibiting homogeneous behavior of a kind. It is possible in such cases that the general level about which fluctuations are occurring may be different at different times. However, the broad behavior of the series, when differences in level are accounted for, may be similar.

Auto-Regressive Integrated Moving Average Method

A commonly used time series model is the Auto-Regressive Integrated Moving Average (ARIMA) Method, which provides analysts with a powerful tool for describing stationary and nonstationary processes. Mathematically, an ARIMA model of order p,d,q, can be represented as

$$W_t = \overline{V}^d X_t \quad (4)$$

$$W_t = [m_1W_{t-1} + m_2W_{t-2} + \dots + m_pW_{t-p}] + [A_t + n_1A_{t-1} - n_2A_{t-2} + \dots - n_qA_{t-q}] \quad (5)$$

where

W_t = set of time series removed from trends or seasonal effects,
$\overline{V}$ = differencing operator such that

$$\nabla X_t = X_t - X_{t-1} = (1 - B)X_t \tag{6}$$

B = backward shift operator such that $BX_t = X_{t-1}$, hence $B^{12}X_t = X_{t-12}$, and

∇^2 = second-order differencing such that

$$\nabla^2 X_t = \nabla(\nabla X_t) = \nabla(X_t - X_{t-1}), \tag{7}$$

hence

$$\nabla^2 X_t = \nabla(\nabla X_t) = \nabla(X_t - X_{t-1})$$
$$= (X_t - X_{t-1}) - (X_{t-1} - X_{t-2})$$
$$= X_t - 2X_{t-1} - X_{t-2} = (1 - B)^2 X_t$$

hence

$$\nabla^d X_t = (1 - B)^d X_t \tag{8}$$

Experience has shown that homogeneous nonstationary behavior can be represented by a model that calls for the dth difference of the process to be stationary. In most cases, d is usually 0, 1, or at most 2.

MICHIGAN CASE STUDY

Truck travel as well as truck-related accidents have grown steadily in Michigan and nationwide during the last 20 years. Further, many analyses predict that this trend is likely to continue. The purpose of the analysis presented in this paper is to develop forecasts of future truck accidents in Michigan based upon past observation through the use of time series analysis techniques.

The project from which this paper is developed used two separate data bases as follows:

Data 1: Number of large-truck accidents (gross vehicle weight > 10,000 lb) per month in Michigan for the 88-month period from January 1978 to April 1985.

Data 2: Number of trucks involved in accidents per year in Michigan between 1966 and 1986.

In this paper, only the analysis pertaining to Data 1 is reported. This is because the results of the forecast can be compared with actual monthly accident data following April 1985. On the other hand, sufficient time has not elapsed to allow a comparison of the annual accident forecast with actual data after 1986 for Data 2. Thus, a goodness-of-fit test cannot be compiled for Data 2. Also, the Box-Jenkins method that serves as the analytic tool for this study recommends the use of a minimum of 50 data points for model development; the only way this minimum data requirement could be met was through the use of monthly accident data (Data 1). In addition, the monthly accident data (Data 1) clearly showed a strong seasonal component, which would have otherwise been masked if the monthly data were combined to make yearly counts. This factor further justified the use of the monthly data so that the model can capture seasonal trends. The necessary accident data for model development were obtained from a recent report compiled by the Michigan Department of Transportation (MDOT) on truck safety, revenue, and taxation (*11*). The testing of the model output was conducted with data compiled by the Technical Services Unit of the MDOT Traffic and Safety Division.

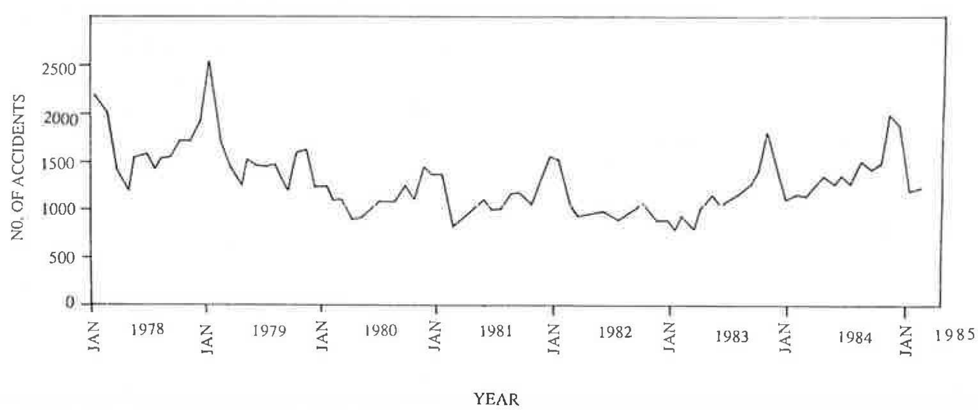
A five-step procedure was used to develop forecasts of truck accidents in Michigan. The well-known Box-Jenkins method of time series analysis was applied (*1*) and the software package MINITAB, developed by MiniTab, Inc. for developing the time series model (*12*), was used.

Data Plotting

Figure 1 from the above-mentioned MDOT study shows the trends in large-truck accidents during the 88-month period between January 1978 and April 1985. Figure 1 shows seasonal fluctuations; the number of accidents reached its highest level during the December-February period and the lowest level during the April-May period. This trend is referred to as the "seasonality factor" in the following text. Figure 1 also shows a long-term upward trend after 1982.

Model Identification

Considering the nonstationary nature of the data base, and in an effort to incorporate the seasonality factor, the authors identified the ARIMA method as the most appropriate approach. Further, following the Box-Jenkins method for data



SOURCE: REF. (2)

FIGURE 1 Trend in large truck accidents in Michigan.

sets not containing constant variance, a multiplicative (rather than an additive) model was used.

In Box-Jenkins, the variable W_t is formed from the original series X_t by differencing to remove both trend and seasonality. Because the data have monthly seasonality (Factor 12),

$$W_t = \nabla^d \nabla_{12}^D X_t \tag{9}$$

where for $d = D = 1$,

$$W_t = \nabla \nabla_{12} X_t = \nabla_{12} X_t - \nabla_{12} X_{t-1} \tag{10}$$

$$= (X_t - X_{t-12}) - (X_{t-1} - X_{t-13}) \tag{11}$$

(The values of the integers d and D do not usually need to exceed 2, according to the Box-Jenkins method.)

Therefore, the Box-Jenkins multiplicative seasonal models could be established by combining the following two processes:

For the seasonal process,

$$\oplus(B^s)\nabla_s^D X_t = \ominus(B^s) Z_t \tag{12}$$

where

s = seasonal period,
$\nabla_s = 1 - B^s$
$\oplus(B^s)$, $\ominus(B^s)$ = polynomials in B^s of degrees P and Q, and
Z_t = error.

For the whole process,

$$m(B)\nabla^d Z_t = n(B) A_t \tag{13}$$

so that, by combining above two equations, the following seasonal model, the ARIMA $(p,d,q) \times (P,D,Q)_s$ model, is obtained:

$$m_p(B)\oplus_P(B^s)\nabla^d\nabla_s^D X_t = n_q(B)\ominus_Q(B^s)A_t \tag{14}$$

Last, through the use of the MINITAB computer package and after more than 20 candidate models were reviewed, the ARIMA $(1, 1, 1) \times (1, 1, 1)_{12}$ model was identified as the most appropriate approach.

Estimation of Parameters

From Equation 14 and for $p = 1$, $P = 1$, $w = 1$, $Q = 1$, $s = 12$, $d = 1$, $D = 1$ [because the model is ARIMA $(1, 1, 1) \times (1, 1, 1)_{12}$],

$$(1 - m_1 B)(1 - \oplus_1 B^{12})\nabla\nabla_{12} X_t = (1 - n_1 B)(1 - \ominus_1 B^{12}) A_t \tag{15}$$

that is,

$$(1 - m_1 B)(1 - \oplus_1 B^{12})\nabla(X_t - X_{t-12}) = (1 - n_1 B)(1 - \ominus_1 B^{12}) A_t \tag{16}$$

Consequently, the equation could be modified as follows:

$$\begin{aligned} X_t = {} & (1 + m_1)X_{t-1} - m_1 X_{t-2} + (1 + m_1)X_{t-12} \\ & - (1 + m_1 + \oplus_1 + m_1\oplus_1)X_{t-13} \\ & + (m_1 + m_1\oplus_1)X_{t-14} - m_1 X_{t-24} \\ & + (m_1 + m_1\oplus_1)X_{t-25} + m_1\oplus_1 X_{t-26} \\ & + \bar{\mu} + A_t - n_1 A_{t-1} - \ominus_1 A_{t-12} + n_1\ominus_1 A_{t-13} \end{aligned} \tag{17}$$

The method of least squares was used in the MINITAB package to develop the following parameters: $m_1 = 0.2256$, $\oplus_1 = -0.3063$, $\bar{\mu} = \bar{\bar{x}} = 8.0876$, $n_1 = 0.9671$, $\ominus_1 = 0.8697$.

Diagnostic Checking

The purpose of the diagnostic check is to assess the degree of correspondence between the model output and the observed data for the 88-month period. This is generally done by examining the residuals, which are the differences between the observations and the fitted values. The following procedure suggested by Box-Jenkins was used:

$$Q = N \sum_{k=1}^{K} r_{k'}^2 \tag{18}$$

where N is the number of data in the difference series and $r_{k'}$ is the autocorrelation function of the residual.

If the fitted model is appropriate, then Q should be approximately distributed as chi-square with $(K - p - q)$ degrees of freedom (df), where p, q are the number of orders in the AR and MA models, respectively. The values of Q for lags 12, 24, 36, and 48 were obtained as follows:

Lag	*Chi-Square (calc.)*	*df*
12	7.1	8
24	19.7	20
36	29.4	32
48	36.6	44

A comparison of the above-calculated chi-square values with critical chi-square values indicates that, overall, the model was built on 70 percent residual autocorrelation. In other words, approximately 70 percent of the autocorrelations are accounted for in this model. Thus the diagnostic check shows a reasonable fit to the observed data.

Forecasting

By substituting the estimated parameters, the following forecasting equation is developed:

$$\begin{aligned} X_{t-1} = {} & 1.2256X_{t-1} - 0.2256X_{t-2} + 1.2256X_{t-12} \\ & - 0.8502X_{t-13} + 0.1565X_{t-14} \\ & - 0.2256X_{t-24} + 0.1565X_{t-25} \\ & - 0.0691X_{t-26} + 8.0876A_t + 0.9671A_{t-1} \\ & - 0.8697A_{t-12} + 0.8411A_{t-13} \end{aligned} \tag{19}$$

By taking the conditional expectation approach, at time $t + h$ (h being the lead time), the model is rewritten as follows:

$$\begin{aligned} X_{t+h} = {} & 1.2256X_{t+h-1} - 0.2256X_{t+h-2} \\ & + 1.2256X_{t+h-12} - 0.8502X_{t+h-13} \\ & + 0.1565X_{t+h-14} - 0.2256X_{t+h-24} \\ & + 0.1565X_{t+h-25} - 0.0691X_{t+h-26} \\ & + 8.0876A_{t+h} - 0.9671A_{t+h-1} \\ & - 0.8697A_{t+h-12} + 0.8411A_{t+h-13} \end{aligned} \tag{20}$$

In Table 1, the expected values of the forecast data for 20 months starting in May 1985 through December 1986, along with the lower and upper 95 percent values, are presented. Also presented are the actual truck accident data experienced in Michigan during the same period and obtained from the records of MDOT. Figure 2 also shows the actual observations and the forecast data, along with the confidence band.

Table 1 provides a comparison between observed data and the model output and shows that in 15 out of 20 cases compared, the expected value of the forecast data is within 10 percent of the actual observation. Further, it is also seen that in only 2 out of the 20 cases the actual observations are beyond the limit of the 95 percent confidence interval of the forecast values.

Two other nonparametric tests were conducted to assess the goodness of fit of the model output. First, in Table 2, the results of the chi-square test are presented for comparing the distribution of the accident data as obtained from the two sources. The calculated value of the chi-square of 0.89 is much smaller than the critical chi-square value of 5.99, at a 5 percent level of significance for 2 df. This implies the absence of any significant difference between the two distributions. Second, in Table 3, the percent root-mean-square (RMS) errors of the estimated values from actual values (computed as a function of the deviations) are also presented. The range of the RMS error is between 4.8 and 11.3 percent, thus indicating excellent correspondence between the observed data and the model output.

Last, the confidence intervals of forecast values are expected to expand gradually as these values move further away from the time of the last real data value available. This is because one becomes less confident that the forecast value will approach the true value as one moves further into the future. The width of the confidence interval (difference between the upper and

TABLE 1 COMPARISON BETWEEN FORECASTED ACCIDENTS AND ACTUAL OBSERVATION

Year (Month)	Forecasted Number of Accidents				Actual Number of Accidents
	Expected Value	95 Percent Limit		Width of Confidence Interval	
		Lower	Upper		
1985 (5)	1455	1108	1802	694	1494+
(6)	1566	1208	1924	716	1542+
(7)	1531	1171	1891	720	1585+
(8)	1595	1234	1955	721	1665+
(9)	1646	1285	2006	721	1612+
(10)	1818	1457	2179	722	2038+
(11)	1888	1527	2249	722	2010+
(12)	2076	1715	2437	722	2726*
1986 (1)	2098	1737	2460	723	2104+
(2)	1788	1426	2150	724	2084
(3)	1755	1393	2117	724	1585
(4)	1650	1288	2013	725	1619+
(5)	1836	1471	2202	731	1840+
(6)	1958	1592	2323	731	2006+
(7)	1930	1565	2296	731	1956+
(8)	2010	1644	2376	732	1883+
(9)	2035	1669	2401	732	2087+
(10)	2232	1866	2598	732	2251+
(11)	2263	1897	2629	732	2081
(12)	2419	2053	2786	733	1915*

* - In 2 out of 20 cases, actual observations are beyond the limit of the 95 percent confidence interval.

\+ - In 15 out of the 20 cases the expected value of the Forecasted Data is within 10% of the actual observation.

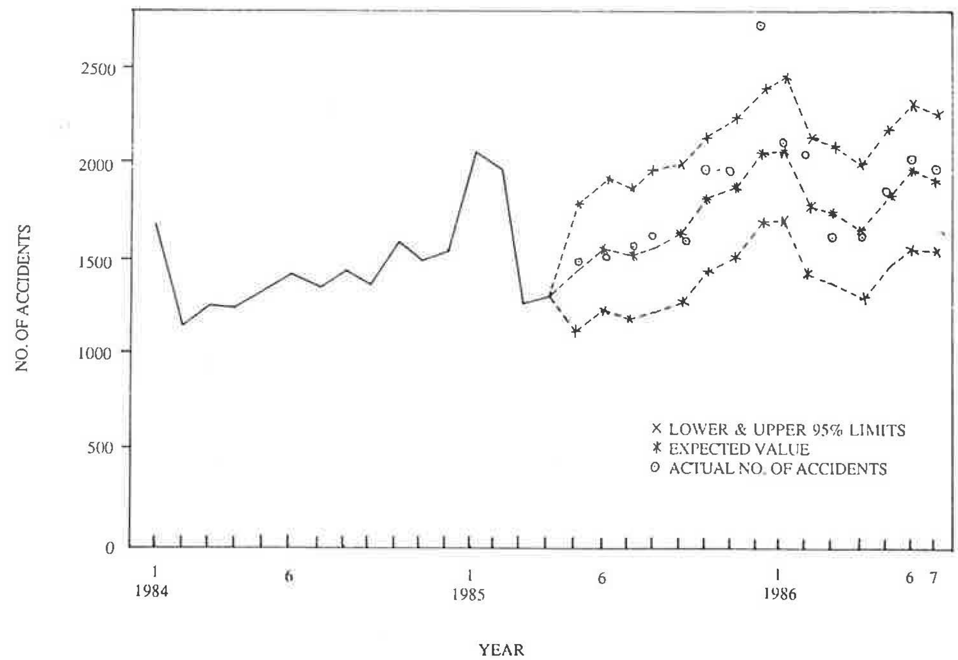


FIGURE 2 Forecasted trend of large truck accidents.

TABLE 2 COMPARISON OF DISTRIBUTION OF ACCIDENT DATA—CHI SQUARE TEST

Range (Accidents/Month	Number of Observations	
	Actual	Model
1450 - 1750	7	6
1751 - 2050	7	9
2051 and above	6	5

Calculated Chi-Sq Value = 0.89

Critical Chi-Sq Value for

2 df at 5% level of significance = 5.991

TABLE 3 COMPARISON OF ACTUAL VS. FORECASTED ACCIDENT DATA—RMS TEST

Range (Accident/Month)	n (# of observations	$\sum(\text{Deviation})^2$	RMS Error = $\sqrt{\sum(\text{Deviation})^2/n}$	Percent RMS Error
1450 - 1750	7	40,930	76.46	4.8%
1751 - 2050	7	321,434	214.28	11.3%
2051 and above	6	497,141	287.80	8.0%

lower percentile values) is also shown in Table 1. Although the increase in the width is not significant, there is a general trend toward an expansion of the confidence interval, as would normally be expected.

CONCLUSIONS

The purpose of this paper is to test the feasibility of using the Box-Jenkins method of time series analysis for forecasting truck accidents. Time series analysis is a technique by which the autocorrelation between sequential observations is analyzed and models are developed to produce forecasts. The authors used the ARIMA Method to develop the model because of the nonstationary nature of the data base. Also, the accident data used for developing the model reflected a strong seasonal component. This feature served as a strong motivation for using monthly accident data.

A total of 88 data points representing 88 monthly observations between January 1978 and April 1985 was used to develop the model. Two types of checks are presented in the paper to test the goodness of fit of the model. First, diagnostic checks were conducted to test the degree of correspondence between the observed data (used for model development) and the model output. This test indicated that approximately 70 percent of the autocorrelations are accounted for in the model. Second, the model was used to forecast monthly accident data for the 20-month period between May 1985 and December 1986 (data base not used in model development). The forecast data were then compared with the actual truck accidents observed during the same period. This test showed that in 18 of the 20 cases analyzed, the actual observations lie within the 95 percent confidence interval of the forecast values produced by the model. Further, in 15 of 20 cases, the expected values and the actual values are within 10 percent of each other.

In addition, two other nonparametric tests (chi-square and RMS) indicated excellent correspondence between the observed data and the model output. Because dependence of sequential observations is a basic assumption in times series analysis, an argument can be made against the use of this technique for accident prediction problems, because accidents are considered random events. However, when the data base reflects seasonal peaking (as in the case study presented), the feature of autocorrelation, although not necessarily reflecting dependence, may be effectively utilized in fitting a time series model. In the case study presented, the model developed appears to indicate a statistically significant correspondence between the observed data and the forecast values. This could be partly because of the seasonal peaking of the accident observations, indicating some degree of seasonal correlation, which may not necessarily be construed as dependence. The authors recommend further studies to test the feasibility of using time series techniques for accident forecasting problems.

Finally, a general comment is in order about the application of the ARIMA method in forecasting truck accidents. ARIMA models are designed to explain the stochastic autocorrelation structure of the series and to filter out any variance in the variable that is explainable on the basis of past history. The ARIMA method thus presents an advantage over standard regression techniques by implicitly taking into account autocorrelations within each variable rather than assuming that the error terms are independent (as is customarily done with ordinary least-squares regression) or by treating only the first-order autoregression. Wagenaar, in his article on the effect of macroeconomic conditions on motor vehicle accidents, has illustrated this point and has described how the above feature of the ARIMA method provides (*13*) "information on the time-ordered structure of the relationship, further increasing the degree of confidence in interpreting observed relationships in causal terms."

ACKNOWLEDGMENT

This paper is the result of research conducted at the Civil Engineering Department, Wayne State University, during 1987–1988. The authors thank the Michigan Department of Transportation and the Michigan Department of State Police for providing the necessary data base.

REFERENCES

1. G. E. P. Box and G. M. Jenkins. *Time Series Analysis, Forecasting and Control*. Holden Day, Inc., Oakland, Calif., 1970.
2. C. Chatfield. *The Analysis of Time Series: An Introduction*. Chapman & Hall, Ltd., London, 1985.
3. W. J. Campbell. Highway Safety Program Evaluation and Research. *Traffic Digest and Review*, Jan. 1970.
4. S. Khasnabis and C. L. Heimbach. Headway Distribution Models for Two-Lane Rural Highways. In *Transportation Research Record 772*, TRB, National Research Council, Washington, D.C., 1980, pp. 44–50.
5. A. Schuhl. The Probability Theory Applied to Distribution of Vehicles on Two-Lane Highways. In *Poison and Traffic*, Eno Foundation, Westport, Conn., 1955.
6. W. L. Grecco and E. C. Sword. Prediction Parameters for Schuhl's Headway Distribution. *Traffic Engineering*, Feb. 1968.
7. A. C. Wagenaar. *Alcohol, Young Drivers and Traffic Accidents: Effects of Minimum Age Laws*. D. C. Heath, Lexington, Mass., 1983.
8. A. C. Wagenaar. Preventing Highway Crashes by Raising the Legal Minimum Age for Drinking: The Michigan Experience 6 Years Later. *Journal of Safety Research*, Vol. 17, 1988, pp. 101–109.
9. A. C. Wagenaar, R. G. Maybee, and K. P. Sullivan. Mandatory Seat Belt Laws in Eight States: A Time Series Evaluation. *Journal of Safety Research*, Vol. 19, 1988, pp. 51–59.
10. R. Arnold. *Effect of Raising the Legal Drinking Age on Driver Inducement in Fatal Crashes: The Experience of Thirteen States*. National Highway Traffic Safety Administration, U.S. Department of Transportation, 1985.
11. *Background Report to the State Transportation Commission on Truck Safety Revenue and Taxation, and Truck Services and Highway Facilities*. Michigan Department of Transportation, Lansing, 1986.
12. *MiniTab Reference Manual: A General Purpose Data Analysis System*. MiniTab Inc., State College, Pa., 1988.
13. A. C. Wagenaar. Effects of Macroeconomic Conditions on the Incidence of Motor Vehicle Accidents. *Accident Analysis and Prevention*, Vol. 16, 1984, pp. 191–205.

The opinions and comments expressed in this paper are entirely those of the authors and not necessarily those of the Michigan Department of Transportation or the State Police.

Publication of this paper sponsored by Committee on Traffic Records and Accident Analysis.