TRANSPORTATION RESEARCH

RECORD

No. 1322

Safety and Human Performance

Large Vehicle Safety: Transit and Trucks 1991

A peer-reviewed publication of the Transportation Research Board

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

Transportation Research Record 1322
Price: $20.00

Subscriber Category
IVB safety and human performance

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Printed in the United States of America

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

Large vehicle safety : transit and trucks.
p. cm.—(Transportation research record ; no. 1322)
ISBN 0-309-05162-2
1. Buses—United States—Safety measures. 2. Trucks—United States—Safety measures. 3. Traffic accidents—United States. I. National Research Council (U.S.). Transportation Research Board. II. Series: Transportation research record : 1322.
TE7.H5 no. 1322
[TL242]
388 s—dc20 92-7775
[363.12′59] CIP

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Contents

Foreword

The topic of this Record is heavy-vehicle safety. The first three papers are about transit buses. The fourth paper concerns drug testing in the transit industry, but the methodology described may well be applicable in other types of transportation operations. The remaining four papers deal with truck accident data bases, accident rates, and risk and accident experience. These topics are of continuing concern to policy makers, state departments of transportation, and truck operators large and small.

Dusseau et al. describe a finite element computer model for the structure of a typical transit bus used by smaller cities and rural communities. The effect of seat belt use during sudden deceleration on structural frame and chassis members was examined with the model. In a related paper, Khasnabis et al. search the literature and describe the state of seat belt use, primarily on transit buses and secondarily on school buses. They discuss the safety and design implications of seat belts on buses. Using approximately 1,800 bus accidents, Jovanis, Schofer et al. identify injury patterns, accident types, and driver characteristics. Lerman describes the problem of disrupting operations with random drug testing in transit properties. The solution he presents is a weighted random sampling technique that allows constraints on the number of employees sampled yet maintains fairness in the probability of being sampled.

The research concerning trucks begins with the paper by Jovanis et al. Using cluster analysis, they found distinct multiday driving patterns that were associated with various levels of accident risk. Their data were drawn from less-than-truckload operations. Chira-Chavala presents procedures for estimating truck accident involvement rates and their confidence limits on the basis of the TRB-proposed National Monitoring System. Problems with prior multitrailer truck accident involvement studies are discussed by Mingo et al. They attempt to overcome sample size and reliability issues by using large national data sources to calculate overall involvement rates of various vehicle configurations. The paper is discussed by Glauz, and Mingo et al. provide a closure. In the concluding paper of this Record Lyles et al. study disaggregate truck accident rates by road class, day or night, and urban or rural operating conditions for bobtail tractors and tractors with single- and double-trailer configurations. This study is of wide interest because Michigan has liberal long-standing truck size and weight regulations.

Impact of Seat Belts on the Structure of a Typical Transit Bus

RALPH A. DUSSEAU, SNEHAMAY KHASNABIS, AND THEODORE J. DOMBROWSKI

A finite element computer model was developed for the structure of a typical transit bus used by smaller cities and rural communities. Assumptions were made regarding the loading conditions of the bus in the event of a rapid deceleration of the bus. Parametric results for floor angles of 0 to 30 degrees at maximum bus deceleration were derived for two loading patterns: (*a*) with seat belts installed on all passenger seats and (*b*) with seat belts installed on the front passenger seats only. The results indicated that the structural members in the bus frame could experience moderate to substantial decreases in maximum stress if seat belts are installed on all seats, whereas the structural members in the chassis could experience moderate increases in maximum stress if seat belts are installed. Thus the presence and presumed use of seat belts on all passenger seats in the event of a rapid deceleration of the bus should moderately to substantially benefit the structural frame members of a typical transit bus, and the absence of seat belts should moderately benefit the structural chassis members.

A study is under way at the Department of Civil Engineering, Wayne State University, to assess the safety and structural implications of seat belt installation on a typical transit bus used by smaller cities and rural communities. One of the objectives is to determine whether changes in the structural members of the bus may be warranted to enable the structure to better withstand any additional accident-induced member stresses caused by the presence of seat belts. A computer-based finite element structural model of a fully loaded transit bus was developed to analyze the forces generated within the structural members of the bus because of the maximum expected deceleration applied to the mass of the bus passengers. Two loading patterns, with and without seat belts, were analyzed using a 20-*g* bus deceleration. The results were used to estimate the differential member stresses caused by the presence of seat belts as a function of the bus deceleration.

A comprehensive literature review conducted as a part of the project indicated little, if any, research into the behavior of the structural components of a bus following a sudden bus deceleration. Thus the analyses presented are to be considered the first that have been performed on a transit bus. The terminology concerning the components of a transit bus and the structural implications of a rapid bus deceleration with and without seat belts are discussed.

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

TERMINOLOGY

In the discussions that follow, "body" refers to the outer shell of the bus, consisting of the sidewalls and roof. "Floor" describes the plywood and metal deck upon which the passenger seats rest. "Frame" refers to the cold-formed steel members that support the body and floor and that are constructed by the bus manufacturer. "Chassis" describes the portion of the bus that supports the bus frame, engine, drive train, axles, and so forth and is built separately by a truck chassis manufacturer.

CRASH TESTS

Over the years, reports dealing with head-on crash tests of school and transit buses have concentrated on the visible damage to the buses tested. The three principle types of visible damage that have been reported are

1. Detachment of passenger seats from the bus floor (*1–4*),
2. Slippage of the bus frame-to-chassis connections (*1,5,6*), and
3. Buckling of the bus floor (*1,2,4*).

The connections involved in the first two types of visible damage tend to be unique to each transit bus design, are more easily corrected, and are not in general relevant to the overall structural integrity of a transit bus. The third type of visible damage is more a structural type of failure, however.

Most crash tests appear to have been done using buses with metal floors, although few researchers specifically mention the bus floor materials. Both the full-size school bus crash tests by the University of California, Los Angeles (*1*) and the crash tests of large transit buses by the General Motors Corporation (*2*) indicated that the bus floors "buckled" in head-on collision tests. This implies that the floors were made of metal, because plywood is expected to splinter, not buckle. The crash responses of the remaining structural components of the buses tested were not reported, however. Therefore, the goal of the present study was to analyze the potential for structural damage to a typical transit bus under rapid bus deceleration.

COMPUTER MODELING

One previously reported use of finite element computer modeling in the analysis of transit buses was a series of models

developed by DAF Trucks, Eindhoven, the Netherlands (7). The goal of these analyses was to measure the effects of bending stiffness and torsional stiffness on the dynamic responses and, hence, the ride comfort of bus passengers. Seven finite element models were developed, each using about 2,700 degrees of freedom. The major differences in these models centered on the designs of the lower sidewalls (the areas of the sidewalls below the windows) and the adhesive materials used to bond the windows to the bus sidewalls. Each model was analyzed to determine its fundamental natural frequencies. The natural frequencies were used to estimate the "comfort level" of the bus passengers. No analyses under simulated accident loads were performed, however. The goal of the study presented here was to use finite element computer modeling to analyze the potential for structural damage to a typical transit bus in the event of rapid bus decelerations (simulated front-end impacts).

MODELS AND ASSUMPTIONS

The thrust of the research has been to develop and analyze a finite element computer model of the structure for a typical transit bus used by transit agencies in smaller cities and rural communities. The model consists of the bus seats, plywood floor, steel frame, and steel chassis for the bus chosen. The model includes the deceleration forces generated by the mass of each passenger applied at the location of the average adult center of gravity (CG). The model was analyzed to determine the maximum stresses in each structural component of the bus under various loading conditions. The finite element code used in these analyses is the ANSYS finite element program, which is a product of Swanson Analysis Systems, Inc., Houston, Pennsylvania.

Transit Bus Studied

The transit bus that was analyzed is 25 ft long and has 13 passenger seats, for a total seating capacity of 26 passengers plus the driver. Longitudinal and transverse cross-section views of the bus seats, floor, frame, and chassis are shown in Figures 1 and 2, respectively. The seats are fabricated from cold-formed tubular steel and are supported by two inverted T legs bolted to the bus floor. The bus floor is composed of exterior grade plywood with steel strapping reinforcing along the lines where the seats are bolted to the floor and along the plywood seam that follows the centerline of the bus floor. Sheet metal reinforcing is also used in the tops of the rear wheel wells.

The bus floor is supported by lateral frame members, which are fabricated from cold-formed steel channels. The lateral

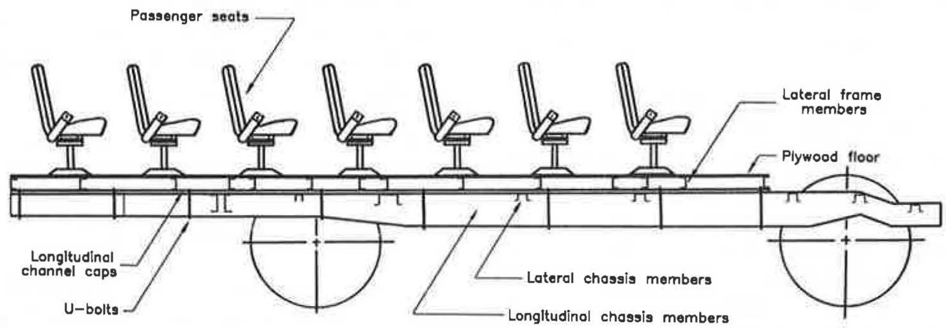

FIGURE 1 Longitudinal cross-section view of bus structure.

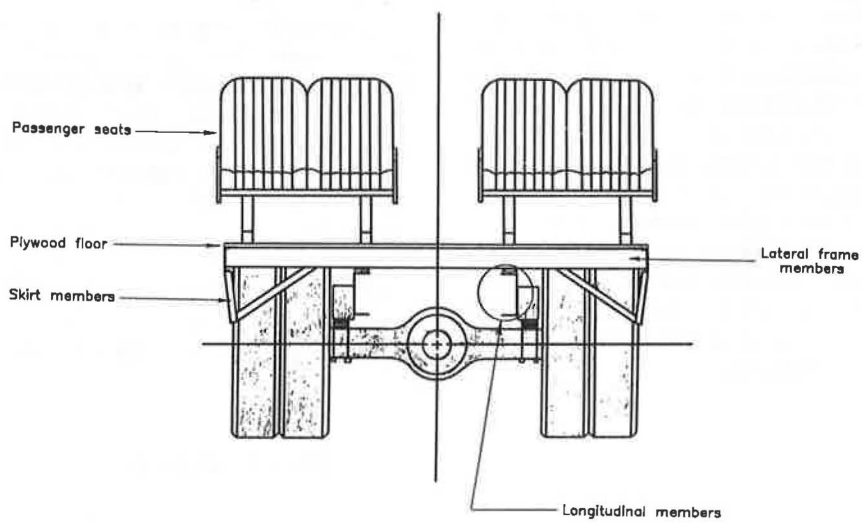

FIGURE 2 Transverse cross-section view of bus structure.

frame members run between the sidewalls of the bus and support the body, floor, and frame of the bus. Cold-formed steel members are also used for the side skirting and other frame members around the perimeter of the bus floor. The lateral frame members are welded to longitudinal channel caps, which are in turn attached to the chassis with U-bolts. The chassis is composed of two longitudinal members fabricated from cold-formed steel channels. The longitudinal chassis members are connected at intervals by lateral channel struts.

Simplifications and Assumptions

A perspective view of the bus model excluding the bus floor and seats is shown in Figure 3. The simplifications and assumptions that were made in developing the model were as follows:

1. To concentrate on the bus responses caused by the mass of the bus passengers under rapid deceleration (and hence the effects of seat belts), the following were excluded from the bus model: engine, drive train, air-conditioning unit, steering components, suspension components, and driver's seat. To further simplify the model and because the passenger seats are not bolted to the sidewalls, the sidewalls, backwall, and roof of the bus were not included in the bus model. In addition, the stairs, battery tray, and other steel reinforcing members that are not directly attached to the plywood floor were also excluded from the bus model.

2. The seats were each modeled using five semirigid (high-stiffness) elements as shown in Figure 4. The elements were arranged like a swing set, with one horizontal semirigid element connecting the nodal points representing the CG of the two passengers in the seat and two diagonal semirigid elements connecting each of these CG nodal points to the bus floor at or near the points where the actual bus seats are bolted to the bus floor.

3. The plywood floor was modeled using plate finite elements as shown in Figure 5. The plywood floor was modeled as continuous without any seams. Thus the steel strapping along the centerline of the bus floor was not included in the model. The steel strapping along the bolt line of the seats and the sheet metal reinforcing in the rear wheel wells were modeled using plate elements as shown in Figure 6. The steel plate elements are superimposed on an outline of the bus floor in Figure 6.

4. To maintain a maximum 2:1 ratio for the longest to shortest dimensions of the plate elements representing the plywood floor, steel strapping, and sheet metal, some nodes corresponding to seat bolt locations were moved longitudinally to coincide with node locations on transverse frame members. The nodes were moved in such a manner that the original spacings between bolts on each seat leg were unaffected.

5. The transverse frame members, perimeter frame members, and longitudinal channel caps were all modeled using beam finite elements as shown in Figure 3. For simplicity, the centroids of the beam elements were all placed in the same horizontal plane as the plywood floor and steel plate elements. To model the vertical offset between the lateral and perimeter

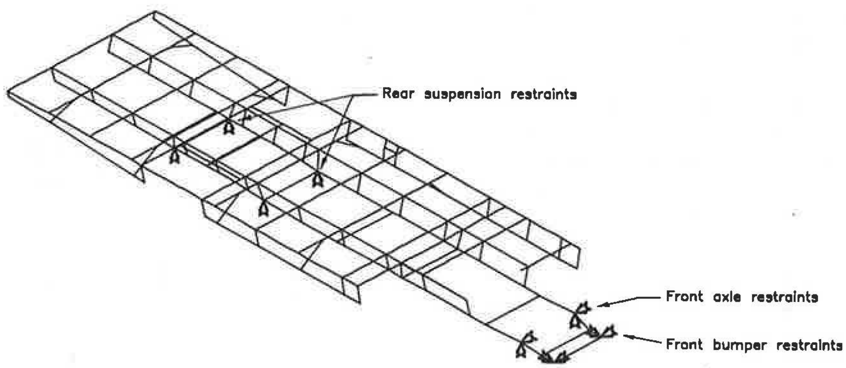

FIGURE 3 Bus model excluding floor and seats.

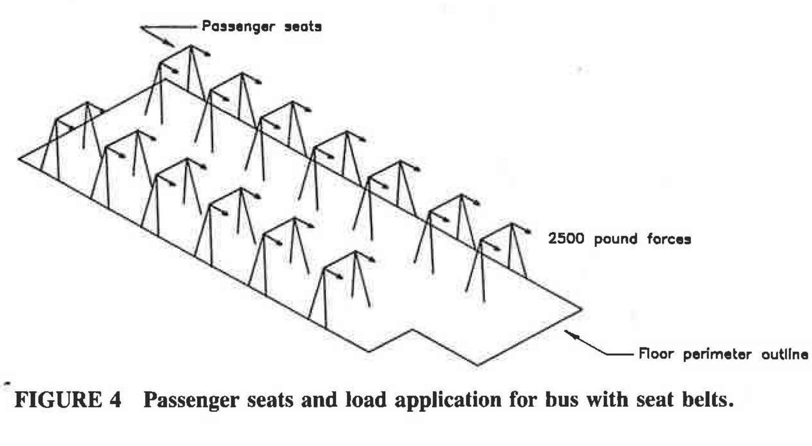

FIGURE 4 Passenger seats and load application for bus with seat belts.

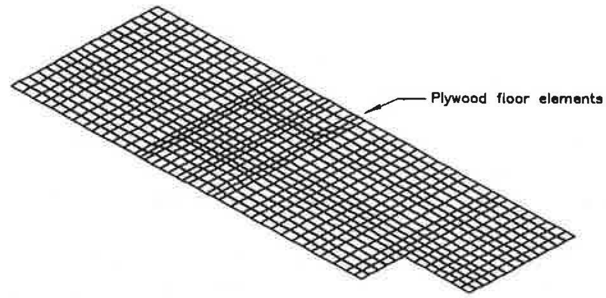

FIGURE 5 Plywood floor elements.

frame members and the plywood floor and steel plate members, 300 semirigid elements would have been required. These additional elements would have caused the model to exceed the storage capacity of the computer that was used in the analyses.

6. The longitudinal and transverse chassis members and the skirting members were also modeled using beam elements as shown in Figure 3. Figure 3 also shows semirigid elements that were used to connect the transverse frame elements with the centroid of the longitudinal chassis members at the points where the transverse frame members are welded to the longitudinal channel caps. Thus each longitudinal chassis member is attached to lateral frame members at 14 locations. In the actual bus, each longitudinal chassis member is attached to the corresponding longitudinal channel caps by eight U-bolt connections. Additional lateral-torsional buckling support for the longitudinal chassis members is provided by nine transverse chassis members. The maximum unbraced length of each longitudinal chassis member in the model is 26 in. versus 32 in. in the actual bus. Because this 32-in. distance is at the rear of the bus where the compressive forces in the longitudinal chassis members would be lowest under rapid deceleration, the effects of any increased buckling resistance of the model versus the actual bus should be relatively small.

7. The front leaf springs are assumed to "bottom out" in the event of a rapid bus deceleration. Therefore, as shown in Figure 3, the front of the bus was modeled with vertical and transverse pin connections at the points where rubber stops are attached to the longitudinal chassis members to prevent damage due to bottoming out of the front axle. Figure 3 also shows transverse and longitudinal pin connections that were used at the front of the longitudinal chassis members where the front bumper is attached.

8. Vertical pin connections were also used at the points where the rear leaf springs are attached to the longitudinal chassis members (Figure 3). The connections are necessary to prevent rigid-body motion of the bus model.

LOAD CASES

To simulate the loads generated by the passengers under rapid deceleration, a maximum force of 2,500 lb was assumed for each passenger, the same force required by the Federal Motor Vehicle Safety Standards (*8*) for testing bus seats. If an average passenger weight of 125 lb is assumed, the deceleration required to generate a 2,500-lb force is 20 *g*. The 2,500-lb forces were applied using seven different angles of the bus floor from 0 to 30 degrees at maximum bus deceleration. The bus floor angles were simulated by "tilting" the 2,500-lb forces as opposed to tilting the entire bus model. The vertical and longitudinal force components that were used to simulate each bus floor angle are given in Table 1.

The angle of the bus floor at maximum deceleration should remain below 5 degrees until the total vertical reaction forces at the rear axle pin connections exceed the maximum loaded weight of the rear axles. For the bus with seat belts this occurs at about 17 *g*, and for the bus without seat belts this occurs at about 15 *g*. At higher levels of maximum deceleration, the floor angle of the bus will exceed 5 degrees, and the total vertical reaction forces at the rear axle will exceed the maximum possible. Thus the member stresses in this region could have inaccuracies at bus decelerations greater than 17 *g* for the bus with seat belts and 15 *g* for the bus without seat belts.

The two seat belt configurations considered were (*a*) with seat belts installed on all passenger seats ("the bus with seat belts") and (*b*) with seat belts installed on the front passenger seats only ("the bus without seat belts"). The loading pat-

TABLE 1 LOAD CASES

Bus Floor Angle (degrees)	Longitudinal Component (pounds)	Vertical Component (pounds)
0	2500.0	0.0
5	2490.5	217.9
10	2462.0	434.1
15	2414.8	647.1
20	2349.2	855.1
25	2265.8	1056.6
30	2165.1	1250.0

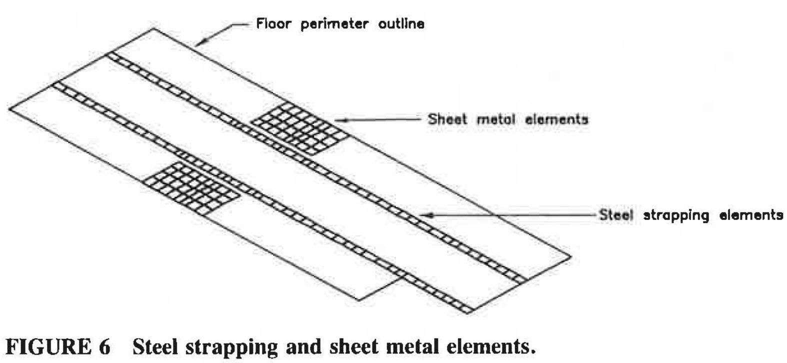

FIGURE 6 Steel strapping and sheet metal elements.

tern used to represent the bus with seat belts consisted of 2,500-lb forces applied to all nodes representing the CG of each passenger as shown in Figure 4. For the bus without seat belts, it was assumed that the forces of the unbelted passengers would be applied to the seat in front of each passenger. Thus, as shown in Figure 7, no forces were applied to the rear seats, 2,500-lb forces were applied to the nodes representing the CG of each passenger for the intermediate seats, and 5,000-lb forces were applied to the nodes representing the CG of each passenger for the front seats.

ANALYSIS RESULTS

The maximum stresses calculated for each element type due to the inertia generated by the bus passengers are given in Table 2 for the bus models with and without seat belts. The floor angles at which the maximum stresses are reached are also given. The longitudinal locations given in Table 2 are measured along the centerline of the bus model beginning at the rear and are normalized with respect to the length of the model. Thus the longitudinal location 0.000 refers to the rear of the model, where the rear bumper would be attached, whereas the longitudinal location 1.000 refers to the front of the model, where longitudinal and vertical pin connections represent the front bumper. The lateral locations given in Table 2 are measured from the centerline of the bus and are normalized with respect to the half-width of the bus. Thus the lateral location −1.000 refers to the left edge of the bus floor, and the lateral location +1.000 refers to the right edge of the bus floor, assuming the reader is facing the front of the bus. For each member type, the maximum and minimum differential member stress to bus deceleration ratios given in Table 3 represent the extreme values derived by calculating the largest and smallest differential member stresses generated for each load case (bus floor angle) for the model with seat belts versus the model without seat belts and then dividing these differential stresses by the 20-*g* bus deceleration. The corresponding floor angles are also given in Table 3.

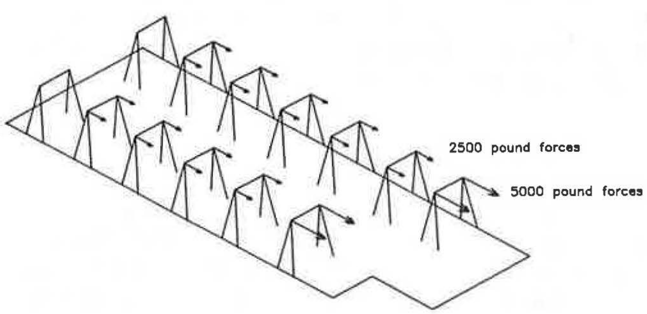

FIGURE 7 Passenger seats and load application for bus without seat belts.

Plywood Floor Elements

The maximum element stresses for the plywood floor elements versus the angle of the floor at maximum bus deceleration are plotted in Figure 8 for the bus with seat belts and for the bus without seat belts. The maximum stresses represent the principal compressive stresses in the plywood floor. The peak stress for the bus without seat belts is 20 percent higher than the peak value for the bus with seat belts. The peak stresses for both bus versions occur near the front passenger seat on the left side, and both occur with a floor angle of 0 degrees. For the bus with seat belts, the maximum stresses are essentially constant versus floor angle, whereas the maximum stresses decrease sharply with increasing floor angle for the bus without seat belts. The reason for the latter is probably a combination of the doubled loads on the front seats of the

TABLE 2 MAXIMUM MEMBER STRESSES AND CORRESPONDING ANGLE OF LOAD AND LOCATION

Description of Member	Model With or Without Seat Belts	Maximum Stress, ksi	Floor Angle, degrees	Location of Maximum Stress	
				Longitudinal	Lateral
Plywood Floor Elements	With	1.5	0	0.837	− 0.418
	Without	1.8	0	0.837	− 0.418
Steel Plate Elements	With	16.1	30	0.300	− 0.418
	Without	19.5	0	0.300	− 0.418
Lateral Frame Elements	With	31.0	0	0.746	− 0.472
	Without	58.2	0	0.746	− 0.472
Perimeter Frame Elements	With	62.0	0	0.194	+ 1.000
	Without	103.8	15	0.681	− 1.000
Skirting Elements	With	29.5	5	0.754	− 0.979
	Without	58.0	0	0.714	− 0.959
Longitudinal Chassis Elements	With	36.8	30	0.288	+ 0.368
	Without	29.0	30	0.577	− 0.368
Longitudinal Channel Cap Elements	With	23.9	30	0.259	+ 0.418
	Without	17.4	30	0.404	− 0.418

TABLE 3 MEMBER STRESS COMPARISONS FOR THE BUS WITH SEAT BELTS VERSUS THE BUS WITHOUT SEAT BELTS

Description of Member	Differential Member Stress to Bus Deceleration Ratios			
	Maximum Value, ksi/g	Floor Angle, degrees	Minimum Value, ksi/g	Floor Angle, degrees
Plywood Floor Elements	+ 0.03	30	- 0.02	0
Steel Plate Elements	+ 0.31	30	- 0.19	0
Lateral Frame Elements	- 0.50	30	- 1.35	0
Perimeter Frame Elements	- 1.90	0	- 2.30	30
Skirting Elements	- 1.15	30	- 1.40	0
Longitudinal Chassis Elements	+ 0.63	15	+ 0.28	0
Longitudinal Channel Cap Elements	+ 0.40	20	+ 0.16	0

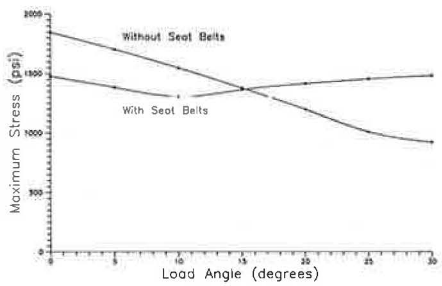

FIGURE 8 Maximum stresses for plywood floor elements.

bus without seat belts and the change in the longitudinal component of the applied loads. The maximum stresses in the bus with seat belts exceeds the maximum stresses in the bus without seat belts at floor angles above 15 degrees.

Steel Plate Elements

For the steel strapping and sheet metal elements, the maximum stresses versus the floor angle of the bus at maximum deceleration are plotted in Figure 9 for the bus versions with and without seat belts. For the bus without seat belts, the peak stress is 21 percent higher than the peak stress with seat belts. The peak stress for the former occurs at an angle of 0 degrees and declines sharply with increasing load angle. The peak stress for the latter occurs at an angle of 30 degrees and is essentially constant. The peak stresses for both bus versions occur near the seats located over the rear wheel wells. This is probably due to the discontinuity of the perimeter and skirting elements along the wheel wells, which tends to concentrate the longitudinal compressive stresses in the floor elements in this region. The relative changes in the maximum stresses for the steel strapping and sheet metal elements versus the angle of the bus floor at maximum deceleration are virtually the same as the changes in maximum stress versus floor angle for the plywood floor elements.

Lateral Frame Elements

Figure 10 shows plots of the maximum element stresses for the lateral frame elements versus the angle of the bus floor for each bus version. The peak stress for the bus without seat belts is 88 percent higher than that for the bus with seat belts. This is probably a result of the doubled loads on the front passenger seats of the bus without seat belts. The peak stresses for both bus versions occur near the front passenger seat on the left side, and both occur with a floor angle of 0 degrees. For the bus with seat belts, the maximum stresses are essentially constant. For the bus without seat belts, the maximum stresses decrease slightly with increasing floor angle. The decrease is probably due to the changes in the longitudinal components of the applied loads.

Perimeter Frame Elements

The maximum stresses for the perimeter frame elements versus the angle of the bus floor are plotted in Figure 11 for the

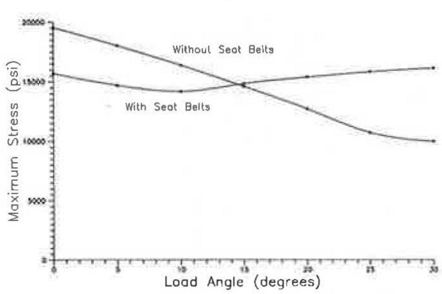

FIGURE 9 Maximum stresses for steel strapping and sheet metal elements.

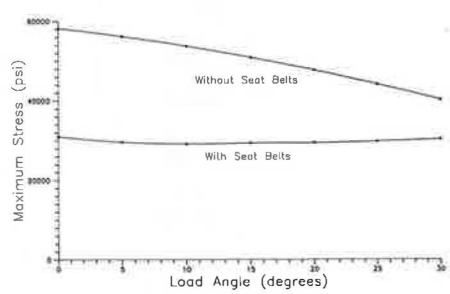

FIGURE 10 Maximum stresses for lateral frame elements.

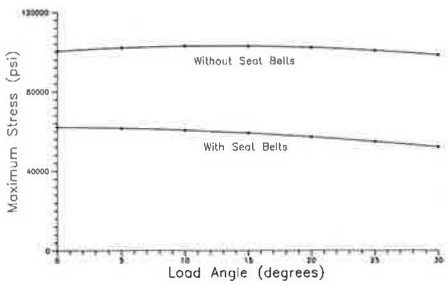

FIGURE 11 Maximum stresses for perimeter frame elements.

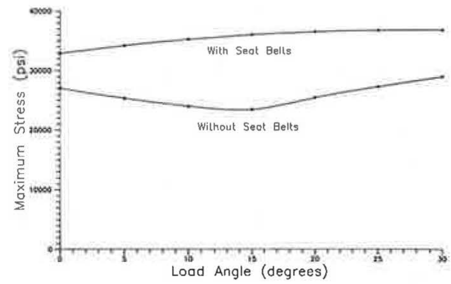

FIGURE 13 Maximum stresses for longitudinal chassis elements.

bus versions with and without seat belts. The peak stress for the bus without seat belts is 67 percent larger than the peak stress with seat belts. For the bus with seat belts, the peak stress occurs along the right side of the bus near the rear wheel wells. The peak stress for the bus without seat belts occurs near the left front seat. For both bus versions, the maximum stresses are essentially constant versus the angle of the bus floor. The peak stresses occur at a floor angle of 0 degrees for the bus with seat belts and at 15 degrees for the bus without seat belts.

Skirting Elements

For the skirting elements, the maximum stresses versus the floor angle at maximum bus deceleration are plotted in Figure 12 for the two bus versions. For the bus without seat belts, the peak stress is 97 percent higher than the peak value for the bus with seat belts. The peak stresses for both bus versions occur along the left side of the bus near the front seat, and both occur at a floor angle of 0 degrees. The maximum stresses are essentially constant versus the floor angle for both bus versions.

Longitudinal Chassis Elements

Figure 13 shows plots of the maximum element stresses for the longitudinal chassis elements versus the angle of the floor for the bus versions with and without seat belts. For the bus with seat belts, the peak stress is 27 percent higher than that for the bus without seat belts. The likely reasons for this difference are the vertical load components that are applied to the rear seats of the bus with seat belts. These vertical loads increase the bending stresses in the longitudinal chassis elements. The peak stresses for both bus versions occur with a floor angle of 30 degrees. For the bus with seat belts, the peak stress occurs on the right side near the rear wheel well. The peak stress occurs near the left front seat for the bus without seat belts. The maximum stresses increase slightly with increasing floor angle for the bus with seat belts and alternately decrease and increase for the bus without seat belts.

Longitudinal Channel Cap Elements

The maximum stresses for the longitudinal channel cap elements versus the bus floor angle are plotted in Figure 14 for the two bus versions. The peak stress for the bus with seat belts is 37 percent greater than the peak stress without seat belts. The reasons for the difference in the peak stresses and the changes in maximum stress versus floor angle are essentially the same as those discussed previously for the longitudinal chassis elements.

SUMMARY AND CONCLUSIONS

A finite element computer model was developed for the structure of a typical transit bus. Assumptions were made about the loading conditions of the bus in the event of a rapid deceleration of the bus. Parametric results for floor angles of 0 to 30 degrees at maximum bus deceleration were derived for bus loading patterns representing the cases with and without seat belts.

The results indicate that the lateral frame members, the perimeter frame members, and the skirting members could

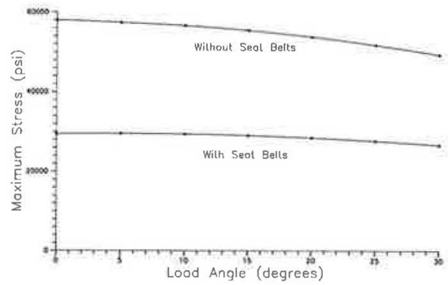

FIGURE 12 Maximum stresses for skirting elements.

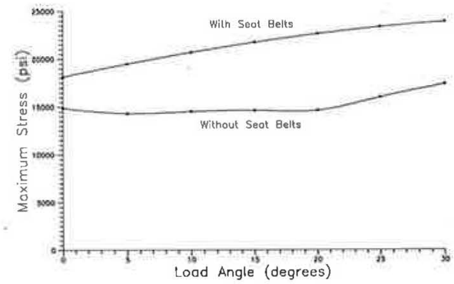

FIGURE 14 Maximum stresses for longitudinal channel cap elements.

all experience moderate to substantial decreases in maximum member stress of −0.50 to −2.30 ksi/g if seat belts are installed on all seats. The plywood floor members and the steel plate members could experience small decreases of −0.02 and −0.19 ksi/g, respectively, to small increases of +0.03 and +0.31 ksi/g, respectively, in maximum member stress if seat belts are installed. The longitudinal chassis members and the longitudinal channel cap members, which represent the backbone of the bus chassis, could experience moderate increases in maximum member stress of +0.63 and +0.40 ksi/g, respectively, if seat belts are installed. Thus the presence and presumed use of seat belts on all passenger seats in the event of a rapid bus deceleration should moderately to substantially benefit the frame members of a typical transit bus, whereas the absence of seat belts should moderately benefit the chassis members.

These concluding remarks pertain to the question of the integrity of the structure for a typical transit bus as it relates to the presence or absence of seat belts. A comprehensive literature review conducted as part of the project from which this paper was developed (not reported in this paper) indicates that researchers are divided in their opinions on the overall effectiveness of seat belts on transit buses in reducing severity of injuries. This question is beyond the scope of the present paper.

ACKNOWLEDGMENTS

This paper is the outcome of a research project currently being conducted at the Department of Civil Engineering, Wayne State University. The project is funded jointly by the U.S. Department of Transportation and the Michigan Department of Transportation. The federal funding was obtained as a part of the Great Lakes Center for Truck Transportation Research at the University of Michigan Transportation Research Institute, Ann Arbor. Matching support was also provided by the Institute for Manufacturing Research and the Graduate School, Wayne State University. The authors are grateful to all of these agencies for providing financial support for this study.

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The opinions and comments expressed in this paper are entirely those of the authors and do not necessarily reflect the policies, programs, or viewpoints of the agencies mentioned in the acknowledgments.

Publication of this paper sponsored by Task Force on Transit Safety.

Safety Implications of Seat Belts on Transit Buses

SNEHAMAY KHASNABIS, RALPH A. DUSSEAU, AND THEODORE J. DOMBROWSKI

The findings of a literature search on seat belt installation for passengers on buses are summarized. The emphasis was on transit buses, but school buses were included. The literature search focused on three major areas: legislation, the effectiveness of seat belts, and any related aspects. The legislation portion dealt with the appropriate Federal Motor Vehicle Safety Standards as well as any state or federal laws that pertain to seat belts or passenger restraints on buses. The portion on the effectiveness of seat belts dealt with crash-testing studies and examined the epidemiological implications, accident analysis, likely seat belt usage, and the seating system as an integrated whole. The related aspects covered seat belt design options, seat design, seat design loads, other current seating options, seat anchorage design, bus floor structure, and bus-to-chassis connections. In addition, a survey was made of transit agencies in the United States and Canada to determine the current state of seat belt use. None of the agencies responding to the survey currently require seat belt installation. Overall, the findings tend to be inconclusive; many research papers express conclusions both for and against seat belt installation on buses. However, researchers generally agree that it is not just a matter of installing seat belts on an existing bus design. The entire seating system must be tested as an integrated whole before a conclusive statement on the effectiveness of seat belts on transit buses can be made.

The question of safety implications of seat belts for the passengers of transit buses has not received much research attention. Though there is overwhelming evidence in the literature on the effectiveness of seat belts in reducing the severity of passenger injuries in accidents involving automobiles, little, if anything, is known about the safety implications of seat belts on transit buses.

A study is currently under way at the Department of Civil Engineering, Wayne State University, to assess the safety and structural implications of seat belts on transit buses. The study, jointly funded by the U.S. Department of Transportation and the Michigan Department of Transportation, has two primary objectives: (*a*) to assess the possible safety implications of seat belt usage in transit buses for reducing the severity of injury resulting from traffic accidents and (*b*) to determine whether major changes in the structural elements of the bus frame may be warranted to enable the frames to withstand the instantaneous stress buildup resulting from sudden activation of seat belts.

The study is being conducted in two phases. A review of the literature on seat belt legislation, usage, and accidents was conducted in Phase I along with a survey of representative transit agencies. In addition, a computer-based structural model was developed to analyze the forces likely to be generated within the bus frame components when seat belts are actuated on a fully loaded transit bus. The primary objective of the computer model is to identify "weak links" in the structural components of the bus frame that may be vulnerable to the stress buildup when seat belts are actuated. The broad purpose of Phase II, likely to be initiated during the latter part of 1990, is to conduct a set of experimental tests to validate the computer model and to recommend means to improve the structural integrity of the bus frame.

As part of the study, a search of the relevant literature on transit seat belts was conducted to determine the level of knowledge on this topic. The emphasis was on seat belt installation, but the literature search included papers that contained related information. A summary of the literature review is presented in this paper, focusing on three primary topics: seat belt legislation, the effectiveness of seat belts, and additional aspects related to seat belt installation. Much of the literature found and presented herein involves school buses. School buses must adhere to different and more stringent federal safety standards than transit buses and, therefore, have structural differences. However, it is believed that the dynamics during an accident are similar and that the safety concepts are equally applicable to the two types of buses.

BACKGROUND

The literature review revealed a set of historical developments concerning seat belt installation on transit buses in North America dating back to 1964 and continuing to 1989. In addition, the federal government, through the National Highway Traffic Safety Administration (NHTSA), an arm of the Department of Transportation, has developed standards for various vehicles and vehicular components, known as Federal Motor Vehicle Safety Standards (FMVSSs). The literature review indicated a number of such standards that pertain directly or indirectly to the question of seat belts on transit buses. A capsule summary of the historical developments and the safety standards follows.

Major Developments Concerning Seat Belts and Buses

The first uninstrumented school bus crash tests were performed in Arkansas in 1964 (no literature was found on these tests).

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

The first instrumented crash tests were performed on a large intercity bus by the General Motors Corporation (GM) in 1965 (*1*).

The University of California at Los Angeles (UCLA) performed crash tests on full-size school buses in 1966 (*2*).

UCLA followed up the 1966 crash tests in 1972 (*3*).

The Southwest Research Institute performed a major literature search concerning seat belts on buses for the California Highway Patrol in 1976 (*4*).

FMVSS 222, School Bus Passenger Seating and Crash Protection, was enacted in 1977 (*5*).

NHTSA performed sled tests on seat and seat belt designs in 1978 (*6*).

Transport Canada had crash tests performed on school buses in 1984 (*7*).

A company, Thomas Built Buses, had crash testing done on its buses in 1985 (*8–10*).

Transport Canada performed sled tests on various types of seats and seat belt configurations in 1986 (*11*).

Massachusetts and New York State enacted legislation requiring the installation and use of seat belts on school buses in 1986.

A provision of the Surface Transportation and Uniform Relocation Act authorized a study on school bus safety in 1987.

The National Transportation Safety Board (NTSB) released the study *Crashworthiness of Large Poststandard Schoolbuses* in 1987 (*12*).

The National School Bus Safety Act (H.R. 1815) was rejected in 1987 (*13*).

A study entitled *Improving School Bus Safety* was released by TRB in 1989 (*14*).

Summary of FMVSSs

A summary of the relevant FMVSSs for seat belt–related components that manufacturers must comply with is given in Table 1. Of the five standards cited in Table 1, FMVSSs 201, 208, and 222 address the question of occupant protection (*5,15,16*). However, none of these deal specifically with passengers on transit buses. FMVSS 210 is a continuation of FMVSS 208 dealing with the question of seat belt anchorage (*17*). FMVSS 207 concerns seating systems and experimental load tests (*18*).

LITERATURE REVIEW

The literature review of three major aspects of seat belts on transit buses—legislation, effectiveness, and additional aspects—is summarized as follows.

TABLE 1 SUMMARY OF FMVSSs PERTAINING TO SEATS OR SEAT BELTS

FMVSS #	Title	Description
201	Occupant Protection	Applies to buses with a GVWR of 10,000 pounds or less and provides for the testing of interior items (instrument panel, seat backs, interior compartment doors, and armrests) to simulate the impact of a passenger's head with a 6.5 inch diameter head form weighing 15 pounds.
207	Seating Systems	Defines the forces a seat (other than a side-facing bus passenger seat) must be able to withstand as well as the methods of applying test loads. A seat for which the standard does apply must be able to withstand a force 20 times its own weight in either forward or rearward longitudinal directions.
208	Occupant Protection	Requires the bus driver to have either a "complete passenger protection system" (i.e. a passive restraint) or a seat belt. Buses manufactured after September 1, 1990 must have an automatic locking retractor for the driver's belt. This standard sets forth requirements for types of seats, seat belts, belt latches, and arm rests as well as crash dummy specifications and test procedures. This standard does not set any requirements for bus passengers.
210	Seat Belt Anchorage Assemblies	Sets forth requirements for the seat belt assembly anchorages specified in FMVSS 208. The anchorage for a Type 1 (lap only) seat belt and the pelvic portion of a Type 2 (lap-shoulder) seat belt must withstand a 5000 pound force. The anchorage for a Type 2 seat belt must withstand a 3000 pound force.
222	School Bus Seating and Crash Protection	Sets forth requirements for school bus seating systems and restraining barriers. Vehicles with a GVWR of more than 10,000 pounds must meet only FMVSS 222. Vehicles with a GVWR of 10,000 pounds or less must meet FMVSS's 208, 209, 210, and 222. The seat back height is required to be 20 inches minimum as measured from the Seat Reference Point (SRP) to the top of the seat back. The SRP is defined by SAE Standard J826 as the point about which the human torso and thigh pivot. The seat back must not deflect forward more than 14 inches with a maximum applied load of 700 pounds nor should it deflect rearward more than 10 inches with a maximum applied load of 2200 pounds. The seat cushion should not separate from the seat when subject to a force five times its own weight. Maximum spacing between seats is 24 inches without a restraining barrier.

Legislation

Currently, the U.S. federal government requires transit and school buses to have seat belts in the driver's position only, as specified by FMVSS 208, Occupant Crash Protection in Passenger Cars, Multipurpose Passenger Vehicles, Trucks and Buses and FMVSS 222, School Bus Seating and Crash Protection (*5,16*). The rationale is that the driver must be properly restrained to be able to maintain control of the vehicle in the event of an accident. The requirement for passenger seat belts is left up to the individual states. The literature review indicates that no state requires the installation and use of seat belts by transit bus passengers at this time (*19*). Some states may require the use of seat belts if they are installed, but enforcement is given only secondary importance.

FMVSS 222 is based on a concept known as compartmentalization, which has an indirect implication for seat belts on school buses (*5*). By limiting minimum seat height, maximum seat spacing, and maximum seat deformation, a "compartment" is created, which restrains the passenger and limits the severity of the injuries sustained in an accident. The seat spacing must be no more than 24 in. as measured from a seat's reference point (SRP) to the back of the next seat. The SRP is defined by SAE Standard J826 as the point about which the human torso and thigh pivot. The seat back must be a minimum of 20 in. high when measured from the SRP to the top of the seat. FMVSS 222 also limits the deflection of the seat back, both forward and rearward. The seat back must deform forward a minimum of 6 in. and a maximum of 14 in. because of a maximum force of 2,400 lb. In the rearward direction, the deformation must not exceed 10 in. with a maximum force of 2,200 lb. This deformation limit, it was believed, allows the seats to deform sufficiently to absorb some of the force of impact while limiting the deflection so that the forces are distributed more evenly over the passenger's head and upper torso. Also, keeping the seat back relatively upright serves to keep the passenger from being forced over the seat and creating a domino effect. There are no similar federal standards for transit bus seats.

Only two states, Massachusetts and New York, require seat belt installation and usage by law for all school bus passengers as well as the driver. Maine requires seat belt usage on school buses only if they are installed by the manufacturer. In addition, New York and Illinois require school bus seats to have 24-in.-high seat backs (as measured from the SRP). At least one foreign country is known to require seat belts in transit buses. Germany requires seat belts to be installed in long-distance buses in only the most forward and rearward seating positions (*20*). Canada does not mandate any seat belts for either transit or school buses, although at least eight provinces require seat belt use if any are installed by the manufacturer (*7*). In addition, the Canadian Motor Vehicle Safety Standards are patterned after the U.S. FMVSSs and are virtually identical in content, format, and specifications. Therefore, any research study done in one country, either the United States or Canada, is equally valid in the other country.

In an effort to compile up-to-date information about seat belts on transit buses, a mail-back survey was conducted among a representative group of transit agencies (a total of 68) in the United States and Canada. The smallest agency owns 26 buses, and the largest has 2,624 buses. Three agencies in Canada and 52 agencies in the United States responded, a response rate of 81 percent. The questionnaire requested information on whether the agency operates buses equipped with seat belts or knows of any agencies that do, whether it has conducted or knows of any research studies involving seat belts, and the bus construction specifications used by the agency. None of the agencies responding currently own transit buses equipped with seat belts or know of any agencies that do.

Seat Belt Effectiveness

There appears to be little doubt that a properly designed automobile passenger restraint system reduces passenger injuries in the event of an accident. One might assume that the same holds true for buses. There is, however, considerable controversy about whether seat belts for transit bus passengers are effective or even desirable. Many questions have arisen concerning possible epidemiological complications, accident analysis, the expected voluntary seat belt compliance, and the seating system as an integrated whole.

Epidemiological Aspects

The possible epidemiological implications are the major source of controversy over seat belt use on buses. Some researchers believe that a seat belt could do more harm than good in three possible types of accidents: front-end, side, and rear-end.

A passenger not wearing a belt in a frontal impact tends to slide forward on the seat and strike the back of the next seat with the knees. Then the upper torso moves forward and strikes the back of the seat. "This results in the forces being spread more evenly over the upper torso" (*7*). On the other hand, a passenger restrained by a lap belt would bend forward and strike the top of the next seat with the head and chest. Thus the lap belt tends to decrease the forces on the lower torso but increase them for the upper body. Transport Canada concludes the following from its 1984 crash test:

> In general the results indicated that the belted dummies experienced higher head and lower chest accelerations than did the unbelted ones. Furthermore, from the film data [of the crash tests] the belted dummies experienced more severe neck extensions due to the angle at which they struck the seat ahead of them than did the unbelted ones. The neck extensions of several restrained dummies was judged to be life threatening. (*7*)

Weber and Melvin, however, question Transport Canada's conclusions about the neck extensions (*21*). Their major criticism concerns the lack of discussion or reference to the biomechanical justification for its judgment. Weber and Melvin state that "we do not believe that the Canadian School Bus Safety Study can be used to draw the conclusion that the use of belts on recent-model large school buses poses a potential danger to the occupants."

Opinions vary concerning the usefulness of a seat belt in a side-impact collision. After its crash tests, Thomas Built Buses concluded that "in the side-impact tests, compartmentalization appears to work just fine, and seat belts would not make any significant difference one way or another, as far as head or chest injuries" (*10*). In the absence of any other lateral support, a passenger with a lap belt could be bent over sideways and possibly suffer abdominal injuries. Ursell notes that

"the human body was not made to flex to a significant degree in the lateral direction and therefore considerable injury usually results from any severe deflections of the upper torso in the lateral directions" (*4*). On the other hand, Transport Canada notes that "in these types of accidents, a seat belt would aid in preventing possible ejection and being thrown around the interior of the vehicle" (*11*).

Few data are available on the implications of a lap belt in a rear-end collision. Severy et al. note that "lap belts should not be used for low seatback units because their use substantially increases the highly adverse forces to the spinal column resulting from whiplash" (*2*). However, they made their comments in 1967 before FMVSS 222 was enacted. There have been no known full-scale rear-end crash tests since 1966, and it is not clear how bus seats conforming to the current standards would perform.

An argument that has frequently been used against the installation of seat belts on both automobiles and buses is that the belt may trap the passenger in the event of an accident that leads to a fire or rollover. Transport Canada claims that "in such an emergency, which is a very rare occurrence, the belted occupant has a much greater chance of remaining conscious and alert" (*7*).

Despite the testing that has been done, opinions on whether seat belts should be used are still divided. Severy et al. state that "lap-type safety belts would provide substantial protection to the school bus passengers, seated in high back seats that have efficient padding on the rear panels of the backrests" (*2*). Wojcik and Sandes state that "for buses provided with safety seats having a performance profile comparable to the UCLA design, seat belts will contribute a significant measure of safety" (*3*). Ursell recommends "that seat belts not be installed in school buses, transit buses or farm labor buses" (*4*). Bayer concludes that "lap belts do not appear to have a significant effect on the response characteristics of a 50th percentile adult male dummy, for the test conditions" (*6*). Transport Canada refrains from making any final recommendation on seat belt installation. NTSB states in a recent report:

> [NTSB] does not recommend that Federal school bus safety standards be amended to require that all new large school buses be equipped with lap belts for passengers. The safety benefits of such actions, both in terms of reduced injuries for school bus passengers and in seat belt use habit formation, have not been proven. (*12*)

Finally, TRB writes in a recent report:

> The committee concludes that seat belts, when properly installed on large, post-1977 buses, are not inherently harmful and that they may reduce the likelihood of death or injury to passengers involved in school bus crashes by up to 20 percent. The committee further concludes that the overall potential benefits of requiring seat belts on large school buses are insufficient to justify a federal requirement for mandatory installation. (*14*)

In all of the crash tests performed, it was assumed that the seat belts were properly installed and adjusted. Transport Canada points out that "the effectiveness of a seat belt in reducing injury and death is, of course, dependent upon its proper use" (*7*).

Accident Analysis

Little information is available on the performance of seat belts in actual accidents. Buses tend to be involved in few accidents compared with automobiles, few of these accidents result in serious injury, and virtually none involve buses equipped with seat belts. TRB reports that "to date there have been no statistical or epidemiological studies of the effectiveness of lap belts on Type I school buses because of the relatively small number of belt-equipped buses involved in accidents" (*14*).

Most attempts at accident analysis involved determination, for bus accidents in which seat belts were not used, of the probable results had the passengers been wearing lap belts. This is the approach taken by NTSB (*12*), Stanisfer and Romberg (*22*), and Hatfield and Womack (*23*). The data for these studies involve comparisons with automobile accidents, bus crash tests, and sled tests rather than with other bus accidents. NTSB states that "arguments for and against lap belts on school buses cannot rely on passenger car data for an answer" (*12*). In addition, there is a lack of uniformity in the reporting of bus accidents. Therefore, there is a large measure of uncertainty in the results of these types of studies.

Estimated Seat Belt Compliance

Some researchers believe that the average voluntary seat belt compliance among bus passengers would be extremely low. Stanisfer and Romberg reported an average expected compliance rate of 10.9 percent and a maximum compliance rate of 17.6 percent (*22*). They based these values on surveys conducted by the National Association of Motor Bus Owners in 1965 and 1973. Because these studies were based more on opinion than experience and automobile seat belt laws have probably increased public acceptance of seat belts, the reliability of these predictions is in doubt. Both Transport Canada and TRB have examined school bus seat belt use in school districts that use them (*7,14*). The reported compliance varied from 20 percent in a district where usage is optional to as high as 95 percent in districts where usage is mandatory. However, seat belt usage tends to decrease as the child's age increases. Of course, experiences with children who are required to wear belts probably have little relation to the reactions of adult passengers on transit buses who were never required to wear belts on buses before.

In addition to mere resistance to the notion of wearing seat belts, transit bus passengers may find the seat belt installations to be inconvenient. Passengers making short trips may not take the time to buckle up, especially if they are carrying packages. A passenger sitting in the aisle seat would find it inconvenient to unbuckle to allow a passenger in and out of the window seat. The seat belt anchorages may protrude and be uncomfortable. The belts themselves, if they are of a nonretractable type, may hang on the floor and accumulate dirt, thereby discouraging their use. The belts and their latching mechanisms are easy targets of vandalism, which would render them inoperative. No matter how effective a seat belt might be, it is of little value if the passenger does not use it. For this reason, some researchers have recommended against the installation of seat belts (*4,20,22*).

Passenger Restraint System

Much of the literature points out that it is not enough to simply install seat belts on a bus. Ursell, in particular, points out that the passenger restraint system is an integrated whole, which includes such items as seat strength, seat height, padding, seat spacing, seat anchorages, seat belts, and bus body-to-chassis connections. He recommends against the installation of seat belts in buses until more thorough and comprehensive research has been done (*4*). Transport Canada reported:

> As a result of the crash tests (in 1985), the need to investigate the entire seating system became apparent. It was not just a simple matter of adding a lap belt to a seat. (*11*)

In summarizing Bayer's test results (*6*), TRB notes:

> This finding emphasizes that any attempt to characterize the safety of school bus seats by a single factor (e.g., seat back height or seat spacing) is overly simplistic. The relative safety of a school bus seat is a function of several variables acting in concert. Among the variables of consequence are seat back height, spacing, padding, deformation characteristics, and the use or nonuse of a lap belt. (*14*)

Related Aspects

The installation of seat belts, as previously noted, involves the entire bus as an integrated passenger restraint system. The type of seat belt to be installed, the design of the seat itself, other seating options, and the magnitude of the load with which the seat is designed must be considered. The manner in which the seats are anchored, the bus floor structure, and the manner in which the bus body is connected to the chassis are also important.

Seat Belt Design Options

The type of seat belt to be used should be considered seriously. Most studies have concentrated on the lap belt only, perhaps because it is the simplest to install. Severy et al., however, state that "the cross-chest lap-belt combination when properly fitted provides significantly more passenger protection than does the use of only a lap belt" (*2*). The Thomas Built Bus crash tests of 1986 appear to verify this conclusion (*9*). However, Severy et al. go on to recommend against the use of such belts in school buses. A shoulder belt, to be of maximum value, must lie across the chest. If a belt designed for an adult were used by a child, it would lie across the neck and could cause more injury than it would prevent. Shoulder belts can also cause "submarining," in which the passenger slides out from underneath the belts. However, submarining would be less of a problem on bus seats than on the relatively softer automobile seats. Adequate anchoring of a shoulder belt is an even more serious problem. The upper part of the belt would have to be attached to the seat back, at least for the aisle seat. Because FMVSS 222 not only allows but also requires a certain amount of seat back deformation under a given load, the shoulder belt would not be capable of serving its function on current seats unless the seat back were considerably strengthened. Transport Canada observed:

> It must be emphasized that if seats with lap and shoulder belts are installed in buses, it is imperative that the belts be worn at all times. Otherwise, any injuries due to unrestrained occupants striking the seat back would be more severe than with an existing seat due to the increased seat rigidity. (*11*)

The type of adjustment and locking mechanisms should also be considered. Severy et al. recommend a "retractable, inertial-lock mechanism" (*2*). Ursell also specifically states that "only retractor type belts should be used on buses" (*4*). Most recently, Transport Canada states that "all belts should be adjustable by means of an emergency locking retractor" (*24*). Transport Canada also concludes that "it is felt that manual belts are too prone to being improperly adjusted to be considered for use" (*11*). However, it warns that "the retractors should be protected to prevent destruction under impact conditions" (*11*). FMVSS 208 requires that bus drivers have a belt with either an emergency locking retractor or an automatic locking retractor for vehicles manufactured on or after September 1, 1990 (*16*).

Seat Design

Seat design is a concern whether seat belts are installed or not. Criteria that must be considered include seat dimensions, seat spacing, padding, armrests, and even the direction the seats face.

As previously noted, FMVSS 222 sets seat back height on school buses at 20 in. above the SRP. Severy et al. repeatedly recommend that the seat back height be a minimum of 28 in. to prevent whiplash (*2*). They go on to recommend against the installation of seat belts on any seat that is less than the specified 28 in. (*2*). However, TRB points out that the UCLA researchers measured their seat backs from the top to the base rather than to the SRP. If measured from the SRP, their seat back would be between 24 and 25 in. high (*14*). TRB currently advocates raising the height of seat backs in school buses to 24 in. and in a recent report states:

> The committee believes that the operational objections to higher seat backs have not been supported by field experience and that they can be installed in a manner consistent with NHTSA standards. (*14*)

Seat spacing can also influence seat belt effectiveness. Bayer studied the results of sled tests done with seat spacings of 20, 22, and 24 in. He concluded that "seat spacing appears to have only a minor effect on the response characteristics of the adult dummy and only a slightly higher effect on the child dummy" (*6*).

Seat padding is an extremely important design factor, because it can help absorb the force of a passenger's impact with the back of the next seat. The padding becomes even more critical if seat belts are installed because, in such a case, a passenger could experience greater forces in the area of the head and upper torso. Several of the papers examined mention the necessity of proper padding to dissipate these forces, but none went into detail on the design criteria that should be considered.

Severy et al. emphasize the benefit of having armrests for lateral support, even if they make entering the seats inconvenient. They recommend that "as a minimum requirement,

each school bus seat should have an armrest on the aisle side" (*2*). UCLA's follow-up crash tests in 1972 included a seat of its own design following the principles Severy et al. advocated after the crash tests of 1966. The seat consisted of a 28-in.-high seat back (by the UCLA method of measurement), an aisle side armrest, and a 3-in.-thick styrofoam head restraint pad. Wojcik and Sandes concluded that "for the side impact exposure, the UCLA armrest side restraint appeared to provide passenger protection as effectively as full use of lap belt restraints" (*3*). Other than these two reports, no mention of armrests has been found.

Some testing has also been done on rearward-facing seats as an alternative to conventional designs. UCLA performed crash tests on a full-size school bus with two rearward-facing seats in 1972. Wojcik and Sandes concluded that this type of seat "appears to offer no apparent safety advantage for either the head-on or the side-impact exposure" (*3*). Transport Canada performed sled tests on various seat designs, including rearward-facing seats with high seat backs and seat belts in 1987. It concluded, in contrast, that "this seat yielded the best results of all configurations" (*11*). Transport Canada subsequently fitted three school buses with high-backed, rearward-facing seats with lap belts and lent them to various school districts for evaluation (*24,25*). Overall, they experienced few real problems with this design except for some cases of nausea and driver complaints about the lack of rearward vision.

Other Current Seating Options

On current transit buses, besides using forward-facing seats, passengers are allowed to use side-facing seats or to stand. There is considerable controversy on how or if such passengers could be restrained. Although these topics are generally outside the scope of this paper, they are briefly examined in relation to a seat belt-equipped bus.

Several researchers have questioned the practice of using side-facing seats. Wojcik and Sandes state that side-facing seats "tend to compromise the safety of the passengers unless strong, well padded armrests are provided to protect passengers from head-on and rear-end collision forces and a high-back seat is provided to support the passengers' heads against the forces of side-impact" (*3*). Ursell states:

> Passengers in a side-facing position are subject to more damage or injury during an impact than those that are facing forward or facing aft. Seat belts on side-facing seats could withstand greater loads than those on the forward-facing seats because the side-facing seat belts could be attached directly to the side wall structural seat rail and easily withstand the seat belt loads. However, the side-facing passengers would be bent over sideways, either in a forward or aft direction and probably receive severe injuries if they were belted in place. (*4*)

Neither Wojcik and Sandes nor Ursell, however, specifically recommended against the use of side-facing seats. In any case, the necessity of providing room for wheelchair restraints in handicapped-accessible buses virtually demands the use of side-facing seats that fold out of the way.

The practice of allowing passengers to stand is also questioned by researchers. Severy et al. state that "the practice of transporting passengers in the aisle is dangerous and should not be permitted, especially for school bus passengers" (*2*). TRB claims:

> Passengers who are out of position during a school bus crash may sustain unnecessary injuries while endangering others as they are thrown about inside the passenger compartment. Several states have enacted laws that prohibit school bus operators from allowing passengers to stand in the aisle. In other states, standees are permitted when school bus seating capacity is exceeded. The committee recommends that all states prohibit standees on school buses operated by or for public or private schools. (*14*)

Transit buses, of course, frequently have standing passengers because of the short distance the passenger may be traveling and the large number of passengers such buses often carry. Ursell points out:

> When seat belts are installed this would be an automatic requirement for elimination of standees and therefore would increase the required number of operating buses and drivers as well as maintenance. (*4*)

One can argue that intercity transit buses travel at slow enough speeds that, given sufficient hand-held support, standing passengers should be able to support themselves adequately. Of course, such an argument would also negate the necessity of having seat belts in the first place. Also, transit buses do occasionally travel at highway speeds. In such a case, there could be legal ramifications should a standing passenger be injured while a seated passenger had the protection of a seat belt.

Interior projections, such as handrails, could be dangerous if a passenger is thrown against them. Severy et al. recommend that "tubular struts, protruding hand grips and similar protruding rigid structures should be eliminated" (*2*). However, because current practice generally allows standing passengers on transit buses, some sort of handrails are necessary. Therefore, Booz-Allen (*26*) conducted a study on the safety of transit bus interior design and reached the following conclusions:

1. On-board observations indicate that these rails (seat back handrails) are generally too low and poorly configured for effective use by standing passengers. Thus, current transit bus seat back grabrails are substantially inferior for passenger support compared with vertical stanchions.
2. All seats should be equipped with passenger assists at the aisle side, which provide the walking passenger with a nearly vertical bar to grab. The bar should be above the shoulder of a typical seated passenger, so that it is always available even in a crowded bus.

Seat Design Loads

The design load applied to a bus seat must be considered in both the design and testing phases. FMVSS 222 is specific about both the loads a school bus seat must withstand and the means of testing (*5*). Researchers, on the other hand, do not appear to agree on what the standards should be. LaBelle recommended that an acceleration of 10 *g* be used (*1*). Rompe and Kruger of Germany made no recommendations but used

accelerations of both 5 and 10 *g* in their studies (*20*). Severy et al., in contrast, recommended that the FMVSS require a design load of 30 *g* (*2*). This recommendation, however, does not appear to have any analytical basis and has never been implemented. Despite the conclusion of Severy et al., the UCLA researchers developed a seat using a 20-*g* design load for their 1972 crash tests (*3*).

Seat Anchorages

Crash tests by UCLA and GM, as well as studies of accident data, have indicated that some of the most serious injuries result from seats becoming detached from the floor. A seat is subject to forces whether from a belted passenger or a passenger striking the seat from behind. Therefore, a seat's anchorages must be able to withstand the force of impact whether seat belts are installed or not. Ursell notes:

> Pull tests of this type seat [wall mounted] indicate that it is much superior to the other types with all legs attached to the floor with respect to the forward direction. On the other hand, all types of structures have their shortcomings and in the event of a side impact on the bus wall, this wall mounted seat would receive a much higher acceleration. (*4*)

The wall-mounted seat supports experience smaller moments than the floor-mounted supports because of the shorter lever arm. No further studies have been found on seat pull-testing. Transport Canada notes that "the use of lag screws to attach seats and barriers to the bus floor appears to be inadequate for some vehicle designs" (*7*).

Bus Floor Structure

Although a large amount of research has been compiled on the testing of bus seats, little information is available on the performance of the floor itself. Contacts with a number of bus manufacturers and transit agencies indicate the dominance of two types of materials for bus floors: sheet metal and plywood. Plywood is by far the more common. Most of the crash and pull tests appear to have been done on buses with sheet metal floors, although few of the researchers specifically make mention of it. The UCLA and the GM reports both point out that the floors buckled in a front-end collision, thereby implying that the floors were made of metal (*1,2*). Plywood, in contrast, would splinter rather than buckle. Ursell, however, points out:

> The sheet metal floor pan is superior to the floor that uses only plywood. The plywood is subject to deterioration much more rapidly than the steel and as a bolt crushes into plywood, even with a large area washer, the bolt can eventually loosen up. (*4*)

He does not elaborate on the subject any further. Plywood does have the advantage of acting as insulation, thus making the interior of the bus quieter.

Bus-to-Chassis Connections

As a consequence of having all of the bus passengers belted in, the bus frame may be subjected to increased forces. One of the buses used in the UCLA crash tests displaced forward by 17 in. (*2*). Transport Canada reported displacements of up to 2 ft in its tests (*7*). Such a displacement would probably have resulted in the death of the bus driver. Severy et al. state that the "collapsing of the passenger compartment applies violent collision forces directly to the driver and passengers, even when they are adequately restrained" (*2*). Therefore, they recommended that "bus design should insure that the passenger compartment is securely attached to the frame of the bus by appropriately sized shear bolts at frequent intervals from front to rear along both frame members" (*2*). On the other hand, Thomas Built Buses crash-tested a bus in 1986 that was specially built with unitized construction, which in crash tests successfully reduced body displacement to ¾ in. (*8–10*). However, it is not clear whether any of these design changes has ever been successfully incorporated into production models or if such changes would adversely affect the safety of the bus passengers because of the increased stiffness of the bus structure.

CONCLUSIONS

This literature search was conducted to determine the current level of information available on seat belt installation on transit buses. Three areas were examined: legislation, effectiveness of seat belts, and additional aspects. In addition, a mail-back survey of a representative group of North American transit agencies was conducted to compile up-to-date information on seat belt installation.

Neither the U.S. government nor any individual state requires the installation and use of seat belts on transit buses except for the driver. In addition, no such legislation is known to be pending. No transit agency responding to the mail-back survey requires seat belt installation in its buses. Only two states, New York and Massachusetts, require seat belt usage in all school buses by law for all of the passengers as well as the driver. The only federal regulations for the testing of bus seats apply to school buses only and not to transit buses.

The findings concerning the effectiveness of seat belts on buses are inconclusive. Some research involving crash testing implies that a bus passenger who is restrained by a lap belt could experience dangerously high acceleration of the head and upper torso in the event of a sudden deceleration of the bus. However, a properly installed shoulder belt may reduce the severity of head injury in such cases. Some researchers believe that seat belt usage would benefit passengers by preventing them from being thrown around the interior of the bus and possibly ejected entirely. Accident analysis has been of little value in resolving the issue because of the relatively small number of serious accidents involving buses and the lack of correlation between automobile and bus accidents. Several early studies conclude that, even if seat belts are installed, voluntary usage would be small. Most researchers agree, however, that the installation of seat belts on buses requires a careful examination of the entire seating system.

The seating system includes, among other factors, the type of belt that is used, the design of the seat itself, the spacing between seats, the method of anchoring the seat, the design of the bus floor, and the method of attaching the bus body to the chassis. The lap-shoulder belt combination is generally accepted as superior to the lap belt only. However, the lap-

shoulder belt is unsuitable for installation on current buses due to the difficulty of adequately anchoring the shoulder belt. For any type of belt, an emergency locking retractor is generally considered to be desirable. Several researchers have advocated the use of seats with a 24-in.-high seat back (as measured from the SRP). One paper contends that a seat anchored to the wall of a bus is generally superior to one anchored to the floor. The same paper states that steel plate is superior to plywood as a flooring material. However, plywood is used more commonly because of its ease of workability and its sound-deadening qualities. Finally, several crash tests have demonstrated the potential problem of the bus body sliding along the chassis during a front-end accident and intruding on the driver's compartment.

Further studies encompassing the preceding factors are recommended to assess the entire seating system. Such an assessment will require comprehensive experimental studies involving crash tests and analytical modeling so that the effects of all the factors and their interactions can be determined.

ACKNOWLEDGMENTS

This paper is the outcome of a research project currently being conducted at the Department of Civil Engineering, Wayne State University. The project is funded jointly by the U.S. Department of Transportation and the Michigan Department of Transportation. The federal funding was obtained as a part of the Great Lakes Center for Truck Transportation Research at the University of Michigan Transportation Research Institute, Ann Arbor. Matching support was also provided by the Institute for Manufacturing Research and the Graduate School, Wayne State University. The authors are grateful to all of these agencies for providing financial support for this study.

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The opinions and comments expressed in this paper are entirely those of the authors and do not necessarily reflect the policies or programs of the agencies mentioned in the acknowledgments.

Publication of this paper sponsored by Task Force on Transit Safety.

Analysis of Bus Transit Accidents: Empirical, Methodological, and Policy Issues

PAUL P. JOVANIS, JOSEPH L. SCHOFER, PANOS PREVEDOUROS, AND KOJI TSUNOKAWA

Reports of approximately 1,800 accidents between 1982 and 1984 were analyzed to identify factors contributing to accidents involving mass transit buses. Data were provided by Pace, the suburban bus agency in the Chicago metropolitan area. Tactics that would enable Pace and similar agencies across the United States to do an even more effective job of safety management are identified. For the entire data set, 89 percent of the accidents involved collision with another object or person, and the remaining 11 percent involved passenger injuries while boarding, alighting, or moving about the bus. Severity levels were generally low; most accidents involved property damage only. Drivers of the other vehicle involved in the accident were much more likely to be injured than the bus driver: 10 percent of collision accidents involved automobile driver injuries, whereas bus drivers were injured in only 2 percent of the collisions. Despite the relative rareness of occurrence, clear patterns of injury have been identified. When the bus is in motion, 40 percent of automobile and bus driver injuries occur because of rear-end collisions. When the bus is stationary, 80 percent of the automobile occupant injuries occurred when the automobile rear-ended the bus. The analysis of bus drivers' attributes indicated that gender does not contribute to accident occurrence. Age appears to have a negative impact on accident involvement when experience is accounted for. Experience with the transit agency was strongly associated with accident occurrence (i.e., drivers with 3 to 6 years of experience at Pace were significantly overrepresented in accidents).

Vehicular safety is an important attribute of public transportation from the perspectives of both the operator and the passenger. To the operator, excessive vehicle accidents inflate costs in an industry already squeezed between limited revenues and high costs. The costs of accidents are multidimensional and may not always be apparent in a carrier's budget. Data from a 1973 study (*1*) suggest that safety costs are approximately 5 percent of agency operating costs. Components of those costs are not clearly described, however. Obvious costs are reflected in insurance premium rates and claims set-asides for partially self-insured carriers. Other costs, such as repair of vehicles damaged in accidents, excessive vehicle downtime, shortened vehicle life, road calls related to accidents, employee medical cost, and absenteeism, may be buried in a carrier's operating budget. In addition, transit accidents may affect ridership because of fears generated in potential users. This cost is measured in lost ridership and revenue.

P. P. Jovanis, Department of Civil Engineering and Transportation Research Group, University of California, Davis, Calif. 95616. J. L. Schofer, Department of Civil Engineering and Transportation Center, Northwestern University, Evanston, Ill. 60202. P. Prevedouros, Department of Civil Engineering, University of Hawaii at Manoa, Honolulu, Hawaii 96822. K. Tsunokawa, Economic Analysis Department, Japan Overseas Development Fund, 51-2-202 Cyodo-cho, 204 Funabashi-shi, Chiha-ken 273, Japan.

Accident statistics suggest that public transit, in general, is safe compared with other modes. Data from the National Safety Council (*2*) indicate that fatality rates for bus transit (per 100 million passenger miles) varied between 0.15 and 0.17 from 1974 to 1980. During the same period, automobile passenger rates varied from 1.40 to 1.30 and railroad passenger rates from 0.13 to 0.04.

These statistics indicate that, on a passenger-mile basis, bus travel has relatively low risk. Furthermore, as many as 63 percent of bus transit accidents involve no collision (*1*). These noncollision accidents have no parallel outcome for automobile accidents. If someone is injured while moving into or out of an automobile, the injury will not appear in a formal transportation accident report. These injuries are reported for transit, however, increasing apparent accident rates.

The key to improved understanding of accident causality lies in the careful analysis of past accident experience, in terms of both detailed attributes of samples of accidents and appropriate exposure measures for determining rates. A fundamental exploration of bus accident data is needed to understand the scope of bus accident experience. This paper focuses on a detailed examination of accident data in an effort to develop a set of testable hypotheses concerning accident causality.

OBJECTIVES

The objectives of this research are to develop refined measures of transit accident rates and to define a set of hypotheses concerning accident causation in public transportation. Refinement of measures of accident rates is essential to understanding where the industry stands today. It is also useful to explore the implications of conducting the analyses at different levels. Broad indicators of safety performance at the system level may be useful for some analyses. For others, route-level safety studies may be required. The search for causality in transit accidents, therefore, is likely to involve analyses at several levels. This paper reports on findings from such analyses.

When accident data bases are derived from accident reports collected in the field, they may be prepared for reasons only

weakly linked to operations management and the assurance of a safe transit system. For example, police accident reports tend to focus on simple explanations of causality in an attempt to assign unitary fault. A pilot study of child pedestrian accidents (*3*) determined that causal factors extend far beyond the immediate actions of the children or drivers involved; for example, environmental characteristics, neighborhood social patterns, family and life-style attributes, and physical and emotional states of the children appear to play major roles in the process. It is important to recognize the limitations of self-reported data when conducting any analysis.

Each time a vehicular collision or other type of accident occurs that results in a personal injury, fatality, or property damage, the transit operator completes an accident/incident report. The report typically contains a description of conditions at the accident scene, vehicle identification, driver attributes, and details of the event, including collision type and bus activity at time of incident. It is useful to consider this information in the broader context of a conceptual structure for accident causation.

To meet these objectives, we undertook a moderate-scale but detailed examination of the accident experience of a major bus transit carrier. Working closely with representatives of the carrier, we examined internal (and normally unpublished) accident records to formulate and conduct preliminary tests on a series of hypotheses concerning accident patterns and causation. We paid particular attention to the limitations imposed by available data and to alternative ways to collect more useful data.

RESEARCH APPROACII

The usefulness of this research was closely linked to the connection we were able to make with transit operators and their data bases. Otherwise, we would have faced the risk of using only published data, which is of a summary nature, and of developing hypotheses that may not lead transit managers to practical solutions to safety problems. Therefore, we established contact with Pace, a major public suburban bus operator that operates and contracts for services in a wide variety of communities in the Chicago region, ranging from extremely low-density hinterlands to routes penetrating the Chicago central business district (CBD). Pace managers expressed a willingness to cooperate with us in this effort, permitted us to use their accident records, and counseled us on directions for our work.

One of the most sensitive issues in bus transit safety research is a strong desire of transit agencies to protect the confidentiality of their accident records. In the course of eliciting support for this research project, the question of confidentiality recurred. Transit agencies appear to be concerned that

1. Analysis of safety (and accidents) may affect litigation on existing or future claims;
2. Analysis of safety data will be used to evaluate the agency's safety program (perhaps negatively);
3. Acknowledgment of the existence of transit safety data will ultimately lead to charges (whether rational or not) that the agency is not doing enough to correct safety deficiencies (these charges may influence litigation and public opinion); and
4. The identity of individuals involved in accidents and incidents be protected.

Whether these fears are real or imagined, it is clear that most transit agencies experience them. Rather than ignore this issue we dealt with it directly. During the analyses, we identified where, when, and how confidentiality questions arise. We discussed these issues in our interactions with participating transit managers and have identified how they may have limited our ability to analyze safety data and develop ameliorative policies.

CONCEPTUAL STRUCTURE

It is traditional to view the occurrence of a highway traffic accident as the result of the interaction of the driver, vehicle, roadway, and environment (*4*). This framework is useful because it provides the analyst with a structure to use in studying the causes of accidents. Urban bus accidents certainly fit within this framework with the additional complication that the risk of an accident is affected by characteristics of the transit service and agency policies (e.g., route design, driver safety incentives, etc.). Furthermore, bus operators are concerned with a significant number of noncollision passenger injury accidents (frequently called incidents). The outcomes of noncollision events have no parallel structure in the traditional highway safety field.

Potential interactions between some possible causative factors, accident risk, and accident outcomes are shown in Figure 1. The four traditional factors as well as transit service characteristics and agency policies interact to define a particular level of accident risk. This level results in a certain probability of having an accident; when combined with exposure to risk, this yields a certain number of accidents. If an accident occurs, it will either be a noncollision passenger accident or a collision accident of a particular type resulting in property damage, personal injury, fatality, or some combination of the three.

Certain boundaries were set for our safety investigations. Specifically, property damage or injuries resulting from crimes and acts of vandalism were excluded. These are deliberate acts of destruction and do not have the same etiology as "accidents" in a traditional sense. Unsubstantiated claims of injury or property damage were also excluded. Whereas a substantial number of these claims are processed by transit operators (*5*), there is considerable doubt concerning the occurrence of these events. To avoid this uncertainty, we decided to focus our attention only on accidents reported by transit agency personnel.

It is best to consider the conceptual framework in the light of what is already known about highway and transit safety. Driver characteristics and their contribution to accident occurrence have been broadly studied in the highway safety field (*4*), but findings that apply directly to the transit industry are limited. Reports from other metropolitan areas (*6*) identify the age and experience of accident-involved drivers but do not compare them with distributions of characteristics for the entire transit driver population. Studies of age and experience of drivers involved in accidents are of limited utility if such a

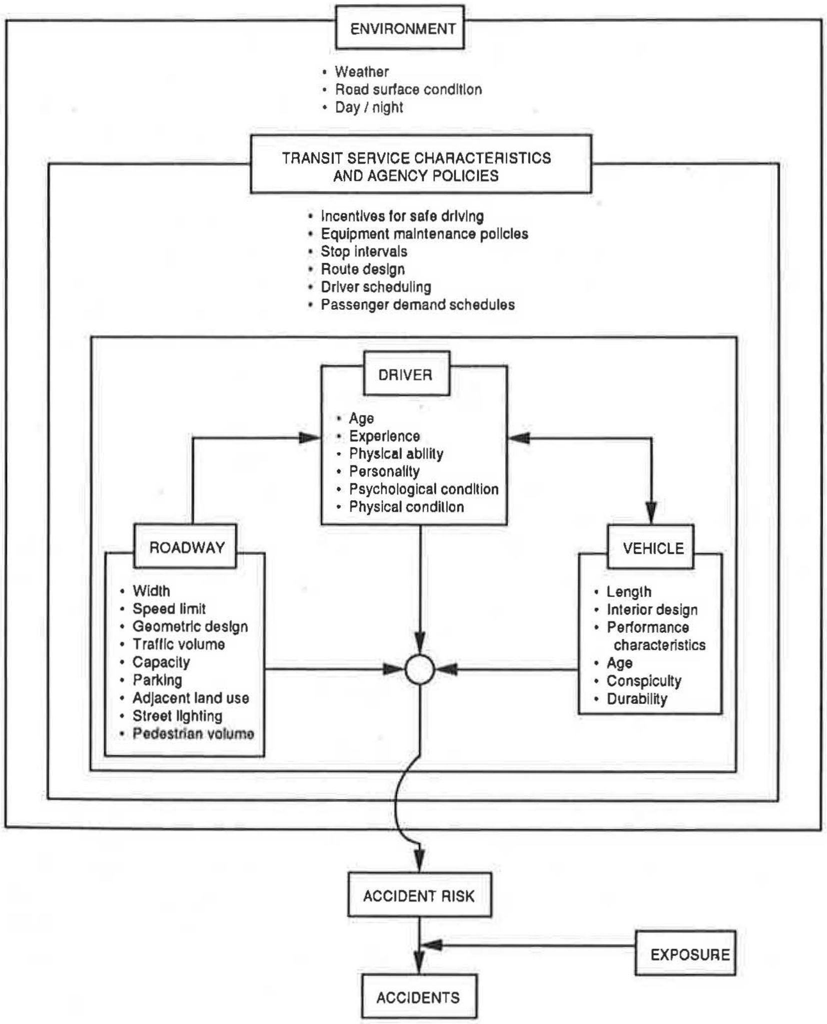


FIGURE 1 Conceptual structure of bus transit safety research.

comparison is not made. For example, a study of truck accidents for several national carriers (*7*) indicated that drivers with less than 1 year of experience are involved in six times the number of accidents that one would expect on the basis of their proportion in the population.

Conversations revealed a belief among transit industry officials that accident rates are highest for first-year drivers, drop for second- through fifth-year drivers, and then rise again. We tested the validity of this belief by comparing the experience of accident-involved drivers with the population of transit drivers. Age can act as a surrogate for physical ability, so we included comparisons of the age of the driving population with the ages of drivers involved in accidents.

Personality, psychological condition, and physical condition at the time of the accident (e.g., drug or alcohol impairment) are difficult to assess without special studies. These factors are discussed in the broad highway safety literature (*8*), although there are no findings that relate them directly to the transit industry. We recognize that these factors are important in accident occurrence, but they are beyond the scope and resources of this study.

Vehicle attributes affect accident occurrence in two ways. First, the handling attributes of the bus affect the driver's ability to take corrective or evasive action when presented with a threatening situation. Vehicle age may affect handling characteristics, and they may vary for different types of buses (e.g., articulated and standard coach). Vehicle-handling characteristics may be particularly important in restricted geometries, heavy traffic, inclement weather, or combinations of these conditions. Second, vehicle attributes affect other drivers, passengers, and pedestrians. Vehicle conspicuity to drivers and pedestrians may affect accident occurrence, particularly at night. Bus interior design may affect the probability (and severity) of noncollision passenger accidents.

Roadway characteristics affect the occurrence of potential accident situations as well as the ability of the driver to maneuver to avoid the collision. Roadway and lane width, geometric design, traffic volume, and parking represent factors that can increase the risk of an accident by increasing opportunities for collisions and reducing opportunities for avoidance. The character and activity level of adjacent land uses determine the amount of pedestrian traffic, which could con-

flict with bus operations. Driveways and cross streets intersecting the bus route also represent opportunities for collisions. Street lighting levels could affect accident risk. The speed limit may affect accident risk by reducing the reaction time available to the driver.

Environmental conditions, including weather (*9*), road surface (*9*), and lighting conditions (*10*) are significant factors in accident causation. Weather conditions may have a smaller effect on bus accidents than automobile accidents because the bus driver is a professional who should be better able to cope with adverse driving conditions. Studies of truck accidents (*11*) tend to support this contention.

In the identification of accident causes (and, eventually, countermeasures), it is useful to separate the four traditional factors mentioned previously from those largely controlled by the transit agency. The existence of a variety of incentives may influence driver behavior and thus accident risk: bonuses, salary increases, and even promotions tied to a good safety record may act as positive reinforcement for safe driving. Driver scheduling may interact strongly with experience, because the most experienced drivers have priority in their choice of runs; they may choose runs that are shorter or less prone to risk. Equipment failure is one cause of vehicular accidents that is directly influenced by an agency's maintenance policies. There may be an indirect effect on driver attitudes if buses are not clean and well maintained. Route design and layout may influence accident risk.

In exploring the factors that may cause bus accidents, it is useful to keep in mind the opportunities for intervention in the accident causation process. These opportunities should be the focus of the inquiry, because several safety studies make it clear that some factors will be outside the control of policy makers, managers, and operators.

DATA COLLECTION AND CODING

Pace is a public agency that both operates direct bus services and contracts for services with carriers and municipalities. Services are provided by Pace for the Chicago metropolitan area, excluding the city of Chicago. Services include collector-distributor hauls to fixed rapid transit and commuter rail stations, local community and intercommunity services, and some express runs from the suburbs to Chicago's business district. Until 1983 Pace was a suburban bus division of the Regional Transportation Authority (RTA). Since that time Pace has become a separate entity subsidized by RTA.

We used data from four contractors of Pace: (*a*) Nortran, which serves the northwest suburbs, (*b*) West Towns, which serves the near-west suburbs, (*c*) Oak Lawn, which serves the near-southwest suburbs, and (*d*) Harvey, which serves the south and far-south suburbs.

Our data from Pace come from two sources: accident/incident reports and descriptions of individual bus routes. From the first source we collected all the information pertaining to an accident or incident occurrence. To shield the identity of individuals from our research team, RTA required that personal information, such as names, addresses, and telephone numbers, be concealed during photocopying of accident reports. Because this information is not essential to the analysis of broad accident trends, it did not hinder our subsequent activities.

The second source provides information about route service that is important in identifying the contribution of route characteristics to accident occurrence. From Pace's *Bus Route Descriptions* (*12*), we were able to get useful operational profiles for each route. Information included route length, duration of trip, revenue miles, bus requirements (peak and off-peak), number of trips, and average headways. Some of these pieces of information were useful in creating exposure measures.

For the collection of data concerning the road and roadside characteristics, we used a computer printout detailing the name of the street each bus route follows as well as the streets intersecting the route. We drove each route and collected information block by block for each of 10 routes served by Nortran. Further details of this data collection and coding are contained in the project final report (*13*). Data from a variety of sources were required to conduct this research study. Whereas some were provided by Pace, important engineering data concerning the routes were almost completely lacking. Data from the service provider must be integrated with roadway and environmental data from other public agencies for a comprehensive analysis of bus accident causality.

DATA ANALYSIS

Overview

The approach we adopted for conducting our empirical analysis was to explore available data from several perspectives, using qualitative (graphical) analysis, correlation, regression, and, where appropriate, more sophisticated modeling.

At the system level we used all the accident/incident report data collected from Pace and conducted an in-depth analysis aimed at the identification of the distribution and effects of various factors. The distribution of accidents with respect to time, the distribution of the types of accidents (alone or conditional), the driver's characteristics, and the effect of environmental factors such as weather, type of traffic control, and so forth were identified.

At the route level, we tried to identify the effect of route-specific operational characteristics, such as ridership, type of area (i.e., CBD or suburban) the route crosses, headway, trip frequency, annual revenue miles, and so forth. Finally, we analyzed the accident propensity of bus drivers. This was based on the hypothesis that the ability of a driver to avoid accidents follows a learning curve.

System-Level Analyses

This section presents the results of the analysis of the accident data at the system level. The data base contains information on the accidents that occurred during the 3-year study period (1982–1984) among the four Pace subsidiary companies (Harvey, Nortran, Oak Lawn, and West Towns). After screening out unreliable or questionable accident reports and verifying the completeness of data contained in the reports, we developed a data base of approximately 1,800 accidents. Of these accidents, 1,600 (89 percent) were collision accidents, and the rest (11 percent) were noncollision passenger accidents. The percentages are approximately the same as those reported in a British study (*14*).

Overview of Accident Characteristics

Figure 2 shows the yearly occurrence of collision accidents for the 3 years. It does not show any distinct trend of accident frequency during the period, but it shows a dramatic decrease in noncollision passenger accidents in 1984. However, this appears to be due to a lack of reporting of noncollision accidents for the last 2 months of 1984. We have been unable to obtain the additional reports, but it is unlikely that they would change our interpretation of the data.

Figure 3 shows the monthly occurrence of collision accidents by year. Accident frequency may be hypothesized to be correlated with weather conditions and thus display an annual cycle, but such a hypothesis is not supported by the data.

Figure 4 shows the distribution of accident occurrence by time of day for each type of accident. Both distributions have four peaks: two high peaks at morning and evening rush hours (6:00–8:30 a.m. and 3:30–7:00 p.m.) and two low peaks occurring around 10:00 a.m. and 2:00 p.m. The peak periods in the morning and evening rush hours for noncollision passenger accidents are narrower than those for collision accidents, displaying higher concentration of the occurrences, which is probably connected with ridership levels. The spikes at 11:00 a.m. and 2:00 p.m. coincide with shift change times for drivers. Limitations in data precluded further analysis of this phenomenon, but it would be of interest to see whether the accidents were more common for drivers who had recently changed shifts.

Analysis of accident locations indicates that, not surprisingly, 70 percent of the collision accidents occur at intersections, whereas 30 percent occur at some other location; the corresponding percentages are 80 and 20, respectively, for noncollision passenger accidents. The observation that a high concentration of noncollision passenger accidents occurs in

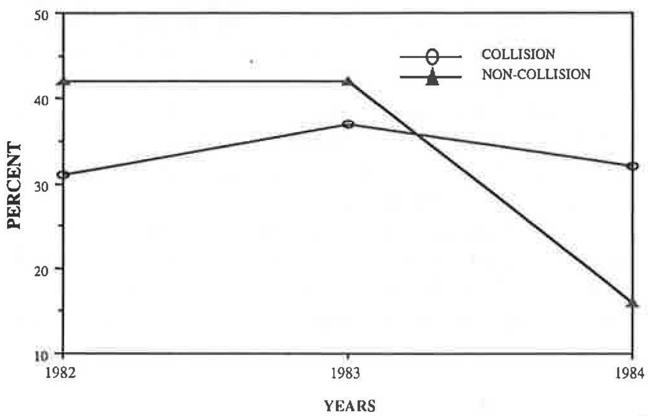


FIGURE 2 Collision and noncollision accidents.

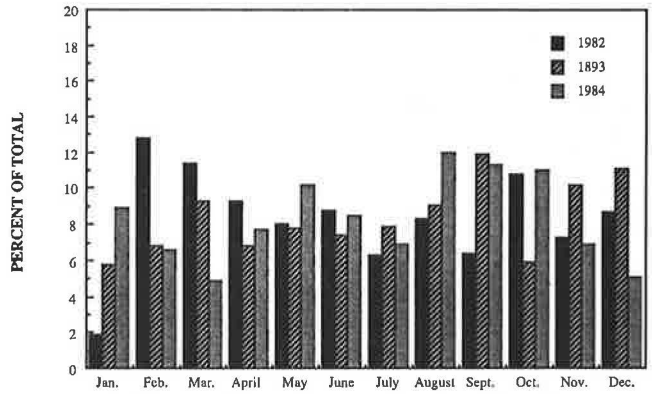


FIGURE 3 Monthly distribution of collision accidents.

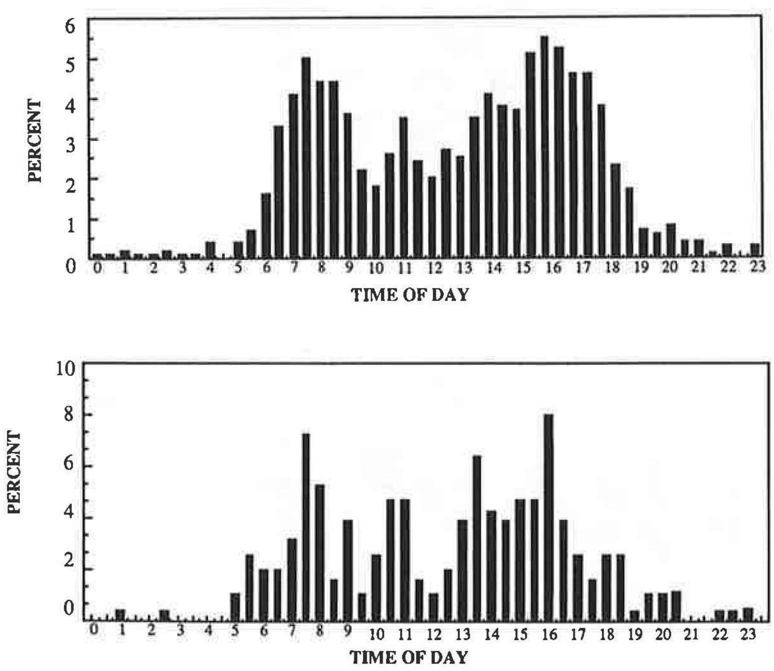


FIGURE 4 Hourly distribution of accidents: *top*, collision; *bottom*, noncollision.

the vicinity of intersections is consistent with the fact that 55 percent of passenger accidents occurred when passengers were either boarding or alighting buses (Figure 5).

Figure 6 shows the proportion of collision accidents by type of occurrence. The two most common collision types are sideswipe (34 percent) and rear end (25 percent). These are followed by right angle (10.5 percent), passenger injury (9 percent), and left angle (7.5 percent).

Driver Characteristics

Figure 7 (top) shows the age distribution for RTA drivers involved in each type of accident. If this age distribution is representative of the driver population for the 3-year study period, the figure indicates the following: drivers in their 20s are only slightly (approximately 2 percent) overrepresented in accidents compared with the population distribution, and drivers in their 50s are slightly (2 percent) underrepresented. Furthermore, bus drivers in their 30s are overrepresented in accidents with other motor vehicles; bus drivers in their 40s and 50s are slightly underrepresented in these collision accidents. Because the distribution in Figure 7 is not adjusted by relevant exposure measures (e.g., route or vehicle miles), these findings are tentative. However, the comparison between these two distributions indicates an age-related difference between proneness to collision accidents and noncollision passenger accidents.

Figure 7 (bottom) shows the sex distribution of RTA drivers who were involved in each type of accident. Both distributions have 90 percent male and 10 percent female drivers, so there appears to be no sex-related difference in accident rate.

Figure 8 compares the seniority distributions for drivers from the four RTA subsidiaries with those involved in each type of accident. The comparison indicates that drivers with 3 to 6 years of service are substantially overrepresented in accident involvement. The opposite is true for drivers with 9 to 11 years of service. Drivers with more than 18 years of experience are moderately underrepresented in the accident involvement population. Caution must be exercised in interpreting these findings, because the seniority distribution for all drivers is not adjusted by appropriate exposure measures.

These findings are particularly interesting because they appear to substantiate the perception of Pace safety officers that the group of drivers with 3 to 5 years of experience is particularly prone to accidents. Targeted driver retraining and education activities may reduce this apparent overrepresentation.

The incidence of injuries in bus crashes is very low. Only a small proportion of RTA drivers (less than 5 percent) are injured in collisions; the percentage is virtually zero while the bus is stationary. Automobile drivers are injured in only 10 percent of the accidents and more often (relatively) when the bus is in motion. We can speculate that this is due to the large difference in mass between a bus and a car.

Despite their comparative rareness, we sought to develop a better understanding of the etiology of injury accidents. Figure 9 shows that, for both RTA drivers and other drivers, more than 40 percent of driver injuries in collision accidents that involved RTA buses are caused by rear-end collisions. Automobile drivers are also slightly more likely to be injured

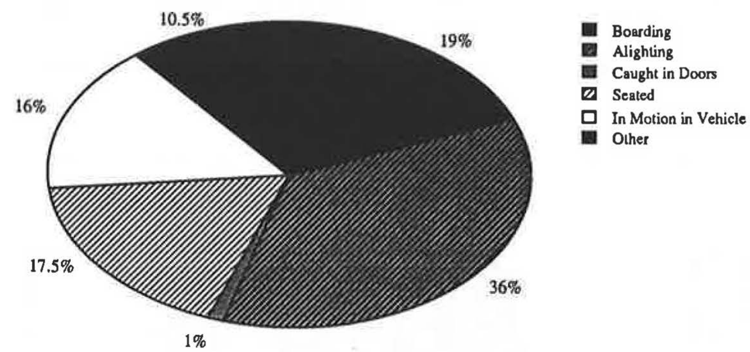


FIGURE 5 Passenger's action (noncollision accidents).

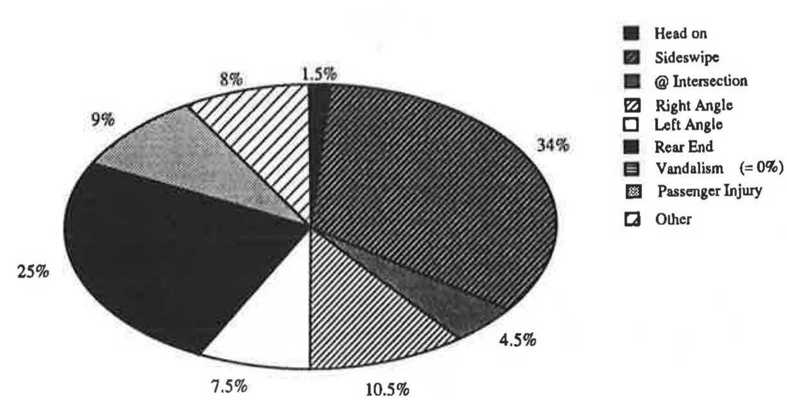


FIGURE 6 Proportion of collision accident types.

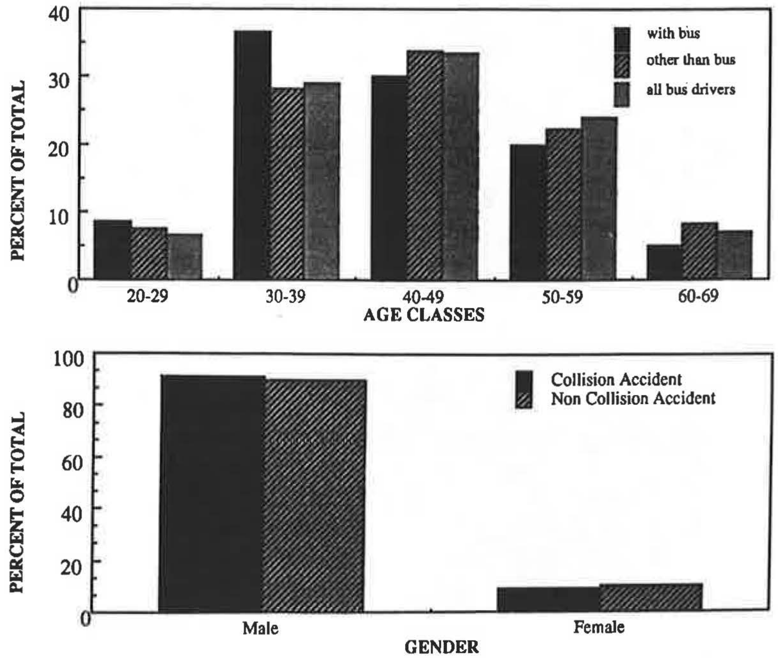


FIGURE 7 ***Top*: Age distribution of RTA drivers involved in accidents. *Bottom*: Sex distribution of RTA drivers involved in each type of accident.**

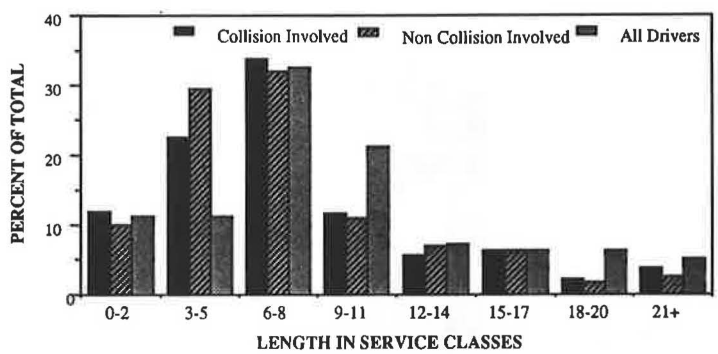


FIGURE 8 Seniority distributions of drivers.

in a sideswipe accident. Figure 10 shows, however, that for collision accidents occurring when RTA buses were stationary, this figure is more than 80 percent for both RTA and other drivers. Thus, the severity is much higher for both bus and automobile occupants in rear-ending a bus compared with the severity of being rear-ended by a bus.

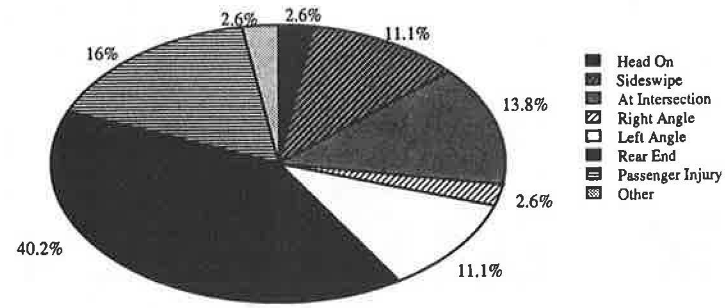
Figure 11 shows that more than 80 percent of the accidents involving buses occur near intersections with either no control or traffic signals in the direction of the bus. It is notable that more noncollision passenger accidents than collision accidents occur at stop signs. This suggests that it may be useful for drivers to warn passengers before buses stop at a stop sign or to slow down more gradually when approaching a stop sign.

The data also indicate that more than 75 percent of accidents occur in clear weather, more than 65 percent on clear roads, and 80 percent during daylight. Thus weather, though important in some accidents, is not a contributing factor in a large percentage of our bus accidents.

Route-Level Analysis

To explore the effect of route characteristics on accident frequencies, an analysis file was created that contains the data on accident frequency by route as well as various descriptors of route characteristics. Accident frequency of a route (ACCYR) is the average number of accidents that occurred on the route per year obtained by compiling the RTA accident/incident report data file. Because some bus routes have shorter service periods than the analysis period (January 1982 through December 1984), appropriate adjustment was made when the average frequencies were computed. Bus route descriptor data were compiled from Pace's *Bus Route Descriptions* (*12*) for 65 separate routes.

As a preliminary step in the analysis, pairwise correlations of a large number of variables were examined using scatter plots. The major findings of this analysis are as follows:



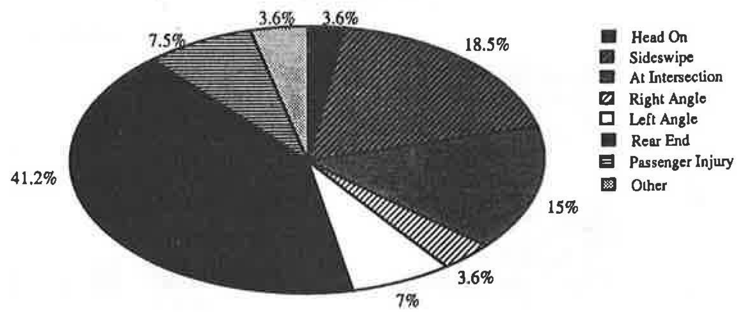


FIGURE 9 Proportion of collision accident types. *Top*: Bus driver was injured and bus was moving. *Bottom*: Other driver was injured and bus was moving.

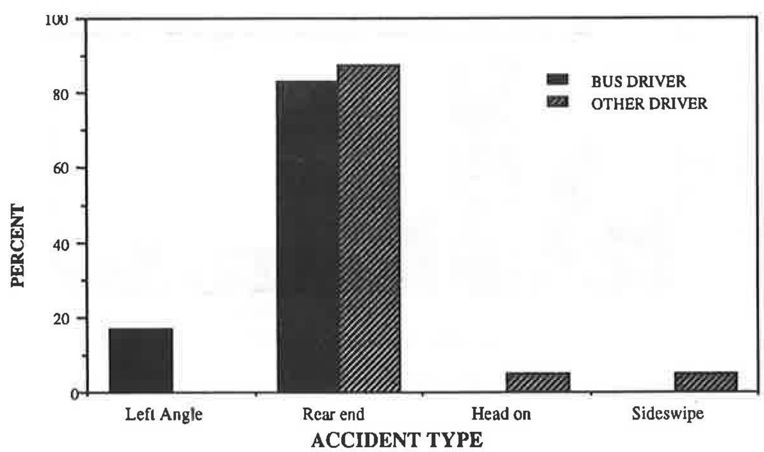


FIGURE 10 Type of accident—driver or drivers injured and bus stationary.

1. Only a small number of routes exist that belong to route categories O (outlying suburban route) and F (feeder service to rail stations); most routes belong to the category I (inner suburban route). Thus, separate analyses by route category are not feasible.
2. Revenue miles, revenue hours, ridership, and number of weekly bus trips have a strongly positive correlation with each other.
3. Morning headways have a moderately negative correlation with all of the preceding variables.
4. Average base headway and speed have a slightly negative correlation with revenue hours, ridership, and number of trips and a slightly positive correlation with morning headways.
5. On the basis of these observations, major variables appear to fall into four groups: revenue miles; revenue hours, riders, and number of trips; morning headways; and base headways and speed.

Revenue miles, ridership, morning headway, and speed were chosen to represent each of these groups. Regression analyses were conducted to estimate models that relate accident frequencies to these variables. Estimation results for log-linear models are summarized in Table 1. They are estimated with reasonable R^2 values ranging from 0.73 to 0.75; all parameters in all models are estimated with signs consistent with the preceding discussion. The third model, which is the

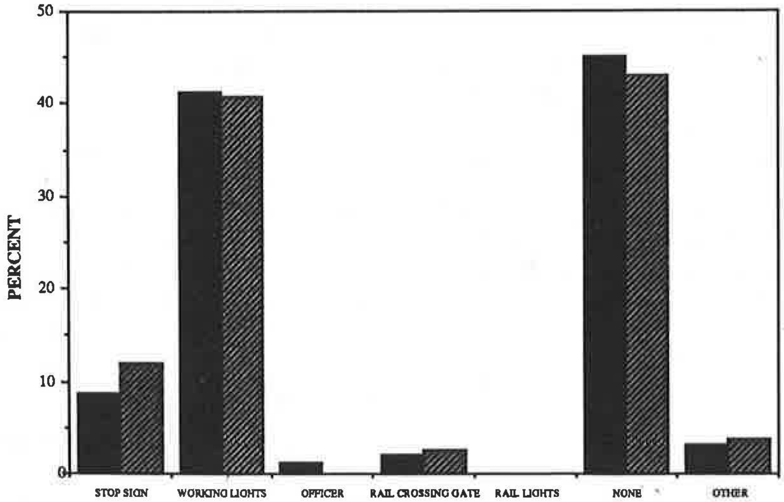


FIGURE 11 Accidents by type of traffic control.

TABLE 1 LOG-LINEAR REGRESSION MODEL OF ACCIDENT FREQUENCY

$\ln(ACCYR) = a + b_1 * \ln(RMYR) + b_2 * \ln(RIDER) + b_3 * \ln(HWAM) + b_4 * \ln(SPEED)$

	a	b_1	b_2	b_3	b_4	
Model 1	2.32	0.70	0.30	-0.42		---> $R^2 = 0.74$
(t)	(1.8)	(5.0)	(2.8)	(2.4)		
Model 2	2.96	0.82	0.28		-0.53	---> $R^2 = 0.73$
(t)	(1.1)	(4.3)	(1.7)		(1.1)	
Model 3	7.60	1.03		-0.43	-0.86	---> $R^2 = 0.74$
(t)	(7.6)	(11.1)		(2.5)	(2.5)	
Model 4	4.13	0.80	0.22	-0.40	-0.38	---> $R^2 = 0.75$
(t)	(1.8)	(5.0)	(2.8)	(2.4)	(0.8)	

where,
RIDER = weekday average ridership,
HWAM = average weekday morning headway (inter-departure time),
RMYR = annual revenue miles,
RHRYR= annual revenue hours,
SPEED = RMYR/RHRYR.

preferred one in the light of the high t-statistics of all parameters, implies that accident frequency is almost linearly proportional to revenue miles and inversely proportional to morning headways and speed raised to the powers of 0.43 and 0.86, respectively.

Speed has a negative relationship to the number of accidents, largely because lower average speed reflects traffic-congested routes along narrow streets, whereas higher average speed reflects routes along high design arterials with moderate traffic volumes.

Although the variables appearing in the models are considered to represent various route characteristics affecting accident frequencies, the models should not be interpreted as directly indicating the causality of bus accidents. Thus, it is unrealistic to expect to reduce the number of accidents by increasing bus speeds while keeping other variables constant. Rather, the models should be interpreted as indicating that the number of accidents would decrease if the determinants of bus speed, such as traffic volume, land use, number of bus stops, road geometry, and so forth, were different. The models may be used to predict the number of accidents expected on new routes. They may also be useful in identifying routes of unusually high or low accident rates, which may provide clues to measures for reducing the number of accidents.

The models presented have been derived using data from a specific area. Model calibration for use in other areas may be necessary for representative results (i.e., avoidance of transferability errors).

Analysis of Accident Propensity of Bus Drivers

The ability of a bus driver to avoid accidents is hypothesized as developed according to some learning curve. The level of this ability, denoted by m, $0 \leq m \leq 1$, may be represented mathematically as follows:

$$m = 1 - 2/(1 + e^{\alpha t}) \quad (1)$$

In this generic learning curve, t is the time elapsed since the start of learning, and α is the parameter that determines the curvature.

We further hypothesize that each driver has a certain basic accident propensity and that a certain portion of accidents are unavoidable even after the driver attains the maximum level of learning. Thus

$$P = P_0(1 - \beta m) \quad (2)$$

where

P = the accident propensity of a driver,
P_0 = the basic accident propensity,
m = the level of learning defined by Equation 1, and
β = the maximum reduction in accident propensity by learning.

To estimate the parameters of the model and test the reasonableness of this hypothesis, an analysis file was created that contained the ratios of the number of drivers who had accidents during the analysis period and those employed as of spring 1985. This file was created by compiling the Pace accident/incident report data file and the seniority lists provided by Pace operators.

If accident propensities of drivers belonging to age and seniority groups are assumed to be these ratios, the model in Equations 1 and 2 can be estimated with this data file. In the estimation, we assumed that parameters and ß were constants that did not depend on age and seniority. However, we assumed that the basic accident propensity depended linearly on the age of drivers. Thus, the model to be estimated has the following form:

$$P(y,t) = P_0(1 - \beta m) \tag{3}$$

or

$$P(y,t) = (a + by)\left[1 - \beta\left(1 - \frac{2}{1 + e^{\alpha t}}\right)\right] \tag{4}$$

where

$P(y,t)$ = the accident propensity of drivers in age and seniority group (y,t),
y = int(driver age/10),
t = int(driver seniority/3), and
int = the integer part of the resulting value.

Noting the difference in the number of drivers in age and seniority groups in the data, we used the weighted nonlinear regression procedure of SAS to estimate Model 4 with the number of drivers employed in each age and seniority group as weights. The R^2 value for the model was 0.82, which indicates a good fit of the model with the data. This estimated model, in a form similar to Model 4, is

$$P = (7.44 - 0.833y)\left[1 - 0.611\left(1 - \frac{2}{1 + e^{0.472t}}\right)\right] \tag{5}$$

(t-scores
4.7 2.2 1.7 1.0)

This result suggests that the learning curve hypothesis is reasonable; as indicated by the estimate of parameter β, the maximum reduction in accident propensity due to learning is as large as 61 percent. As indicated by the negative estimate of parameter b, the basic accident propensity appears to decrease with driver age.

Summary

The objectives of the empirical analyses were to obtain substantive information about the safety performance of the case study transit system and to explore the use of a variety of statistical methods to analyze bus safety data. Rather than a single analysis technique, a broader-based approach appeared more appropriate to the exploratory nature of the research. A multilevel approach was used to guide the empirical studies. First, system safety performance was assessed by analyzing data that reflected systemwide accident experience. The primary techniques used to conduct these studies were cross-classification analysis and simple graphical plots.

Additional studies were conducted at the route level to obtain a more detailed understanding of factors that contribute to accident occurrence. Use of the transit route as the analysis unit allowed the infusion of a number of useful exposure variables; the principal analytic technique was nonlinear regression. Finally, several studies were undertaken at the disaggregate or individual level. Driver age and experience were used to estimate a learning curve model.

CONCLUSIONS

Reports of approximately 1,800 accidents occurring over a 3-year period (1982–1984) were analyzed to identify factors contributing to bus accident occurrence. Data were provided by Pace, the suburban bus agency of the Regional Transit Authority in the Chicago, Illinois, metropolitan area. For the entire data set, 89 percent of the accidents involved a collision with another object or person, and the remaining 11 percent involved passenger injuries while boarding, alighting, or moving about the bus.

Severity levels were generally low; most accidents caused only property damage. Drivers of the other vehicle were much more likely to be injured than the bus driver: automobile drivers were injured in 10 percent of collision accidents, whereas bus drivers were injured in only 2 percent of the crashes. Despite their relatively rare occurrence, clear patterns of injury have been identified. When the bus was in motion, 40 percent of automobile and bus driver injuries occurred because of rear-end collisions. When the bus was stationary, 80 percent of automobile occupant injuries occurred when the automobile rear-ended the bus. The findings suggest that stationary buses (for example, buses stopped for a queue of vehicles or to process passengers) pose the greatest risk to automobile occupants. Data limitations did not permit the determination of how many crashes occurred because buses were stopped to process passengers while the nearby traffic signal displayed a green light. The unexpected stop under this condition could surprise the automobile driver and lead to an accident. Because of the relatively high severity of rear-end accidents, serious consideration should be given to expanding the use of bus bays (adjacent to the general roadway) so that buses do not impede through traffic. This is particularly important along high-speed (e.g., 40-mph speed limit) roads with long bus headways.

Trends in total accident occurrence or the separate occurrence of collision and noncollision accidents could not be identified from examination of monthly accident totals. Weather was clearly a contributing factor in some accidents but not a major overall factor, because 75 percent of the accidents occurred during clear weather with dry pavement. These findings are similar to those reported for trucks (*11*). Bus accidents do not appear to be more frequent during darkness. Accident occurrence drops dramatically during night hours, reflecting both changes in service frequency and lowering of automobile traffic flows.

The analysis of bus drivers' attributes indicated that gender does not appear to contribute to accident occurrence; the

observed accident frequencies are similar to what would be expected given the proportion of each sex in the bus driver population as a whole. Age, on the other hand, appears to have a negative effect on accident involvement, when experience on the job is accounted for. Experience with the transit agency, however, was strongly associated with accident occurrence. Drivers with 3 to 6 years of experience at Pace were significantly overrepresented in accident occurrence and are the only category of experience that is overrepresented. These findings are consistent with the qualitative expectations of Pace safety officials. The results are pronounced but difficult to explain. Some Pace officials speculate that drivers become overconfident and more ready to take risks after 1 to 2 years of relatively safe driving. The increase in risk taking, presumably, results in more accidents. Though plausible, the theoretical foundations of this hypothesis could not be established. Again, recent findings in the motor carrier industry indicate increased risk of accidents both at the beginning and end of a driver's duty cycle (*15*).

Whereas plots of accident frequency by time of day generally tracked urban congestion patterns (i.e., on morning and evening peaks), there were also smaller peaks around 10:00 to 11:00 a.m. and at 2:00 p.m. These correspond to shift change times for transit drivers. Data limitations precluded further study, but it would be of interest to identify whether the increases in occurrence are associated with drivers just beginning or ending a shift.

At the level of individual routes, regression analyses yielded results that were consistent with expectations. The expected number of accidents on a route was virtually linear with route miles operated and of strong statistical significance ($t = 11$). Mean accident frequency was also negatively associated with vehicle headway and with speed along a route. Whereas the models explained a significant amount of the variance in the data ($R^2 = 0.73$ to 0.75), they did not directly relate accident occurrence to causal factors. For example, the negative association with speed is interpreted to represent lower accident occurrence on high-speed roads, which are more likely to be well designed, carry smaller traffic flows, and have fewer stops. Good design, low volumes, and infrequent stops would result in lower accident risk, but it is not sensible to argue that transit routes should be located exclusively by these criteria; routes must serve markets (i.e., patrons) where they are located. If transit planners have a routing choice, these results imply that routes that may be characterized as yielding higher speeds, because of the combination of these three factors, are preferred for safety purposes.

RECOMMENDATIONS FOR FUTURE RESEARCH

Lack of comprehensive information about drivers involved in accidents (both bus and other vehicle drivers) limited the research team's ability to identify driver factors that may have contributed to accidents. It would be of interest to examine the driving records (citations and accidents) of bus drivers to determine whether their service records with the agency are similar to their driving records with private vehicles. Evidence from the trucking industry indicates that professional drivers with poor driving records in their private cars are more likely to have poor professional driving records as well. Union agreements and other legal considerations may prohibit actions against currently employed drivers, but it may be possible to use an individual's driving record as a screening device for new hires. It would also be useful to conduct a study of automobile drivers involved in bus accidents, and in particular to compare them with the population of all drivers and the population of drivers involved in automobile accidents. This would provide additional insight into whether particular segments of society (e.g., the elderly) are overrepresented among victims of bus accidents. Safety programs targeted at these groups could then be developed. Confidentiality concerns may limit these studies, but they should be explored.

There is a need for a focused study of the potential effect of driver shift changes on accident occurrence. The lack of driver shift changes data in this study meant that it remains unclear whether accidents are more likely at the beginning of a shift (e.g., a "warmup" phenomenon) or at the end of a shift (e.g., driver fatigue). Evidence from the trucking industry is that both occur (*15*). Noncollision accidents appear to be particularly clustered near the shift changes, indicating that bus drivers may be having difficulty with fine vehicle control. Empirical studies should include analysis of driver performance on actual routes. Particular caution should be exercised in controlling for effects of driver experience that may result from the minimum guarantee.

There is a need to improve data collection tools for noncollision accidents. Use of a data collection tool oriented to road accidents leads to collection of insufficient information to identify countermeasures. It is not possible to identify events antecedent to or the contribution of detailed interior design features to a passenger's fall in a bus. Countermeasures involving changes in vehicle design will thus be based more on belief than on solid evidence.

Whereas aggregate systemwide analysis of accident data is useful in identifying general trends in accident characteristics, more sophisticated techniques are needed to obtain greater insight into accident causality. Two recent studies of motor carrier accidents (*16,17*) use disaggregate trips at the individual level. This structure allows a more accurate assessment of the driver, roadway, route, environment, and agency policy characteristics that contribute to accident occurrence. Accident data are generally available in this form. The utility of these disaggregate approaches depends on the availability of individual nonaccident data for comparisons. These data are more likely to be available and complete as information systems become more common in the industry.

ACKNOWLEDGMENT

The findings presented herein were part of a report prepared for the Urban Mass Transportation Administration. The support of UMTA and Pace is gratefully acknowledged. Omissions and errors are the sole responsibility of the authors.

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The views and interpretations in this paper do not necessarily reflect the views and policies of UMTA or Pace.

Publication of this paper sponsored by Task Force on Transit Safety.

Random Drug Testing Under Constraints on Subsample Sizes

STEVEN R. LERMAN

Recent federal regulations requiring random drug testing of all transit agency employees are now being tested in the courts. However, many managements are still planning procedures for testing at least a portion of their work forces for substance abuse. In devising appropriate sampling procedures, management must ensure that four distinct goals are met: fairness to all employees, unpredictability of who will be tested each day, maintenance of service, and economic efficiency. The goal of maintaining service may require a limitation on the number of employees sampled from any one location or occupational category in any one day. Simple random sampling, however, provides no guarantee of such a limit. A weighted random sampling technique is described. It was developed for the Massachusetts Bay Transportation Authority and allows constraints on the number of employees in various categories sampled yet maintains fairness in the sense that all employees subject to random drug testing have equal probability of being sampled. Whereas the proposed procedure is complicated compared with simple random sampling, it can be implemented and run on a personal computer. Implementation requires that a set of weights be computed for the work force and that the weights be used in the daily sampling procedure. The use of the weights on a daily basis is straightforward and requires only slightly more computational effort than construction of a simple random sample. Determination of the weights is more computation intensive but would typically be required only on a monthly or quarterly basis.

The federal regulation for testing of transportation employees involved in safety-sensitive occupational categories required transit agencies throughout the United States to develop sampling plans for random drug testing. Though this regulation has been successfully challenged in the courts on the grounds that the enabling legislation creating UMTA did not grant it the authority to promulgate such regulations, it is likely that individual transit operating organizations will implement drug-testing procedures. A sample method that meets the conflicting needs of fairness and maintenance of service is developed. [A more detailed description of alternative sampling procedures is given elsewhere (*1*)]. This approach, developed for the Massachusetts Bay Transportation Authority (MBTA), applies to situations in which it is necessary to maintain a sufficient number of employees on the job while conducting drug tests.

In planning for random drug testing of employees in safety-sensitive occupations, MBTA wanted to achieve four distinct goals:

- Fairness: All employees in designated safety-sensitive occupations should have equal probability of being tested, regardless of work site, managerial status, or other factors.
- Unpredictability: It should be impossible for employees to predict the days they are likely to be sampled.
- Maintenance of service: The sampling should eliminate the possibility that too many employees from a single area or occupation will be sampled on a given day.
- Economic efficiency: Unless it interferes with the three preceding goals, the sampling should be done in a way that reduces its cost.

Simple random samples, by definition, achieve the goals of fairness and unpredictability. However, when simple random sampling is used, there is a probability that the group of employees tested on any one day will include a significant number of people from one operating location, thus making provision of service unreliable. Ideally, transit companies should be able to limit the number of employees from various groups (defined either by their work location or their job category) who will be tested on any one day.

This paper describes and analyzes a procedure in which constraints on the subsample size for any one group of employees can be imposed while maintaining a "fair" sample. As one would expect, imposition of subsample size constraints on a simple random sample makes it "unfair" in that some employees will, on the average, be tested more often than others. The procedure developed corrects that bias by computing an appropriate sampling weight for each employee.

In the following sections we derive the sample probabilities for alternative sampling strategies and a computational method for reweighting the sample. We also consider correction of weights so that sampling can be limited to weekdays rather than requiring testing 7 days a week. Finally, we consider how the elements of unpredictability can be introduced when samples are created using conventional Monte Carlo computer simulation.

DEFINITIONS

For the purpose of clarity in exposition, we assume that all employees are assigned to work sites (or areas) and that the transit operator wishes to restrict the maximum number of employees sampled in any one site to at most either one (for small areas) or two (for larger areas). Sites or areas can also be thought of as occupational categories. The restriction of maximum sample size in any area to either one or two is not central, but it makes the notation and analysis easier to present. It also characterized the goals of MBTA management. Generalization of the results to subsample constraints greater than two is straightforward.

Intelligent Engineering Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Mass. 02139.

We define the following variables as inputs to the analysis: K is the number of samples taken per day, S is the number of areas from which samples are taken, and N_i is the number of employees in Area i. Note that K, the total daily sample size, is assumed to be set by the transit management. Larger daily samples increase the costs of random drug testing but increase the probability any one employee is sampled, presumably increasing the deterrent effect of the testing procedure.

Using these definitions, we can compute N, the total number of employees, as

$$N = \sum_{i=1}^{S} N_i$$

and p_i, the probability that any one employee sampled randomly from the population as a whole works in Area i, as

$$p_i = N_i/N$$

Now consider a set of sampled individuals drawn on a single day. We define a nonnegative vector $\mathbf{q} = [q_1, q_2, \ldots, q_s]$ as a set of samples, where q_i is the number of employees on a given day that are sampled from Area i. If exactly K employees are sampled in a given day, the entries in the vector $\mathbf{q}$ must satisfy

$$\sum_{i=1}^{S} q_i = K$$

We also assume that q_i/N_i is always small enough so that we do not have to be concerned with the effects of small populations. Alternatively, we can view the sampling as done with replacement, so that the same individual can be drawn more than once. In actual applications, the number of employees will generally be large compared with the sample size, and the differences between sampling with and without replacement will be negligible.

DERIVATION OF CHARACTERISTICS OF RANDOM SAMPLE

Consider first the case in which the sample of employees is taken completely at random, allowing the possibility that an unacceptably large number of sampled employees are from the same work area. The probability of drawing q_1 employees from Area 1, q_s employees from Area 2, . . . , q_S employees from Area S is given by a multinomial distribution as follows:

$$P(\mathbf{q}) = P(q_1, q_2, \ldots q_S) = \frac{K!}{q_1!q_2! \ldots q_s!} p_1^{q_1} p_2^{q_2} \ldots p_S^{q_S}$$

In this simplified situation, one can derive $P_i(k)$, the marginal probability that exactly k employees from Area i are sampled for $k = 0, 1, 2, \ldots, K$. This is binomially distributed as follows:

$$P_i(k) = \frac{K!}{k!(K-k)!} p_i^k (1 - p_i)^{K-k}$$

In addition, given that Area i has k people sampled from it, the conditional probability of any particular employee being in the sample is given by

$$R_i(k) = 1 - \left(1 - \frac{1}{N_i}\right)^k$$

These results can be used to derive the probability that any single employee working in Area i is sampled on a given day. This value is defined as Y_i. It can be found using the total probability theorem as follows:

$$Y_i = \sum_{k=1}^{K} [P_i(k)\, R_i(k)]$$

Because this simplified case represents a simple random sample, the value of Y_i is the same for all areas. As a check, in a totally random sample, if K employees are sampled each day, the probability that any one employee is tested on that day is given by

$$Y = 1 - \left(1 - \frac{1}{N}\right)^K$$

EFFECTS OF LIMITING THE NUMBER OF EMPLOYEES SAMPLED AT EACH AREA

Using the preceding notation as a starting point, we now consider the case in which it is not feasible to sample an arbitrary number of employees from any one area. The need to maintain operating service requires that no more than one employee be sampled on any given day from small areas (those with fewer than L employees) and that no more than two employees be sampled from larger areas. In this situation, the sampling outcomes are restricted such that $q_i = 0$ or 1 if $N_i < L$, and $q_i = 0$, 1, or 2 if $N_i \geq L$.

Define $\mathbf{Q}$ to be the set of all possible values of $\mathbf{q}$ that produce a sample of size K. Furthermore, define $\mathbf{Q}^*$ to be the subset of $\mathbf{Q}$ that also satisfies the size restriction above. We can then compute c^*, the probability that any random sample will yield a disallowed (or, as we shall refer to it, censored) sample as follows:

$$c^* = \sum_{\mathbf{q} \in \mathbf{Q} - \mathbf{Q}^*} P(\mathbf{q})$$

For the censored sample the new probability of any outcome $\mathbf{q}$ is given by

$$P^*(\mathbf{q}) = \begin{cases} \dfrac{P(\mathbf{q})}{1 - c^*} & \text{if } \mathbf{q} \in \mathbf{Q}^* \\ 0 & \text{otherwise} \end{cases}$$

The new values for the marginal probabilities that the sample contains exactly k employees from Area i are, unfortunately, no longer binomially distributed. Instead, they must be computed from $P^*(\mathbf{q})$ by summing all the sample probabilities yielding k employees in Area i. If we define $\mathbf{Q}_i^*(k)$ as the set of all samples that have exactly k employees for Area i, the

censored marginal probability functions are

$$P_i^*(k) = \sum_{\mathbf{q} \in \mathbf{Q}_i^*(k)} P^*(\mathbf{q})$$

The censoring of the sample shifts the probability that any one employee from Area *i* is sampled from the random value *Y* (equal across all areas) to a new value that varies across areas. Define Y_i^* as the probability (using the censored sampling method) that any one individual from Area *i* is sampled. This value can be computed as follows:

$$Y_i^* = \begin{cases} \frac{1}{N_i} P_i^*(1) & \text{if } N_i < L \\ \frac{1}{N_i} P_i^*(1) + \left[1 - \left(1 - \frac{1}{N_i}\right)^2\right] P_i^*(2) & \text{if } N_i \geq L \end{cases}$$

NUMERICAL EXAMPLE

To illustrate the preceding results, we consider a simplified case in which there are only five areas with employment of 50, 70, 100, 130, and 150, respectively. For convenience, we use a size cutoff of $L = 100$ and a total sample size of $K = 3$. This is summarized in the following table:

Area (*i*)	*Size* (N_i)	p_i
1	50	.10
2	70	.14
3	100	.20
4	130	.26
5	150	.30

These data result in the following values of $P_i(k)$, the marginal probability that exactly *k* employees from Area *i* are chosen in a simple *random* sample:

Area (*i*)	$k = 0$	$k = 1$	$k = 2$	$k = 3$
1	.7290	.2430	.0270	.0010
2	.6361	.3106	.0506	.0027
3	.5120	.3840	.0960	.0080
4	.4052	.4271	.1501	.0176
5	.3430	.4410	.1890	.0270

Each row of this table can be interpreted as the probability that 0, 1, 2, or 3 of the employees sampled come from the particular area. The value of *Y*, the probability of any single employee being sampled, is .005988. In a random sample, it is identical for all areas.

For the *censored* sample with $L = 100$, the marginal probabilities $P_i^*(k)$ change to the following:

Area (*i*)	$k = 0$	$k = 1$	$k = 2$	$k = 3$
1	.7262	.2738	0	0
2	.6462	.3538	0	0
3	.4663	.4229	.1108	0
4	.3602	.4665	.1733	0
5	.3034	.4784	.2182	0

Note that with the censoring of the sample, outcomes in which $k > 1$ for areas with less than 100 employees and outcomes in which $k > 2$ for larger areas have zero probability. The censoring has shifted the marginal probabilities, increasing the values for $k = 1$ in all areas and for $k = 2$ in larger ones.

The values of Y_i^*, the probabilities of any single employee being sampled on a given day, vary across the areas. The following table gives the values for each area.

Area (*i*)	Y_i^*
1	.005476
2	.005054
3	.006434
4	.006239
5	.006089

Some insight into why the restrictions produce unequal sampling probabilities can be gained by considering two hypothetical areas, one with 99 employees and one with 101. Suppose that exactly three employees are sampled each day. In a purely random sample, every employee would have equal odds of being sampled. However, when the limitation that no more than one employee from the smaller area and no more than two employees from the larger area be sampled is imposed, the employees in the larger area are almost twice as likely to be sampled as those in the smaller area.

Moreover, the nonrandomness is not limited to areas near the *L*-employee borderline. For example, consider another hypothetical case having two areas, one with 100 employees and the other with 200. Even though there are twice as many workers at the larger site, the proposed sample limitation makes the probability of samples having more than two employees from either site equal to zero in both cases. This has the effect of shifting some of the "burden" of the sampling away from employees at the larger site and onto those at the smaller site.

REWEIGHTING THE SAMPLE TO ACCOUNT FOR CENSORING

The preceding results provide a way to weight employees in the sample to achieve equal probabilities of being sampled for all employees, even with the censoring process in effect. Employees in any one area need to be weighted so that the probability of every employee being sampled equals *Y*, the value for a random sample. Define $\mathbf{w} = [w_1, w_2, \ldots, w_S]$ as the vector of weights corresponding to each area. To produce a sample in which all employees have equal probability of being tested, the values in **w** must result in a set of marginal probabilities $P_i^*(k)$ that in turn produce individual sampling probabilities equal to *Y* at all areas. The simultaneous equations that reflect this relationship are extremely complex. However, they can be solved by the following fairly straightforward iterative method:

Step 0: Compute *Y*, the probability of any employee being sampled for a random sample. Initialize tolerance measure *T* to some large value. (See Step 3.) Initialize weights as 1 for all areas.

Step 1: Compute the marginal probabilities $P_i^*(k)$ for each area using the weighted sizes as follows:

$$p_i = \frac{w_i N_i}{\sum_{j=1}^{S} w_j N_j}$$

Step 2: Compute the probabilities of any one employee being selected for each area as

$$Y_i^* = \begin{cases} \frac{1}{N_i} P_i^*(1) & \text{if } N_i < L \\ \frac{1}{N_i} P_i^*(1) + \left[1 - \left(1 - \frac{1}{N_i}\right)^2\right] P_i^*(2) & \text{if } N_i \geq L \end{cases}$$

Step 3: Compute the measure of convergence. One reasonable measure is the average absolute difference between the Y_i^*'s and Y, computed as follows:

$$T = \frac{1}{S} \sum_{i=1}^{S} |Y_i^* - Y|$$

Step 4. If T is less than some predefined threshold, stop and output results. Otherwise, compute a new set of weights as follows:

$$w_i = Y/Y_i^*$$

and go to Step 1.

The algorithm requires a method to compute the marginal choice probabilities. This can be done directly by looping over all censored states and accumulating the marginal probabilities or by Monte Carlo simulation.

Weights computed by this method would be used in the actual daily sampling procedure. Each employee would be sampled with probability proportional to the weight computed for his or her site. If the resulting sample has more than one employee from any small site or more than two from any large site, a new sample would be drawn until a sample that does not violate the subsample size constraints is drawn. This procedure is described in greater detail later, in the Issues in Implementation section.

NUMERICAL EXAMPLE REVISITED

When the algorithm described in the preceding section is applied to the simple numerical example, the first iteration produces the following results for the probabilities that any one employee is sampled:

Area (i)	Y_i^*
1	.005905
2	.005716
3	.006060
4	.006062
5	.006046

After just four iterations, the average absolute error is less than 0.1 percent of the random value, yielding individual probabilities that are virtually equal across all areas. The weights that resulted after four iterations are as follows:

Area (i)	w_i
1	1.1089
2	1.2642
3	0.9185
4	0.9411
5	0.9670

APPLICATION TO MBTA

The method described was tested using data provided by MBTA. MBTA management defined 76 "areas" (typically garages and occupational categories) with employees in safety-sensitive occupations as defined by federal regulations. The 76 areas included 5,738 employees. Because the computational requirements of the proposed method grow exponentially with the number of areas, the sites with a small number of employees were aggregated into five "pseudoareas" as follows:

- Areas with 1 to 10 employees, comprising 21 of the original sites and 86 employees;
- Areas with 11 to 20 employees, comprising 10 of the original sites and 151 employees;
- Areas with 21 to 30 employees, comprising 8 of the original sites and 200 employees;
- Areas with 31 to 40 employees, comprising 7 of the original sites and 250 employees; and
- Areas with 41 to 50 employees, comprising 5 of the original sites and 229 employees.

The aggregation reduced the original 76 sites to a total of 30. Moreover, because each of the original sites in the groups was small compared with the entire population of employees, grouping them has virtually no effect on the analysis of the sampling process other than to reduce the computational requirements.

In a simple random sample of seven employees (the value for K selected by MBTA), each employee would have a probability of .001219 of being tested each day. However, if the sample is constrained with MBTA's selected value of L = 300 without reweighting, the probability of being sampled varies depending on an employee's work area. In the MBTA case, the range of variation was from .001328 (8.9 percent more than for a random sample) to .001067 (14.5 percent less than for a random sample).

The procedure to compute the correct weights was implemented in the C programming language on a Digital Equipment Corporation VAXstation 3100 running a variant of the Berkeley UNIX operating system. (VAXstation is a trademark of the Digital Equipment Corporation. UNIX is a trademark of AT&T Bell Laboratories.) The program was compiled using the Berkeley pcc compiler. Computation of the correct weights required approximately 2 hr of CPU time. Similar performance would be expected on a high-end personal computer that had a floating point coprocessor.

Monte Carlo simulation of the weighted sampling strategy confirmed with 99 percent confidence that it produces equal sampling probabilities for all areas.

EFFECT OF SAMPLING ON WEEKDAYS ONLY

The original MBTA plan calls for sampling seven workers every day, including weekends. This ensures that all employees (after weighting) have the same probability of being sampled. However, it imposes the expense and managerial burden of conducting drug tests during the weekend.

The entire testing program would be simpler and less expensive if testing were done only on weekdays. All employees who are part of the pool to be tested work 5 days per week; however, many work some of those days on weekends. Without some correction, a testing program on weekdays only would unfairly burden MBTA employees who do not work weekends; they would be available for testing every day a sample was drawn, whereas their counterparts who work 1 or 2 weekend days would be available on fewer weekdays.

A simple correction to the weighting method can adjust for this bias. Specifically, if testing is done only on weekdays, each employee's sampling weight should be adjusted as follows:

$$w_n^a = w_n \cdot \frac{5}{h_n}$$

where w_n^a is the adjusted weight for Employee n and h_n is the number of weekdays per week worked by Employee n.

Further adjustments in sampling weights could be made to account for employees who work less than 5 days per week. At the time this paper was written, MBTA was phasing out the already small number of employees in safety-sensitive occupational categories who worked part-time. For this reason, further correction of the sampling method for part-time employees was not explored.

ISSUES IN IMPLEMENTATION

The procedure described in this paper resolves only one of the many problems transit operators face in developing fair drug-testing policies. If operators decide to conduct such testing (either on their own initiative or as a result of some legally sustainable federal requirement), they will have to resolve other sampling issues.

Whether or not absenteeism and vacation time should be factored into the sampling weights must be decided. For example, in the current procedure employees with high rates of absenteeism will be tested less often than those with lower rates simply because they will not be at work as often when their names are drawn. The sample weights could be modified to account for this effect.

Another problem is the technique used to construct daily samples. Most computer-based sampling methods rely on pseudo-random number generators which, given set starting conditions, produce a deterministic sequence of numbers that appears random. The danger of using these methods for selecting who will be tested is that it is possible for someone to know who will be tested in advance, removing the unpredictability of the sampling procedure. A method (proposed initially by MBTA) for removing the predictability is to reorder the list of employees each day.

The reordering is done by sorting the employee list by the remainder from the following computation: (employee number · social security number)/d, where d is an integer found by concatenating the Julian day, hour, minute, and second when the computer program is executed.

After the sorting is done, the daily procedure for sampling is as follows:

Step 0: Compute B, the sum of the weights over all employees, as

$$B = \sum_{n=1}^{N} W_n$$

where w_n is the weight for Employee n.

Step 1: For each employee, compute v_n, the cumulative weight, as follows:

$$v_1 = w_1$$

$$v_n = v_{n-1} + w_n \qquad n = 2, 3, \ldots, N$$

Step 2: Take K samples, each one as follows: first, draw a random value u that is uniformly distributed between 0 and B; second, select the employee n such that $v_{n-1} < u \leq v_n$, where v_0 is defined to be 0.

Step 3: Check whether the resulting sample of K employees satisfies the constraint that no more than one employee be taken from areas with employment less than L and no more than two employees be taken from any area. If so, output the sample and stop. Otherwise, go to Step 2.

CONCLUSION

There is still substantial debate about the legality and morality of drug testing in the United States. The debate is likely to continue, with some compromise emerging between the public's right to safe operations of transportation services and the individual's right to freedom from unwarranted intrusion. To the extent that random testing is part of any such compromise, it is crucial that sampling be fair and unbiased and highly desirable that it not interfere with the efficient provision of transportation. The sampling method described in this paper allows both objectives to be met concurrently.

The appropriate number of employees to be tested each day was not addressed in this study. Small samples such as those discussed here may effectively deter drug use, but they will result in relatively long average intervals between successive tests for any one employee. Larger daily sample sizes would shorten the average interval at the expense of greater testing costs and lost employee time. The appropriate tradeoff between these factors is an area for further research.

ACKNOWLEDGMENT

The methods described in this paper were developed under funding from MBTA. However, all errors, opinions, and other statements are those of the author.

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Publication of this paper sponsored by Task Force on Transit Safety.

Exploratory Analysis of Motor Carrier Accident Risk and Daily Driving Patterns

PAUL P. JOVANIS, TETSUYA KANEKO, AND TZUOO-DIN LIN

Driving at different times of day within 1 day and over several days is associated with different levels of accident risk. Analyses of accident and nonaccident data from a less-than-truckload carrier representing 6 months of operation in 1984 are used to explore changes in daily and multiday accident risk. Cluster analysis is used to extract a distinct pattern of driving over a 7-day period from a sample of 1,066 drivers (including those with accidents and nonaccidents on the eighth day). The analyses yielded clear interpretable driving patterns that could be associated with levels of relative accident risk. Higher risk was generally, but not exclusively, associated with extensive driving in the 2 to 3 days before the day of interest. The two patterns with the highest risk of an accident were those that contained heavy driving during the preceding 3 days and consisted of driving from 3:00 p.m. to 3:00 a.m. (Pattern 1) and from 10:00 p.m. to 10:00 a.m. (Pattern 8). The lowest risk was associated with driving from 8:00 p.m. to 6:00 a.m. but with limited driving on the preceding 3 days. Given the virtually limitless possible combinations of driving schedules, it is encouraging that interpretable distinct multiday patterns could be extracted from a data base of more than 1,000 observations. Within each pattern, drivers experienced similar duty hours: cumulative driving during the 7 days ranged from 47 to 49 hr. Continuous driving (between mandatory 8-hr off-duty periods) ranged from 7.8 to 8.4 hr. Individual drivers also experienced a cycle of on-duty and off-duty time that ranged from 22.3 to 23 hr, closer to the 24-hr period that is desirable from the perspective of human performance theories. The findings suggest that it is possible to identify and extract patterns of multiday driving and that these patterns are associated with different levels of accident risk. Additional empirical tests and the development of refined accident risk models are suggested for future research.

Interstate motor carriers are subject to limitations on the hours that their drivers may be on duty and driving. The regulations require that a driver be off duty for a minimum of 8 hr after driving for 10 hr or being on duty for 15 hr. There are also cumulative restrictions for on-duty time over several days: 70 hr on duty in 8 days for carriers operating 7 days a week and 60 hr in 7 days for those operating 5 days a week. These limitations, referred to as the hours of service regulations, were initiated in the 1930s. Since then the U.S. highway system has changed dramatically, as has the nature of the trucking business and the technology of the vehicles. Despite the changes, attempts to assess the safety implications of the hours of service for contemporary conditions have been limited.

One of the difficulties in assessing the safety implications of hours of service policies is in understanding how accident risk varies with continuous hours driven and multiday driving.

P. P. Jovanis and T.-D. Lin, Department of Civil Engineering and Transportation Research Group, University of California, Davis, Calif. 95616. T. Kaneko, Sato Kogyo Co. Ltd., Gifu, Japan.

Whereas accident risk variation within a day has received limited study, multiday assessments were extremely limited in the literature. This paper focuses on variations in accident risk with alternative driving schedules and over several days. A companion paper (*1*) assesses multiday driving risk along with the risk due to continuous driving.

In a major book on fatigue, safety, and the truck driver, MacDonald (*2*) discusses the inconsistency and vagueness in how researchers have defined and used the concept of fatigue. For some researchers it is subjective, dealing primarily with individuals' perceptions of how they feel. Others use physiological correlates or performance decrements to study fatigue. An excellent review of psychological, physiological, and performance components of fatigue is contained in a recent review by Australian researchers (*3*).

There also appears to be confusion in some studies about the distinction between fatigue attributable to continuous driving and other time-related driving factors. Circadian rhythms are changes in body function that follow an approximate 24-hr period, so there is a point of low rhythm that corresponds to generally depressed levels of arousal. In addition, sleep deprivation, which arises because of a combination of on-duty time and off-duty activities, may also influence arousal and, ultimately, accidents.

Fatigue is a sufficiently vague concept that it does not appear to be a useful focal point for this study. As an alternative, declines in performance as measured by accident risk are used as a measure of the quality of the driving task. The research recognizes the separate effects of declines in performance due to cumulative driving over several days and circadian effects. The focus of the study is on accidents and exposure that occur during actual motor carrier operations. All effects other than sleep deprivation during off-duty hours are thus considered.

Perhaps the most extensive studies of hours of service and accident risk were conducted in the 1970s as part of a series of studies sponsored by the National Highway Traffic Safety Administration (*4–7*). The studies included analyses of retrospective accident data and field tests, with an instrumented cab, of drivers asked to drive particular schedules. The effects of heat, noise, vibration, and cargo-loading activities were also assessed.

The studies consistently found that a higher proportion of accidents occurred in the last half of a trip. Separate analyses of single-vehicle accidents and crashes for which the driver was reported to be "dozing at the wheel" indicated a particularly strong increase in accident risk as continuous hours of driving increased. Circadian effects were significant for the dozing drivers; the accident risk was highest from 2 to 6 a.m. Some studies included a separate collection of exposure data,

but most of the analyses with accident data compared the actual number of accidents with those expected if there were no increased risk due to hours driven. This method is based on the assumption that accident-involved drivers are representative of the general population of drivers. The studies also relied primarily on accident data from the then Bureau of Motor Carrier Safety (now the Office of Motor Carriers of the Federal Highway Administration), although some data were provided directly from carriers. The studies using accident data and exposure from actual motor carrier operations do not explicitly consider the effect of total hours driven during preceding days nor the time of day when the driving occurred.

The 1978 report by Mackie and Miller (*7*) describes the findings of a series of field experiments. A set of drivers operated a truck along a fixed route in California using predetermined driving schedules for a week. Detailed physiological, perceptual, and driving performance data were collected at several points during the duty regimen. The study found significant consistent evidence of reduced driving performance, particulary during the fifth and sixth days on duty, particularly for drivers who undertook moderate cargo loading, and particularly for rotating rather than fixed schedules. Unfortunately, the schedules assigned to all drivers exceeded the U.S. Department of Transportation (DOT) maximums established for interstate operations. It is problematic that performance reduction manifested itself most often during these illegal hours. Furthermore, the number of alternative driving schedules examined was extremely limited and could not typify those in broad trucking operations. Nevertheless, despite its experimental shortcomings, the study has significant scientific merit and stands as a classic work in the field of accident risk and hours of service.

Several recent studies have explored aspects of accident risk and driving hours. The Insurance Institute for Highway Safety recently completed a study of drivers in sleeper berth operations (*8*). It was found that regularity of schedule was an important predictor of road safety. In another study (*9*), a nonrandom set of accidents (primarily in the western United States) was selected for detailed follow-up. Interviews with firms and family members were used to reconstruct how the truck driver spent his time both on and off duty in the day or so before the crash. The findings were that fatigue was a major contributing factor because of a combination of excessive (and illegal) hours of work and lack of rest during off-duty time. The findings are of interest, but the study suffers from methodological shortcomings: the criteria for selection of crashes appear to be biased toward severe outcomes, and the method used to determine the contribution of fatigue to accident occurrence appears subjective.

Studies have also been conducted in Europe. Hamelin (*10*), in an analsyis of professional and nonprofessional drivers, found that professionals had lower accident rates than nonprofessionals, particularly during extended driving. He concluded that the professionals could better cope with the rigors of on-road performance. Fuller reached similar conclusions in his study of driving performance in Ireland (*11*). No difference was found in the mean following headway of drivers, even after extended hours on-duty and driving.

Further research seeking to relate accident risk and motor carrier driving patterns could take any of several paths. Detailed physiological and perceptual data could be sought from drivers undertaking truck-driving tasks. This approach, best exemplified by Mackie and Miller (*7*) is both costly and subject to criticism because it is not representative of actual driving conditions. An alternative is in-depth study of selected accidents (*9*). The generalizability of this approach can also be questioned. A third approach is to analyze accident data from actual truck operations, make comparisons with nonaccident events, and seek to identify accident patterns that support or refute a relationship with time of day and driver hours regulations [much in the spirit of the research by Harris in 1972 and 1977 (*4,5*)]. Each approach has its strengths and weaknesses, and a decision must be made on the approach to use in any particular study.

The approach taken in this research is to follow the lead of Harris and his colleagues and to seek to identify relationships between accident risk and driving hours. In particular, an attempt is made to identify changes in accident risk with time of day as well as over a multiday period. The multiday pattern considers the time of day of on-duty hours as well as the cumulative number of hours. The approach is predicated on the belief that a primary concern is the effect of driving patterns on performance (i.e., a safely completed trip or an accident-producing trip). Whereas driver health and welfare issues are also important considerations, the focus of this study is on driving patterns and accident outcomes. Instead of relying on information from accident reports or driver interviews that attempt to attribute causality to factors such as fatigue, the approach in this research is more empirical. By linking specific patterns to accident risk, it is hoped that high-risk as well as low-risk patterns will be identified. The linkage to real driving and on-duty time can then be related to existing and proposed hours of service regulations to determine their safety effectiveness.

OBJECTIVES

The review of the literature suggests that there is a clear need to develop a method to analyze the effect of different daily driving patterns on accident risk. In particular, it is important to consider both the time of day when the driving occurs and the times of day of driving over multiple days so that the cumulative effect of multiday driving can be assessed. A second objective is to test the method with data from trucking company operations. Data from accident reports as well as comparable nonaccident data should be included so that relative accident risk can be assessed.

METHODOLOGY

What Is a Driving Pattern?

A driving pattern, for the purposes of this research, is a description of the status of the driver over several days. The status of the driver includes off duty, on duty and driving, and on duty but not driving (as defined by DOT). A driver's status is typically recorded for each of every 15 min throughout the day. If a driver is involved in an accident, the pattern is interrupted while forms are completed, repairs are under-

taken, and individuals are treated as necessary. For drivers not involved in accidents, driving patterns continue, dependent on the need to move freight and the constraints imposed by hours of service limits. Obviously, a large number of driving patterns are possible over multiple days. For this research to succeed, a statistical method to identify drivers with similar driving patterns is needed so the effect of the pattern on risk can be assessed.

Statistical Methods

Statistical analysis of the driving patterns proceeds in two phases. First, data are presented on the change in accident risk with time of day. These are disaggregate data consisting of a sample of accidents and the time of day of their occurrence. To provide a measure of exposure to risk, a sample of nonaccident trips is analyzed. The nonaccident data include the beginning and ending time of each trip; the driver is assumed to be exposed to the risk of an accident throughout this time. Though drivers take breaks for meals and other purposes, this appeared to be a reasonable starting point for these exploratory studies.

Second, a method to extract similar driving patterns from a large pool is needed. It is important that the determination of similarity be conducted in a way that is blind to accident occurrence—that is, the method should first group drivers with similar patterns. Once similar patterns are identified, knowledge of the accident involvement of drivers with particular patterns can be used to assess accident risk.

Disaggregate exposure trips present no problem in this regard. A trip for a driver for one day can be randomly selected, and the driving pattern for that day and many previous days can be coded. Accidents are more problematic, because the occurrence of the accident interrupts the driving pattern, producing unknown biases. To avoid these biases the following approach is adopted. Driving patterns are described for the 7 days preceding the accident or comparable exposure trip. This approach simplifies the statistical treatment of the data but is based on the implicit assumption that the observed driving pattern over 7 days is carried into the eighth day. As will be seen shortly, the patterns that result from this analysis are regular enough that this assumption does not appear to be unreasonable. The day of interest does not have to be the eighth day but can be any day that corresponds to any hours of service regulation. The carrier used in the empirical modeling operated 7 days a week, so the operative cumulative restriction is 70 hours in 8 days.

Cluster analysis is a method that classifies objects by creating homogeneous groups. An individual driver is considered as the object; each driver is assigned to a cluster on the basis of the similarity of the driving pattern over 7 days with that of other drivers in the cluster. The driving patterns provide important information, including (*a*) hours on and off duty over 7 days, (*b*) the time of day that the on-duty and off-duty hours occurred, and (*c*) trends of on-duty and off-duty time over several days. Cluster analysis does not yield a single optimum set of clusters for a data set. The user selects the number of clusters desired, and the clustering algorithm assigns each observation to its most statistically similar cluster. A range of cluster numbers can be used, but a criterion is needed for selecting the clusters to be carried to the next step of the analysis. The procedure used in this research tested a range of clusters from five to nine; the maximum number of clusters was determined by a rule of thumb that approximately 100 observations be contained in each cluster. Furthermore, limitations on computer memory precluded testing more than nine clusters. Because the driving patterns that were derived from the nine clusters were interpretable, the pattern search was stopped.

Data Used To Identify Driving Patterns

All data are obtained from a national less-than-truckload (LTL) firm. The company operates "pony express" operations from coast to coast with no sleeper berths. The findings are thus not intended to typify the trucking industry as a whole. Because the carrier takes reasonable steps to adhere to DOT service hour regulations, most drivers in the study can be assumed to operate within legal duty hour limits. The empirical results are intended as a test of the proposed methodology and as a contribution to the admittedly scant research on accident risk and driving patterns.

Two sets of data are used in the analysis. To examine variation in accident risk throughout the day, accident and nonaccident data from 1984 and 1985 are used. The accidents include all those experienced by the carrier for the 2 years in question (independent of DOT reportability thresholds). Nonaccident data were determined by obtaining a random sample of two nonaccident trips for every accident that occurred. Whereas the sample was obtained at random, it does not represent the true probability of an accident. Detailed analysis of data from one terminal (*12*) indicates that accidents occur approximately once in every 3,000 trips. Rather than build the huge data bases necessary to test this true probability, a two-to-one oversample of exposure to accidents is used so that the relative probability of an accident is determined. Because the primary concern is the relative probability with respect to a set of predictor variables, this appears to be a reasonable approach.

The time of each accident is recorded on the accident report. The time of day when each nonaccident trip is on the road is known from the driver's daily log. Because the carrier operates LTL with timed runs between fixed terminals, there is little incentive for the driver to falsify logs. Nonaccident trips are on the road for several hours each day and thus must be counted as exposed to risk for each hour they operate.

Multiday analyses required additional data. For the accident data, the first through the seventh days are defined by specifying the date of the accident as the eighth day. Thus the patterns may be thought of as representing the effect of the prior driving pattern over 7 days on accident risk for the eighth day. Similarly, for the nonaccident data, by defining the date of the nonaccident trip as the eighth day, the first through the seventh days are used to characterize the effect of the prior driving pattern.

Data from January through June 1984 are used to determine driving patterns and include 1,066 observations of accident- and non-accident-involved drivers.

If a 7-day interval is considered, the number of variables is 672 (4 time periods per hour $\times$ 24 hours $\times$ 7 days). Com-

puter memory limitations dictate that the finest time resolution that can be used is 30 min, decreasing the number of variables to 336 (2 × 24 × 7). The methods used to transform the 15-min data to 30-min intervals are as follows:

- If both 15-min intervals have the same working status, the new variable (30-min interval) has the same working status.
- On duty and driving and on duty and not driving are treated as one working status, on duty (this is consistent with DOT cumulative hours regulations).
- If one of two 15-min intervals is off duty and another is on duty, the entire 30-min interval is treated as off duty.

The last transformation may cause an underestimate of hours on duty, but, if typical hours on duty last for 3 to 5 hr continuously, this approximation will not cause substantial error. Furthermore, the transformed data are only used as input to the cluster analysis, not in subsequent tabulations. Because most driving trips in the data include consecutive driving times of greater than 3 hr, the approximation appeared reasonable.

RESULTS OF DATA ANALYSIS

Accident Risk and Time of Day

Table 1 is constructed to assess the relative accident risk throughout a day. The first row is the number of accidents occurring in each 2-hr period. The second row is a count of the number of non-accident-involved trucks on the road during the same 2 hr. The risk is the ratio of the number of accidents to the number of exposure units (i.e., the sum of accidents and nonaccidents).

It is clear that elevated accident risk occurs from midnight to 8 a.m. The highest risk occurs from 4 to 6 a.m. These findings are consistent with the theory of circadian rhythms, which anticipates a diurnal drop in arousal typically from 4 to 6 a.m. each day. The table is also generally consistent with results reported by Harris (*5*) for drivers diagnosed as dozing at the wheel compared with a sample of nonaccident driving times obtained by interviews at truck stops.

The findings are interesting but of limited utility. They are for only 1 day (the accident day or a randomly selected nonaccident day) and are not related to driving schedule. They are more related to times of truck movement than an analysis of driver policies such as hours of service. Additional insights can be obtained by examining multiday driving patterns.

Overview of Multiday Driving Patterns

After experimenting with five to nine clusters to describe driving patterns, the cluster analysis with nine homogeneous driving patterns was used for further modeling. A 2 × 9 contingency table was constructed from the nine patterns and the two levels of trip status (i.e., accident or nonaccident). Each of the 1,066 observations fell into 1 of the 18 cells, allowing the test of the null hypothesis that trip status is independent of cluster number. This hypothesis was rejected at $\alpha = .10$ but accepted at $\alpha = 0.5$, a mixed result (*1*).

The nine cluster patterns appeared to be the most distinct. Cluster analysis allocates observations to clusters on the basis of their statistical distance from cluster centroids; as each observation is added to a cluster, the centroid can shift slightly in reponse. The shift in centroid location can result in misclassifications of previously assigned observations. The clustering algorithm used in this study (BMDP) accounts for this by automatically reassigning observations and calculating centroids until no misclassifications occur. In the five to eight cluster analyses, reassignment and reallocation were necessary. The nine cluster patterns exhibited more stability by not requiring any reassignment of observations or recalculation of centroids.

Figure 1 shows the overall average driving pattern, and Figures 2 through 10 represent individual clusters. The horizontal scale represents the elapsed time for each of the seven 24-hr periods. The time scale starts at midnight (Point 0) and runs to 24 hr for the first day; 24–48 represents the second driving day, and so on; 144–168 represents the seventh driving day, just preceding the accident day. The vertical scale represents the proportion of drivers within the pattern that were driving or on duty at that time. For example, in Figure 2, about 30 percent of drivers in Pattern 1 are on duty at midnight at the end of the first day (Hour 24). The percentage of drivers on duty then drops to about 10 percent at 6:00 a.m. on the second day (Hour 30).

What is most startling about the figures is the difference in interpretation that is possible when comparing the aggregate pattern (Figure 1) with the individual clusters. Figure 1 merely

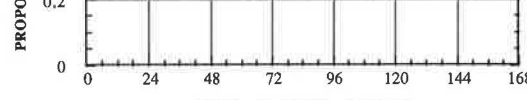

FIGURE 1 Aggregate pattern of driving over 7 days.

TABLE 1 RELATIVE ACCIDENT RISK BY TIME OF DAY

	TIME												
	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	TOTAL
Accident Count (A)	344	292	322	279	240	228	203	194	213	212	245	242	3014
Non-Accident Count (E)	2406	2269	2072	2044	1930	1861	1798	1628	1693	1952	2167	2337	24157
Relative Risk (A/[A+E])	.125	.114	.134	.120	.111	.109	.101	.106	.112	.098	.102	.094	.111

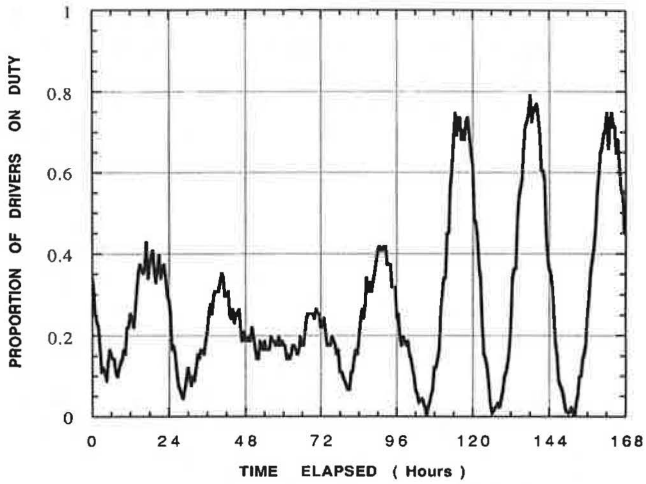

FIGURE 2 Proportion of drivers on duty, Pattern 1.

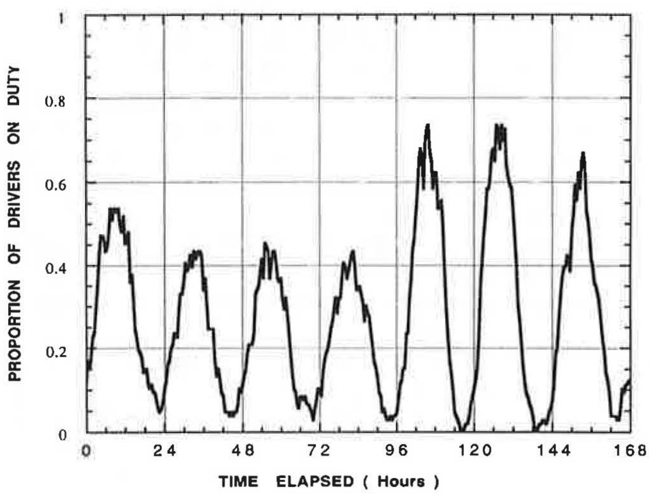

FIGURE 3 Proportion of drivers on duty, Pattern 2.

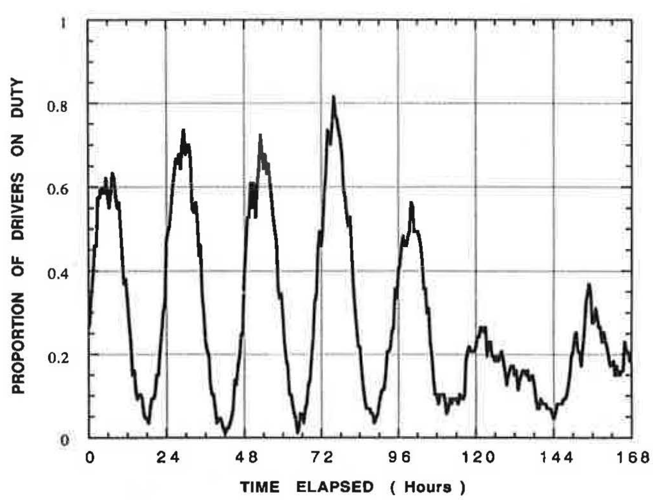

FIGURE 4 Proportion of drivers on duty, Pattern 3.

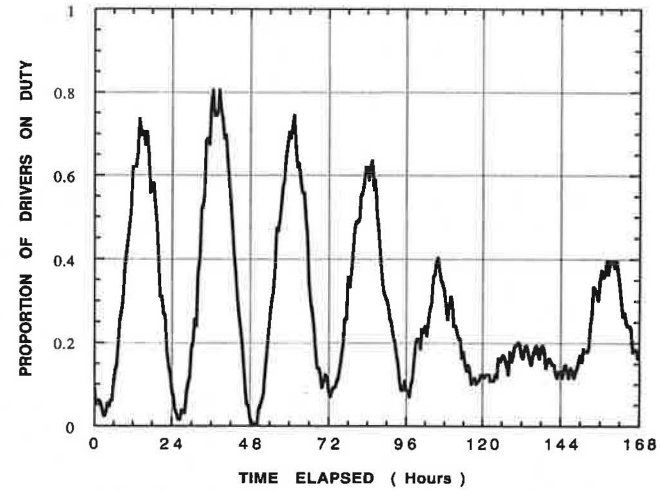

FIGURE 5 Proportion of drivers on duty, Pattern 4.

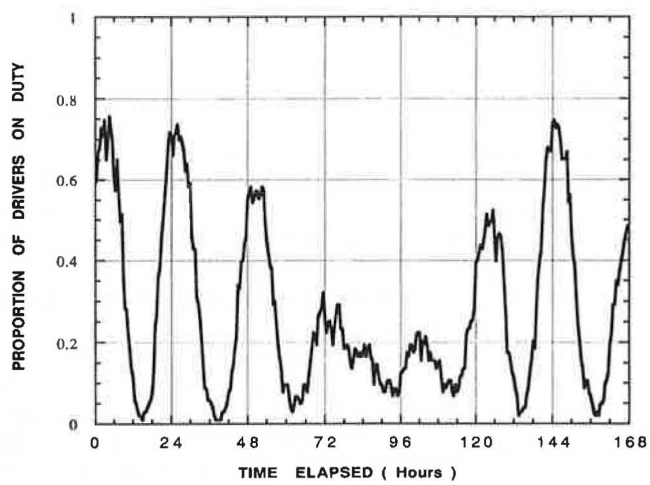

FIGURE 6 Proportion of drivers on duty, Pattern 5.

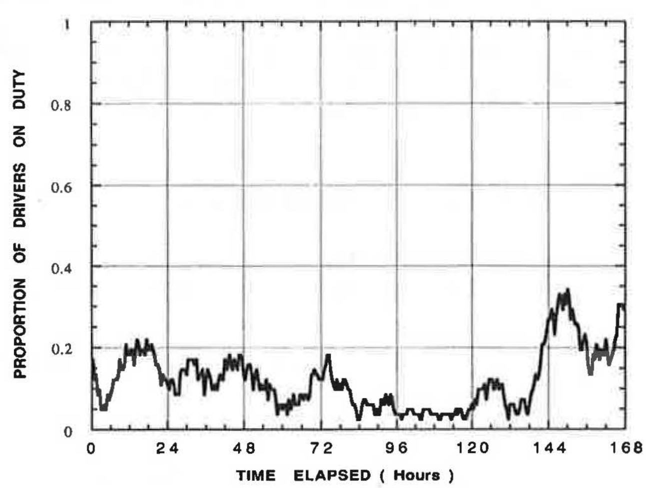

FIGURE 7 Proportion of drivers on duty, Pattern 6.

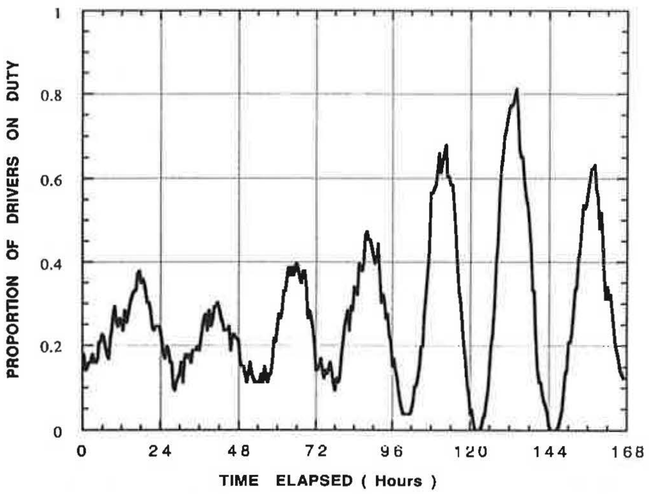

FIGURE 8 Proportion of drivers on duty, Pattern 7.

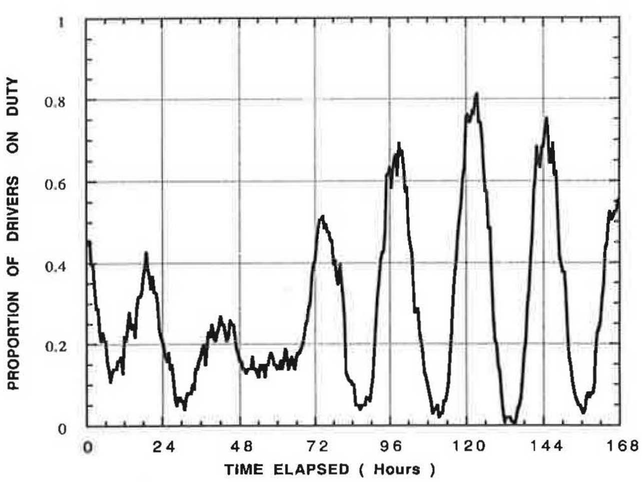

FIGURE 9 Proportion of drivers on duty, Pattern 8.

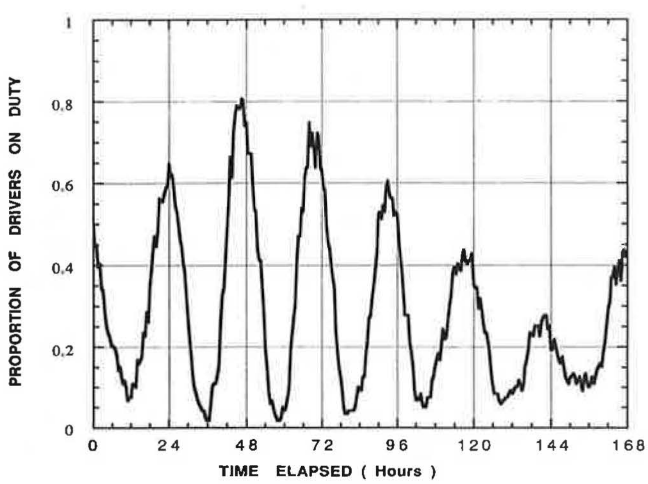

FIGURE 10 Proportion of drivers on duty, Pattern 9.

reflects for this firm what has been commonly reported elsewhere for the industry as a whole. Truck drivers are on duty throughout the 24 hr day for all 7 days, but there is a slight increase in the percentage of drivers on duty in the evening and early morning hours from about 6 p.m. until 8 a.m.). Overall, the change in drivers on duty is from slightly more than 30 percent at midnight of the seventh day to a low of about 22 percent around noon of Days 3, 4, 5, and 6.

Individual driving patterns are clearly identified using the clustering technique. In addition to a summary of the on-duty trends for each cluster, a relative accident risk is reported. The relative accident risk associated with each cluster is calculated as

$$\text{Relative accident risk } n = \frac{a_n}{a_n + e_n}$$

where

a_n = number of trips resulting in an accident in Cluster n,
e_n = number of trips resulting in no accident in Cluster n, and
n = the cluster number.

In addition to the relative accident risk, a number of descriptors are used for each pattern. These include the times of day of most frequent on-duty and driving time, the most frequent off-duty times, the mean and standard deviation of the total hours on duty per driver for the 7 days, the mean and standard deviation of the consecutive hours driving per driver (a measure of average trip length), and the mean and standard deviation of the driving cycle. A driving cycle is defined as the time elapsed between a period of driving or on-duty time and the subsequent off-duty time that is at least 8 hr (consistent with DOT regulations). The rationale is that the driving and on-duty time dictates (causally) the requisite hours off duty. Drivers with off-duty times in excess of 24 hr (and their previous on-duty times) are not included in the reported statistics because the driving cycle is intended to measure the periodicity of individual driving patterns per driver. Off-duty times in excess of 24 hr are probably caused by reaching the limit of DOT cumulative hours levels. When a driver is off-duty in excess of 24 hr, it is assumed that a substantial recovery occurs from the effect of any previous continuous driving.

The following paragraphs contain summary descriptions of each of the nine driving patterns displayed in Figures 2 through 10.

Pattern 1

The most frequent driving periods in this pattern occur from early afternoon (about 3 p.m.) until about midnight but frequently extend until 3 to 4 a.m. Off-duty hours are thus most frequent from 4 a.m. until noon. Driving is irregular for the first 4 days of the pattern but regular for the last 3 days; for example, more than 80 percent of the drivers are on duty at 10 p.m. of the sixth day. This pattern is associated with a somewhat high level of accident risk, a relative accident risk of 0.420.

Pattern 2

The most frequent driving periods in this pattern occur from early morning (about 2 a.m.) until slightly before noon. Off-duty times occur from early afternoon until near midnight. Driving is irregular during the first 4 days of this pattern but highly regular for the last 3 days with steep peaks; for example, nearly 75 percent of the drivers are on duty at 11 a.m. on the sixth day. This driving pattern is associated with a low level of accident risk, a relative accident risk of 0.307.

Pattern 3

The most common on-duty hours in this pattern are in the morning, beginning after midnight and extending until nearly noon. The most common off-duty time is noon to midnight. Driving becomes infrequent during the last 2 days of the pattern but is highly regular during the first 5 days; for example, on the fourth day nearly 80 percent of the drivers are on duty at about 6 a.m. This pattern is associated with moderate accident risk, a relative accident risk of 0.398.

Pattern 4

The most frequent on-duty hours in this pattern are from morning, about 10 a.m., through the afternoon, until about 6 p.m. Hours are regular for the first 3 days but somewhat less so during the fourth and even less so during the fifth. Driving is unlikely during Days 6 and 7. Off-duty hours typically occur from evening (about 6 p.m.) through early morning (about 6 a.m.). Nearly 80 percent of the drivers in this group are on duty at noon on the first and second days. This pattern is associated with a low level of accident risk, a relative accident risk of 0.322.

Pattern 5

The most frequent on-duty time for this group of drivers occurs from early evening, around 8 p.m., through early morning, about 6 a.m. Off-duty times are typically late morning through early afternoon. This pattern is highly regular during the first 2 days (more than 80 percent of the drivers on duty at the beginning of the second day) and somewhat less so during Days 3, 6, and 7. The least frequent on-duty days are the fourth and fifth. This pattern is associated with the lowest level of accident risk, a relative accident risk of 0.241.

Pattern 6

This pattern contains drivers that are very infrequently scheduled, particularly during the first 6 days. On the seventh day, only 30 percent of the drivers in this pattern are on duty from midnight until about 6 a.m. This pattern is associated with moderate accident risk, a relative accident risk of 0.370.

Pattern 7

The most frequent on-duty times for drivers in this group are from about noon until about 6 p.m. The most likely off-duty time is from midnight until about 10 a.m. The pattern is regular on the last 3 days of the 7-day period, with nearly 80 percent of the drivers on-duty during Day 6, and somewhat less regular during Days 5 and 7. The first 4 days of the pattern demonstrate more variability, but there is a pronounced peak period; typically 40 percent or more of the drivers are on duty during the peak time. This pattern has a moderate relative accident risk of 0.340.

Pattern 8

The most frequent driving times start at about 10 p.m. and continue through about 10 a.m. The most frequent off-duty times are 10 a.m. through about 10 p.m. The pattern is highly regular during the last 4 days, with a peak of 70 percent of the drivers on duty on Days 5, 6, and 7. The first 3 days exhibit much higher variability. This pattern has the highest accident risk in the data set, a relative accident risk of 0.442.

Pattern 9

The most frequent on-duty time for these drivers is throughout the afternoon and evening from about 6 p.m. until just after midnight. The most likely off-duty time is late morning and early afternoon. The most frequent on-duty days are Days 1 through 5, but there is much less peaking within this pattern. This pattern is associated with low accident risk, a relative accident risk of 0.341.

Comparisons Between Patterns

Several trends emerge from an inspection of the clusters. Patterns 1, 2, 7, and 8 all contain infrequent, irregular driving during the first 3 to 4 days but highly regular driving thereafter. This is derived from, for example, the observation that 40 percent or fewer of the drivers in Pattern 1 are on duty or driving from about noon to midnight on Days 1 through 4, but this percentage rises to 70 percent on Days 5 and 7 and 80 percent on Day 6. On the other hand, Patterns 3, 4, and 9 have regular driving during Days 1 though 4 and more irregular driving thereafter.

Several sets of patterns have similar peak hours of driving within the day but differ principally in which days of the 7-day period have irregular duty hours. For example, both Patterns 1 and 9 contain peak driving from early afternoon (e.g., 3 p.m.) until early morning (e.g., 3 a.m.). The major difference is that Pattern 1 has irregular duty hours on the first 4 days, whereas Pattern 9 has irregular duty hours on Days 5 though 7. This "phase shift" is also apparent in comparisons of Patterns 2 and 3, 4 and 7, and 5 and 8.

Additional insight is obtained by comparing the accident risk of the pairs of patterns that appear similar except for the phase shift of 3 to 4 days. Recall that these phase shift pairs

are Patterns 1 and 9, 2 and 3, 4 and 7, and 5 and 8. Examination of the relative accident risks indicates that patterns containing signficant on-duty time during Days 5 through 7 (Patterns 1, 2, 7, and 8) have a consistently higher accident risk than the comparable paired patterns (i.e., Patterns 9, 3, 4, and 5), which have off-duty time during Days 5 through 7 with one exception. Pattern 2 has a lower risk than Pattern 3 (0.307 versus 0.398) even though Pattern 2 contains frequent driving on Days 5 through 7. Thus there appears to be increased risk due to cumulative driving that occurs over several driving days, even for similar times of day. It is clear, however, that this effect is not consistent across all pairs: Patterns 4 and 7 show small accident risk differences, whereas Patterns 1 and 9 and 5 and 8 have large differences; Patterns 2 and 3 show an opposite trend.

A detailed comparison of the accident risk of the phase shift pairs provides additional insights into the cumulative effects of driving. Pattern 5 (with the lowest relative accident risk) has, as a pair, Pattern 8, which has the highest risk. One may think of these two patterns as the same except for the day within the driving pattern that the observation is initiated. For example, the drivers in Pattern 8 drive infrequently during the first 2 days of observation. Drivers in Pattern 5 drive infrequently during Days 3 and 4. It can thus be hypothesized that Patterns 5 and 8 represent two similar driving patterns over an 8-day period; the primary difference is when within the 8-day period the accident occurred or the nonaccident trip is sampled. Therefore, it appears that drivers who begin their trips near midnight and typically end them around 10:00 a.m. face a particularly high risk after driving for several consecutive days. Comparisons of Patterns 1 and 9 yield similar findings: Pattern 1 drivers have much higher relative risk than Pattern 9 drivers, the principal difference being the amount of driving during Days 5, 6, and 7. It can be concluded that drivers who complete their trip during early morning are particularly susceptible to increased accident risk due to cumulative duty hours.

In contrast, consider the primarily daytime driving associated with Patterns 4 and 7. The relative risk changes only slightly when driving is conducted during Days 1, 2, 3, and 4 (relative risk = 0.322) rather than Days 5, 6, and 7 (relative risk = 0.370). Thus, for drivers on a fairly regular daytime schedule (i.e., 10 a.m. to 6 p.m.), there is evidence of a much smaller risk increase due to cumulative driving than for late-night and early-morning drivers.

The pair consisting of Patterns 2 and 3 illustrates a reversal in accident risk associated with the combination of frequent driving. It appears that drivers who start their trips around midnight have a higher risk when initiating a driving cycle than when driving frequently. This may be because of difficulties in transitioning from off-duty days that are "normal" (wake during day, sleep at night) to working days that are the opposite.

Measures of Individual Driver Duty Hours Within and Across Patterns

Figures 1 through 10 provide useful information about driving patterns as a description of the aggregate behavior of sets of individuals. The duty hours of individual drivers within each pattern and how they compare across patterns are also of interest. For example, it would be useful to know if the length of driving time (i.e., mean and standard deviation of consecutive driving hours) varies across patterns. Whether daily driving really has a 24-hr cycle, as is apparent from Figures 1 through 10, is important to circadian rhythms. Because the patterns are measures of aggregate behavior, they may mask the driving cycles experienced by individual drivers. In this section, a number of measures of individual driver duty hours and their implications for safety are discussed.

Table 2 presents the mean and standard deviation of the consecutive hours driven per driver for each pattern. The consecutive hours driven is defined as the total driving time that occurs between 8-hr off-duty periods mandated by DOT regulations. There is remarkable consistency in mean driving hours across all patterns. The range is from 8.38 to 7.73 hr, a mean difference of only about ½ hr. The standard deviation values are more dispersed, particularly for Pattern 6 (a value of 3.57 hr), which is the "odd" pattern with infrequent driving. Apparently Pattern 6 also contains more short driving trips than other patterns. Whereas there is some variability, the remaining standard deviations range from 0.91 to 1.47. More important, there does not appear to be any association between relative accident risk and either the mean or standard deviation of consecutive driving hours. Company scheduling policies appear to apply uniformly across the patterns, so, aside from Pattern 6, there are only small differences across patterns.

Data on cumulative driving and on-duty (not driving) time for each driver during the 7 days are summarized in Table 3. The table presents statistics on the mean and standard deviation of three measures: driving time, time on duty but not driving, and the sum of the two (total time on duty). As in Table 2, Pattern 6 stands out as one with considerably less driving. The mean cumulative hours are generally similar, as are the standard deviations except for Pattern 6 and the extremely low standard deviation for Pattern 1.

If the phase shift pairs discussed previously are considered, an interesting pattern appears. For each pair, except Patterns 2 and 3, the pattern with the higher relative accident rate also has the lower cumulative driving hours over the 7 days. It is erroneous to conclude that less driving is less safe, however, because the higher cumulative driving hours result from more duty hours on Days 1 through 4 for the low-risk patterns. They are more completely filling their limit of DOT cumulative hours during the first few days of the pattern. Those

TABLE 2 CONTINUOUS DRIVING HOURS FOR EACH PATTERN

PATTERN NUMBER	Continuous Driving (Hours/Trip)	
	Mean	Standard Deviation
1	7.81	1.31
2	8.38	0.91
3	8.33	0.93
4	8.23	1.28
5	8.00	1.47
6	7.73	3.57
7	8.01	1.01
8	7.90	1.18
9	8.06	1.43

TABLE 3 CUMULATIVE ON-DUTY HOURS FOR EACH PATTERN

PATTERN NUMBER	Driving Time (Hours)		On-Duty Not Driving Hours		Total on Duty Time	
	m*	S**	m*	S**	m*	S**
1	42.86	0.89	3.57	0.42	46.43	0.28
2	44.85	0.79	2.71	0.32	47.56	0.75
3	45.48	0.72	3.97	0.38	49.45	0.65
4	44.67	0.67	3.55	0.43	48.22	0.56
5	43.72	0.79	4.83	0.54	48.55	0.65
6	19.00	0.97	1.42	0.16	20.42	1.02
7	44.78	0.73	2.31	0.24	47.08	0.71
8	43.20	0.71	4.09	0.34	47.29	0.71
9	45.69	0.64	3.58	0.27	49.27	0.63

KEY
* m = mean
** S = standard deviation

patterns with higher risk have more driving on Days 5 through 7 but not enough to approach the DOT cumulative maximum, which is more likely to be reached on the eighth day, which is not shown. The conclusion is that these statistics support and are consistent with the presence of an increased accident risk with more recent extensive duty time.

A third indicator of individual driving within each pattern is the driving cycle, defined as the sum of consecutive driving and on-duty times and the subsequent off-duty time of 8 hr or more. The driving cycle is thus intended to estimate the periodicity of driving. To screen cycles that include 1 or more full days off duty (due to lack of freight or being "out of hours"), a maximum of 24 hr off duty is allowed for a driving cycle. The result is a variable that describes the period of duty when the driver is regularly scheduled. The concern is that the aggregate behavior displayed in Figures 1 through 10 is almost too good. There is a nearly 24-hr period despite the fact that drivers may be scheduled with an 18-hr period (i.e., 10 hr driving and 8 hr off duty). The driving cycle variable is intended to check whether individual drivers actually are scheduled with a nearly 24-hr period, which would clearly be beneficial with respect to circadian rhythms. If the actual period is significantly less than 24 hr, the driver's time on the road will not be stable with respect to time of day, and, according to theory, additional decrements in performance can be expected (*7*).

Table 4 summarizes the driving cycle data for each of the nine patterns. The mean and standard deviation of the driving cycle are reported in the sixth set of columns (labeled Driving Cycle). Columns 1 through 5 report the same statistics for the duty hours that make up the driving cycle: the time on duty and driving; the time on duty and not driving (e.g., time for pretrip inspection); time on duty and not driving during the trip because of short rest breaks (e.g., meals), the total on-duty time (the total time in activities represented in Columns 1 through 3), and subsequent off-duty time of at least 8 hr. Whereas Pattern 6 is again anomalous, all other patterns have mean driving cycles from 22.08 to 23.03 hr, with most in the range 22.7 to 22.9 hr. There appears to be substantial evidence that the driving cycle, as defined, is much closer to 24 hr than the minimum driving times might suggest. This could be due to one of two reasons or a combination of the two. First, as Table 4 indicates, there is a mean of approximately 1 hr on duty with short rest and 0.50 hr on duty and not driving for each driving cycle. This pushes total on-duty time to close to 10 hr. Consecutive off-duty time, however, has a mean of 12 hr or more (even when excluding off-duty times beyond 24 hr). Drivers thus do not appear to be scheduled for maximum driving time and minimum off-duty time (on the basis of DOT regulations). One explanation could be that the schedules are determined partially by freight demand as well as DOT regulations. Because most businesses served by LTL operators open and close with a 24-hr period, freight movement demand may coincide (somewhat serendipitously) more closely with driver circadian rhythms, contributing to road safety.

SUMMARY

Driving at different times of day within 1 day, and over several days, is associated with different levels of accident risk. Analysis of accident and nonaccident data from an LTL carrier

TABLE 4 SUMMARY OF DRIVING CYCLES FOR EACH PATTERN

	ONDUTY-DRIVE		ONDUTY-NOT DRIVE		ONDUTY-SHORT REST		ONDUTY-TOTAL		OFFDUTY TIME		DRIVING CYCLE	
	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV	MEAN	ST. DEV
PATTERN 1	8.05	1.62	0.53	1.10	0.96	0.79	9.55	1.83	13.18	3.90	22.73	4.32
PATTERN 2	8.40	1.62	0.42	1.00	1.04	0.89	9.86	2.20	12.92	3.60	22.79	4.21
PATTERN 3	8.32	1.46	0.49	1.00	1.04	0.70	9.84	1.77	13.03	3.69	22.88	4.12
PATTERN 4	8.25	1.35	0.42	0.96	0.91	0.74	9.58	1.62	12.73	3.74	22.31	4.00
PATTERN 5	8.12	1.56	0.64	1.12	1.03	0.80	9.78	2.02	13.06	3.67	22.84	4.21
PATTERN 6	7.88	1.34	0.28	0.58	0.94	0.76	9.10	1.93	11.98	3.64	21.08	4.22
PATTERN 7	8.13	1.37	0.37	0.81	0.95	0.80	9.45	1.92	12.63	3.66	22.08	4.13
PATTERN 8	8.18	1.57	0.63	0.99	1.05	0.89	9.86	2.06	12.95	3.46	22.81	3.93
PATTERN 9	8.43	2.49	0.49	0.84	0.97	0.91	9.89	2.95	13.14	3.70	23.03	4.63

representing 6 months of operation in 1984 are used to explore changes in daily and multiday accident risk. Cluster analysis is used to extract a distinct pattern of driving over a 7-day period from a sample of 1,066 drivers (including those with accidents and nonaccidents on the eighth day).

The analyses yielded clear interpretable driving patterns that could be associated with levels of relative accident risk. Higher risk was generally, but not exclusively, associated with extensive driving in the 2 to 3 days preceding the day of interest. The two patterns with the highest risk of an accident were those that contained heavy driving during the preceding 3 days and consisted of driving from 3:00 p.m.to 3:00 a.m. (Pattern 1) and from 10:00 p.m. to 10:00 a.m. (Pattern 8). The lowest risk was associated with driving from 8:00 p.m. to 6:00 a.m. but with limited driving on the preceding 3 days.

With the exception of a pattern representing infrequently scheduled drivers (Pattern 6), the remaining 8 patterns are classified into 4 pairs identified by common times of driving within a day. The differentiating feature is whether driving occurs in the first 3 to 4 days of the driving period or the last 2 to 3 days before the day of interest. Given the virtually limitless possible combinations of driving schedules, it is encouraging that interpretable distinct multiday patterns could be extracted from a data base of more than 1,000 observations.

Within each pattern, drivers experienced similar duty hours: cumulative driving over the 7 days ranged from 47 to 49 hr. Continuous driving (between mandatory 8-hr off-duty periods) ranged from 7.8 to 8.4 hr. Individual drivers also experienced a cycle of on-duty and off-duty time that ranged from 22.3 to 23 hr, closer to the 24-hr period that is desirable from the perspective of human performance theories.

It is clear, however, that there are no simple explanations for multiday accident risk. Rather, drivers who drive at particular times of day appear to face changing accident risks within any 8-day driving period. The findings indicate that it is possible to quantitatively account for both hours of driving over a 7-day period and the time of day when the driving occurred. Numerous additional analyses are possible with the existing data set or with enhancements made to the existing data. The following paragraphs summarize areas for fruitful future research.

There is a need to explore additional driving patterns and their effect on accident risk. Whereas the nine clusters in this study yielded interpretable results, additional insights may be gained by developing a larger number of clusters that are more precise in their driving patterns. This analysis requires additional data, beyond the 1,066 cases used in this study. It is difficult to determine when the optimal number of clusters has been identified because the statistical method, cluster analysis, is heuristic. Analyses of additional driver variables, such as age and experience, and descriptors of the routes used by the drivers (road design, traffic level, and terrain) would be useful additional information to include in subsequent analyses. Individual driver sociodemographic characteristics, such as marital status and family structure, may also help explain accident risk.

It is hoped that the use of cluster analysis to identify multiday driving patterns will encourage similar studies with this methodology. Disaggregate analyses are becoming much more common in the truck safety literature (*13,14*) and offer the prospect of more accurate identification of relative accident risk as well as the absolute probability of accident occurrence (*12*). It is hoped that this paper contributes to this trend.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the University of California Transportation Center (through Caltrans and the U.S. Department of Transportation) and Yellow Freight System, Inc.

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

Data from TRB-Proposed National Monitoring System and Procedures for Analysis of Truck Accident Rates

T. CHIRA-CHAVALA

To follow trends of truck accident involvement rates requires reliable information on truck accidents and travel. Procedures for estimating truck accident involvement rates and their confidence limits on the basis of variabilities inherent in the sample design of the TRB-proposed National Monitoring System (NMS) are presented. Formulas for computing confidence limits of national and state truck accident involvement rates per mile of travel are given for any level of disaggregation. The quality of truck accident and travel data that may be expected from implementing the NMS, together with consistent estimation of confidence limits of accident involvement rates, would represent significant improvement over truck safety statistics available from existing data programs.

Fatalities, personal injuries, and property damage resulting from truck crashes constitute major public health and economic problems. Each year, about 5,000 deaths, 50,000 personal injuries, and up to $1 billion in property damage are caused by accidents involving heavy or medium trucks (those with gross vehicle weight more than 10,000 lb) (*1*). Public concern is growing that truck safety is quickly deteriorating. However, existing truck accident and travel data are inadequate to address this concern, support essential government planning functions, guide public and private policy decisions on truck operations, or guide actions to reduce accidents and losses.

The annual numbers of truck accidents reported by NHTSA's National Accident Sampling System (*2*), the National Safety Council accident statistics (*3*), and the Office of Motor Carriers (OMC) accident data (*4*) are not in agreement. Estimates of annual truck miles of travel reported by existing sources also vary greatly [e.g., FHWA's *Highway Statistics* (*5*), the Census Bureau's *Truck Inventory and Use Survey* (*6*), and the private National Truck Trip Information System (*7*)]. As a result, information is not available to reliably assess the magnitude and the trends of the safety performance of various truck types or to determine the extent to which truck safety may be improving or worsening (*1*). This has helped to fuel the controversy about truck safety.

Recently, two major studies aimed at closing the truck safety information gap have been completed. They are the National Governors' Association (NGA) study on uniform truck accident reporting among states (*8*) and TRB's *Special Report 228: Data Requirements for Monitoring Truck Safety* (*1*). The NGA study recommends uniform data elements and criteria for states to use in reporting accidents involving trucks or buses. *Special Report 228* recommends a plan for developing the National Monitoring System (NMS) that will assemble nationwide accident and travel data of medium and heavy trucks (those with gross vehicle weight ratings more than 10,000 and 26,000 lb, respectively) on an ongoing basis. Recommendations from the two studies are related and complementary in that implementation of the NGA recommendations would bring about uniform truck accident data among states. Uniform state accident data could then be combined into a single national truck accident data base, a major component of the proposed NMS.

University of California, Berkeley, Calif. 94720.

Among the recommendations of *Special Report 228* are a detailed data plan for developing the NMS, an implementation timetable, organizational arrangements, and cooperative efforts among federal and state governments and industry. To illustrate intended applications of the NMS, the TRB report identifies benchmark questions that the NMS should, as a minimum, provide the data to address (Figure 1). The TRB report states that accurate information on trends of truck accident frequency, truck miles of travel, and rates (Benchmark Question 1) is particularly important because it is needed for guiding and evaluating policy decisions concerning truck operations.

The TRB report, however, does not describe procedures for analyzing the accident and travel data to be available from the NMS. This paper provides this missing link. Its objectives are to describe truck accident and travel data that can be expected from the implementation of the NMS and to present procedures for estimating truck accident involvement rates and their statistical confidence limits on the basis of variabilities inherent in the sampling of accidents and truck miles.

SUMMARY OF NGA RECOMMENDATIONS ON UNIFORM TRUCK ACCIDENT REPORTING AMONG STATES

The NGA study (*8*) recommends that states report all truck accidents that result in fatalities, serious injuries (in which the injured is taken from the scene), and property damage only (PDO) in which at least one of the vehicles involved is towed away because it is inoperable as a result of the accident. States may choose lower accident reporting thresholds as long as "towaway" accidents can be distinguished from other PDO accidents. The study also recommends that states include uniform data elements (*9*) in their accident report forms or supplemental forms.

Question 1. What are the trends in numbers of truck accidents, amount of truck travel, and truck accident involvement rates per mile traveled, disaggregated by truck type, road class, region, and carrier type?

Question 2. What are the relationships between truck accident involvement rates and driver age?

Question 3. What are the kinds of crashes (e.g. overturn, jackknife, separation of units, collision with another vehicle) in which different types of trucks are likely to be involved, and what are the corresponding severity levels?

Question 4. What are the trends in the numbers and severity of crashes involving trucks placarded for carrying hazardous cargoes, disaggregated by truck type, road class, region, carrier type, and driver age?

Question 5. What are the possible underreporting and other biases of other truck accident and travel data programs, on the basis of comparisons of statistics between these programs and the proposed National Monitoring System?

FIGURE 1 Benchmark questions defining the NMS (*1*).

The NGA conducted a pilot test in five Midwestern states for 3 months in 1988 to determine whether police officers who report accidents might encounter major reporting problems. The pilot test does not indicate major reporting problems by police officers who participated in the test (*9*).

OVERVIEW OF DATA EXPECTED FROM TRB-PROPOSED NMS

The proposed NMS calls for the development of two data modules: national truck accident data and national truck travel data. Data elements and their levels of details for these two modules are shown in Figures 2 through 4. Data from the NMS would eventually permit derivation of statistically reliable estimates of truck accident rates both nationwide and for individual states. However, it will take a number of years for all states to adopt uniform truck accident data reporting within their boundaries. *Special Report 228*, therefore, recommends that the NMS be implemented in two phases so that improved national truck accident and travel data can become available immediately.

Vehicle
- o Vehicle configuration
- o Cargo body style
- o Vehicle identification number
- o Hazardous cargoes involvement:
  - - Was hazardous cargo present in the truck?
  - - Hazardous cargo class
  - - Was hazardous cargo released?

Carrier
- o Carrier identification

Driver
- o Driver identification
- o Driver age

Accident
- o Accident events
- o Accident severity
  - - Number of fatalities
  - - Number of injured people, transported away
  - - Number of vehicles towed away

Roadway
- o Roadway functional class
- o Degree of urbanization (Rural or urban)
- o Trafficway (undivided or divided)
- o Access control
- o Road surface condition

Environment
- o State
- o Weather
- o Time of day
- o Light condition (day or night)
- o Day of week
- o Month
- o Year

FIGURE 2 Accident data elements required by the NMS (*1*).

Vehicle
- o Vehicle configuration
- o Cargo body style

Carrier
- o Carrier identification number

Driver
- o Driver age

Roadway
- o Roadway functional class
- o Degree of urbanization (rural or urban)

Environment
- o State
- o Light condition (day or night)
- o Season

FIGURE 3 Truck travel data elements required by the NMS (*1*).

Phase 1 Data

The TRB report recommends that a national truck travel component and a short-term national truck accident component be developed in Phase 1.

Short-Term National Truck Accident Data

While states are moving toward adopting the NGA uniform truck accident reporting recommendations, short-term national truck accident data could be developed immediately by augmenting data from the truck subset of NHTSA's Fatal Accident Reporting System (FARS) and General Estimates System (GES). The short-term national truck accident data, to be available on a quarterly basis, would include the following:

- A census of the nation's fatal truck accidents, with a level of detail similar to that shown in Figure 2, would be available. Data from the truck subset of NHTSA's FARS would be augmented by adding carrier ID, cargo body style, and hazardous cargo class. These additional variables will be obtained by matching the FARS cases to OMC accident (50-T) reports and by examining available state sources for the FARS cases with no matching 50-T reports. The short-term fatal truck accident data will permit derivation of statistically reliable estimates of fatal truck accidents at both the national and the state levels.
- A sample of the nation's total truck accidents (fatal and nonfatal) with a level of detail similar to that shown in Figure 2 would be available, possibly with up to 10,000 involvements per year. Data from the truck subset of the NHTSA's GES would be augmented by adding carrier ID, cargo body style, hazardous cargo presence and release, hazardous cargo class, and "towaway." The additional variables will be acquired by matching the GES cases with the OMC 50-T reports and examining available state sources for the GES cases that have no matching 50-T reports. Because the GES accident sample is designed for making national accident estimates, these short-term total truck accident data will permit derivation of sta-

Vehicle configuration
- Single unit truck (two-axle, six-tire)
- Single unit truck (three-or more axles)
- Truck/trailer
- Truck-tractor (bobtail)
- Tractor-semitrailer
- Tractor (double)
- Tractor (triple)
- Cannot classify

Cargo body style
- Van
- Tank
- Flatbed
- Dump
- Concrete mixer
- Auto Transporter
- Garbage/refuse
- Other

Was hazardous cargo present in the truck?
- Yes
- No

Hazardous cargo class
- four-digit placard number or name
- one-digit placard number

Was hazardous cargo released?
- Yes
- No

Carrier identification
- U.S. Department of Transportation number
- Interstate Commerce Commission motor carrier number
- State number
- Other number
- None

Driver age

Accident severity
- Number of fatalities
- Number of injured people, transported away
- Number of vehicles towed away

Accident events (in order of occurrence)
- Ran off road
- Jackknife
- Overturn
- Downhill runway
- Cargo loss or shift
- Fire
- Separation of units
- Collision with pedestrian
- Collision with motor vehicle
- Collision with parked vehicle
- Collision with train
- Collision with pedalcycle
- Collision with animal
- Collision with fixed object
- Collision with other object
- Other

Roadway functional class (source: states)
- Interstate
- Other principal arterial
- Major arterial
- Major collector
- Minor collector
- Local road or street

Degree of urbanization (source: states)
- Rural
- Urban

Trafficway
- Undivided two way
- Divided, without traffic barriers
- Divided, with traffic barriers
- One way

Access control
- Unlimited access
- Full control
- Other

Road surface condition
- Dry
- Wet
- Snow
- Ice
- Sand, mud, dirt, oil
- Other
- Unknown

State

Weather
- No adverse conditions
- Rain
- Sleet or hail
- Snow
- Fog
- Blowing sand, soil, dirt, or snow
- Severe crosswind
- Other
- Unknown

Time of day

Light conditions
- Daylight
- Dark (not lighted)
- Dark (lighted)
- Dawn
- Dusk
- Unknown

Day of week

Month

Year

FIGURE 4 Levels of detail of the NMS data elements (*1*).

tistically reliable national estimates of total truck accidents, but not estimates for individual states.

National Truck Travel Data

National truck travel data with a level of detail similar to that shown in Figure 3 can be assembled immediately in Phase 1 for use in deriving national and state estimates. National truck travel data would be assembled from truck classification–travel data that individual states are collecting for FHWA's Highway Performance Monitoring System (HPMS) on the basis of probability samples of HPMS road sections. The TRB report recommends that states follow guidelines published in FHWA's *Traffic Monitoring Guide* (*10*) in collecting truck classification–travel data. The state data, however, would not have information on cargo body style, carrier type, or driver age. These three variables will be obtained from the fraction of the state Motor Carrier Safety Assistance Program's (MCSAP's) truck safety inspections that is based on random selections of trucks.

Phase 2 Data

After states adopt the NGA uniform truck accident reporting recommendations, a long-term national truck accident data base will be developed to replace the short-term accident data. Uniform truck accident data from individual states will be combined into a national truck accident data base. The long-term accident data will have a level of detail as shown in Figure 2 and will permit derivation of statistically reliable accident estimates nationwide and for individual states.

National truck travel data developed in Phase 1 will also be applicable in Phase 2.

Quality of the NMS Data

Special Report 228 emphasizes that the NMS accident and travel data must have known quality and limitations that can be accounted for in the analysis of truck accident involvement rates.

GENERALIZED FORMULAS FOR ESTIMATING ACCIDENT RATES AND CONFIDENCE LIMITS

Accident involvement rates per mile of travel are the most commonly accepted measure for comparing safety performance of various truck types or operating conditions. Truck travel data of the NMS will be derived from truck counts on samples of road sections conducted independently by states. Estimates of truck miles of travel within individual states will have random variations due to the sampling. Random variations due to sampling will also exist in national estimates of truck accidents that are obtained from the short-term total truck accident data of Phase 1, because these data will be derived from the truck subset of GES (a probability sample of the nation's police-reported accidents). Truck accident involvement rates derived from the sampled accident and travel data will inherit these sampling variabilities, which must be accounted for in order to correctly interpret trends of accident involvement rates. This can be accomplished by estimating statistical confidence intervals (CIs) of accident involvement rates. Formulas to do this are presented below for the following two cases:

- Both accident and travel data come from probability samples; the source of random variations to be accounted for in estimating confidence limits is that due to the sampling of accidents and truck miles.
- Truck travel data come from probability samples, whereas the accident data come from the census of reported truck accidents. The source of random variations to be accounted for in estimating confidence limits is that due to the sampling of truck miles; there is no random variations due to sampling for the census of accidents.

The following formulas are derived for accident involvement rates per mile of travel, disaggregated by two variables. Disaggregation involving any other number of variables follows the same procedure.

Case A: Both Accident and Travel Data Come from Probability Samples

Let i and j denote the ith truck type and the jth road class; Y_{ij} and X_{ij} denote the number of accidents and truck miles, respectively, for the ith truck type on the jth road class; and R_{ij} denote the accident involvement rate per mile of travel for the ith truck type on the jth road class.

Kish (*11*) derived a theoretical value of the sampling variance of R_{ij}, $Var(R_{ij})$, as shown in Equation 1. All parameters in Equation 1 are expected values (i.e., theoretical values).

$$\begin{aligned}\mathrm{Var}(R_{ij}) &= E[R_{ij} - E(R_{ij})]^2 \\ &= \frac{1}{X_{ij}^2}[\mathrm{Var}(Y_{ij}) + R_{ij}^2\mathrm{Var}(X_{ij}) \\ &\quad - 2R_{ij}\mathrm{Var}(Y_{ij}, X_{ij})] \end{aligned} \tag{1}$$

An unbiased estimate of the sampling variance of R_{ij} can be obtained by substituting sample values throughout Equation 1 to yield Equation 2.

For Equation 2 and all the formulas that follow, the parameters shown are sample values (i.e., unbiased estimates of the expected values shown in Equation 1). The same symbols are used in Equation 1 and in all the other equations to eliminate the need for two different sets of symbols—one denoting the theoretical values and the other unbiased sample values. In this way, the volume of notations may be reduced significantly.

$$\begin{aligned}\mathrm{var}(R_{ij}) &= \frac{1}{X_{ij}^2}[\mathrm{var}(Y_{ij}) + R_{ij}^2\mathrm{var}(X_{ij}) \\ &\quad - 2R_{ij}\mathrm{cov}(Y_{ij}, X_{ij})] \end{aligned} \tag{2}$$

where

$\mathrm{var}(X_{ij})$ = an unbiased estimate of the sampling variance of truck-miles, $\mathrm{Var}(X_{ij})$;
$\mathrm{var}(Y_{ij})$ = an unbiased estimate of the sampling variance of the number of accidents, $\mathrm{Var}(Y_{ij})$; and
$\mathrm{cov}(Y_{ij}, X_{ij})$ = an unbiased estimate of sampling covariance of accidents and truck miles, $\mathrm{Var}(Y_{ij}, X_{ij})$.

For truck accident and travel data that are independently collected from different sample designs and sample units, $\mathrm{cov}(Y_{ij}, X_{ij})$ does not exist. Therefore, an unbiased estimate of the sampling variance of R_{ij} becomes

$$\mathrm{var}(R_{ij}) \approx \frac{1}{X_{ij}^2}[\mathrm{var}(Y_{ij}) + R_{ij}^2\mathrm{var}(X_{ij})] \tag{3}$$

The $(1 - \alpha)$ percent CI of R_{ij} is expressed as

$$(1 - \alpha)\text{ percent CI}(R_{ij}) = R_{ij} \pm c\sqrt{\mathrm{var}(R_{ij})} \tag{4}$$

where α is the Type I error and c is a two-sided normal variate corresponding to α.

Substituting Equation 3 into Equation 4 yields a generalized formula for CI of accident involvement rate for the ith truck type on the jth road class, as follows:

$$\mathrm{CI}(R_{ij}) = R_{ij} \pm c\,\frac{\sqrt{\mathrm{var}(Y_{ij}) + R_{ij}^2\mathrm{var}(X_{ij})}}{X_{ij}} \tag{5}$$

Case B: Accident Data Come from a Census and Travel Data Come from a Sample

For the census of accident involvements, variability due to sampling does not exist. Therefore $\mathrm{var}(Y_{ij}) = 0$, and the generalized CI formula of Equation 5 becomes

$$\mathrm{CI}(R_{ij}) = R_{ij} \pm c\,\frac{\sqrt{R_{ij}^2\mathrm{var}(X_{ij})}}{X_{ij}}$$

or

$$\mathrm{CI}(R_{ij}) = \frac{R_{ij}}{X_{ij}}[X_{ij} \pm c\sqrt{\mathrm{var}(X_{ij})}] \tag{6}$$

PROCEDURES FOR CALCULATING CIs OF INVOLVEMENT RATES USING NMS DATA

Accident involvement rates per mile of travel by truck type, road class, carrier type, and so on can be calculated from future NMS data. Random variations in accident involvement rates due to sampling variabilities of truck miles and accidents can be quantified by estimating statistical confidence intervals of these rates. Because truck accident data in Phases 1 and 2 of the NMS are expected to be different, different procedures for estimating CIs of accident involvement rates are suggested for the two phases, as follows. The notation is first introduced. For ease of illustration, the CI procedures are based on truck accident involvement rates dissaggregated by two variables, truck type and road class. Other levels of disaggregation involving any number of variables follow the same procedure.

Notation	*Meaning*
i	subscript denoting the ith truck type
j	subscript denoting the jth road class
k	subscript denoting the kth state
y	unbiased estimate of accident involvement within state
x	unbiased estimate of truck miles within state
r	unbiased estimate of accident involvement rate for the state
Y	unbiased national estimate of accident involvement
X	unbiased national estimate of truck miles
R	unbiased estimate of national accident involvement rate

Confidence Interval Procedure for Phase 1 Data

The NMS accident data in Phase 1 would consist of two short-term components: the census of nationwide fatal truck accident involvements and a sample of up to 10,000 nationwide total (fatal plus nonfatal) truck accident involvements.

Truck-mile estimates by state would be available from the classification counts that individual states carry out on samples of HPMS road sections. Procedures for calculating CIs for fatal and nonfatal involvement rates are as follows.

CI of Fatal Involvement Rates Nationwide and by State

The annual number of fatal truck involvements nationwide, Y_{ij}, would be known without sampling variance, because it is the census of fatal accident involvements. Estimates of truck miles of travel by state (x_{ijk}) and their sampling variances [$var(x_{ijk})$] would also be known from individual states' samples.

An unbiased estimate of the national fatal involvement rate for the ith truck type on the jth road class, R_{ij}, is obtained as

$$R_{ij} = \frac{Y_{ij}}{X_{ij}} = \frac{Y_{ij}}{\sum_k x_{ijk}}$$

From Equation 6,

$$\mathrm{CI}(R_{ij}) = \frac{R_{ij}}{X_{ij}} \left[X_{ij} \pm c \sqrt{\mathrm{var}(X_{ij})} \right]$$

States independently derive estimates of truck miles from samples of road segments, and then these estimates are combined to yield a national estimate. Therefore

$$\mathrm{CI}(R_{ij}) = \frac{R_{ij}}{\sum_k x_{ijk}} \left[\sum_k x_{ijk} \pm c \sqrt{\sum_k \mathrm{var}(x_{ijk})} \right] \quad (7)$$

An unbiased estimate of the fatal involvement rate for the ith truck type on the jth road class in the kth state, r_{ijk}, is

$$r_{ijk} = \frac{y_{ijk}}{x_{ijk}}$$

From Equation 6,

$$\mathrm{CI}\ (r_{ijk}) = \frac{r_{ijk}}{x_{ijk}} \left[x_{ijk} \pm c \sqrt{\mathrm{var}(x_{ijk})} \right] \quad (8)$$

CI of Nonfatal Involvement Rates Nationwide

In Phase 1, only estimates of the national number of nonfatal accident involvements would be available from the NMS. Estimates of nonfatal accident involvements by state would not be statistically reliable. Therefore, only nationwide nonfatal truck involvement rates can be reliably estimated, not rates by state.

An estimate of the annual nationwide number of nonfatal involvements for the ith truck type on the jth road class (Y_{ij}) as well as its sampling variance, var(Y_{ij}), would be known. Estimates of truck miles of travel for individual states (x_{ijk}) and their sampling variances [var(x_{ijk})] would also be known from individual states' samples, which are independent of one another. These states' estimates of truck miles can be combined to yield a national estimate of truck miles.

An unbiased estimate of the national nonfatal involvement rate for the ith truck type on the jth road class is as follows:

$$R_{ij} = \frac{Y_{ij}}{X_{ij}} = \frac{Y_{ij}}{\sum_k x_{ijk}}$$

From Equation 5,

$$\mathrm{CI}\ (R_{ij}) = R_{ij} \pm c \frac{\sqrt{\mathrm{var}(Y_{ij}) + R_{ij}^2\ \mathrm{var}(X_{ij})}}{X_{ij}}$$

Substituting $X_{ij} = \sum_k x_{ijk}$ yields

$$\mathrm{CI}(R_{ij}) = R_{ij} \pm c \frac{\sqrt{\mathrm{var}(Y_{ij}) + R_{ij}^2 \sum_k \mathrm{var}(x_{ijk})}}{\sum_k x_{ijk}} \quad (9)$$

Confidence Interval Procedure for Phase 2 Data

Recall that in Phase 2, the census of fatal and nonfatal accident involvements would be available nationwide and by state. Estimates of truck miles by state identical to those of Phase

1 would continue to be available in Phase 2. Because fatal and nonfatal accident data of Phase 2 would be derived from the same source, the same CI procedures apply for fatal and nonfatal accident involvement rates.

The numbers of accidents for individual states, y_{ijk}, would be known without any sampling variances. Estimates of truck miles of travel for individual states (x_{ijk}) and their sampling variances [$\text{var}(x_{ijk})$] would be known from individual states' samples, which are independent of one another.

A national estimate of involvement rate for the ith truck type on the jth road class is expressed as

$$R_{ij} = \frac{Y_{ij}}{X_{ij}} = \frac{\sum_k y_{ijk}}{\sum_k x_{ijk}}$$

From Equation 6,

$$\text{CI}\ (R_{ij}) = \frac{R_{ij}}{X_{ij}} \left[X_{ij} \pm c\sqrt{\text{var}(X_{ij})} \right]$$

Substituting $X_{ij} = \sum_k x_{ijk}$ yields

$$\text{CI}\ (R_{ij}) = \frac{R_{ij}}{\sum_k x_{ijk}} \left[\sum_k x_{ijk} \pm c\sqrt{\sum_k \text{var}(x_{ijk})} \right] \quad (10)$$

The estimate of involvement rates for the ith truck type on the jth road class in the kth state is expressed as

$$r_{ijk} = \frac{y_{ijk}}{x_{ijk}}$$

From Equation 6,

$$\text{CI}\ (r_{ijk}) = \frac{r_{ijk}}{x_{ijk}} \left[x_{ijk} \pm c\sqrt{\text{var}(x_{ijk})} \right] \quad (11)$$

CONCLUSION

Once the NMS is implemented, improved national truck accident and travel data will be available for the analysis of truck accident involvement rates by various levels of disaggregation. Reliable truck safety information will be available to support public and private policy decisions concerning truck safety and operations. In particular, various important trends of truck accident involvement rates could be more accurately measured, and random variations of these rates due to sampling variabilities inherent in the accident and travel data could be assessed. This would represent significant improvement over truck safety statistics available from existing data programs.

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

Accident Rates of Multiunit Combination Vehicles Derived from Large-Scale Data Bases

ROGER D. MINGO, JOY R. ESTERLITZ, AND BRET L. MINGO

The operating characteristics of multitrailer vehicles could be expected to make them more dangerous than other vehicles, but previous accident involvement studies have produced mixed results, with no consistently strong indications of greater hazard. A review of these studies, however, indicates sufficiently severe limitations in their sample sizes and data reliability to readily explain the great degree of scatter in their findings. The size and reliability issues of previous studies are overcome by using large national data sources to calculate overall involvement rates of various vehicle configurations. No suitable sources of nonfatal accidents or disaggregate travel information were located. Use of national data rather than state and highway-type-specific data obscures the safety effects of differences in vehicle operations but at least allows an overall comparison of fatal accident involvement rates. Because current multitrailers are concentrated more than single trailers on the safest highways, rural Interstates, multitrailers appear in this study to be safer than they would if differences in operations were considered. The most reliable sources of fatal accident and travel data indicate that multitrailers, single trailers, and single-unit trucks have fatal accident involvement rates of 9.96, 6.01, and 3.00 per 100 million mi traveled, respectively. The ratio of fatal accident involvement rates for multitrailers to single trailers is 1.66. The multitrailer to single-unit truck ratio is 3.32. Most previous studies have indicated doubles or multitrailer fatal accident rates to be higher than singles, but with less difference. The higher ratios here can be attributed in part to larger and more reliable data sources than have been used in the past.

As trucks have grown in size and prevalence in recent years, the safety of heavy trucks has become an increasingly important public policy issue. The driving public overwhelmingly considers large trucks, especially doubles and triples, to be unsafe. Public fears of such vehicles have been widely expressed through opinion surveys as well as letters to the press and elected representatives. Because large multiunit trucks are less stable, more subject to environmental forces, more difficult to stop safely, and more difficult to keep on a desired path than other vehicles, such fears appear to be intuitively justified.

Despite the commonsense expectation of the greater danger of large multiunit trucks, studies of accident and fatality involvement rates of large multiunit vehicles have produced mixed results. Most such studies have been hampered by data availability and reliability. Most have been based on small sample sizes. Many have compared accident rates of vehicles in general use with accident rates of a small number of vehicles operating in special environments or under special conditions. Together, the unreliable data, small samples, and great differences in how various vehicles are used could be expected to produce a great deal of scatter in estimates of accident involvement rates, as appears to be the case.

The objective of this study was to identify and analyze the most valid large-scale sets of national accident and travel data available and to use these data sets to derive the best possible estimates of accident or fatality involvement rates of multiunit and other truck configurations. A lack of sufficient data prevented the desirable disaggregate comparison of relative accident rates on different highway facility types in different regions of the country. Although the aggregate comparison presented obscures the differences in operations of multiunit and other vehicles, the approach used overcomes previously prevalent sample size deficiencies.

REVIEW OF PREVIOUS STUDIES

Operating Characteristic Studies

Two recent reports to Congress by FHWA discussed safety issues associated with large multiunit combination vehicles. *The Feasibility of a Nationwide Network for Longer Combination Vehicles* (*1*) in June 1985 reported large multitrailer vehicles to be much worse than current large one-trailer vehicles at accelerating to and maintaining highway speeds. Triples and Rocky Mountain doubles were also reported to be much less stable—more likely to jackknife, overturn, and wander from a straight path while traveling on a straight highway. All of these larger combinations were found to be more prone to unsafe braking as a result of poor brake adjustment. The study concluded that despite the safe records of such vehicles in their specially permitted operations, there was not enough evidence to indicate that these difficulties could be overcome sufficiently to allow them to be safely operated in general use.

The other FHWA study, *Longer Combination Vehicle Operations in Western States* (*2*), reaffirmed the findings of the earlier study. In addition, a high percentage of drivers who operated triples during tests in Utah and Colorado were reported to have pointed to the triples' sway and other characteristics as factors making them less safe than more conventional trucks. Several drivers who wrote to the docket for

R. D. Mingo and B. L. Mingo, R. D. Mingo and Associates, 2233 Wisconsin Avenue, N.W., Suite 542, Washington, D.C. 20007. J. R. Esterlitz, The Emmes Corporation, 11325 Seven Locks Road, Suite 214, Potomac, Md. 20854.

public comment set up as part of the study said that triples are unsafe vehicles with poor handling characteristics, particularly in poor weather.

According to a recent study by the University of Michigan's Transportation Research Institute (*3*), length, weight, and number of trailers all have significant influences on such vehicle characteristics as low- and high-speed offtracking, ability to brake in a straight line, rollover, handling during turns, and rearward amplification (the tendency of following trailers to deviate from a straight line when very small steering adjustments are made). The study found that the higher gross weight of larger multitrailer trucks causes a loss in turning ability at higher speeds, increasing the likelihood of sideswipe accidents. Higher weight also increases the tendency for a vehicle to roll over during turning maneuvers. Although higher gross weight decreases the tendency of an individual axle to lock up during braking, as long as there is relatively uniform trailer loading, a much more reliable way to lessen wheel lockup would be to install antilock brakes.

Increasing the number of trailers even without increasing the gross weight of a vehicle was found to greatly magnify rearward amplification and decrease the braking efficiency of a vehicle (*3*).

Accident Rate Studies

Numerous studies of multiunit combination vehicle accident rates have been performed in the past 10 years. All suffer from some degree of data reliability problems. In 1986, TRB published a special report (*4*) that in large part confirmed our assessment of the degree of data unreliability in such studies. The report contains a discussion of accident involvement and severity rates and reviews 14 studies reporting relative accident rates for twins and tractor-semitrailers. Five of the 14 studies were found by TRB to be most nearly free from obvious methodological flaws, although they still had limitations concerning the accuracy or representativeness of the data.

In a 1981 study, Chira-Chavala and O'Day (*5*) found accident involvement rates for twin-trailer and single-trailer combinations to be nearly identical. The accident data for this study were taken from accidents reported to FHWA for 1977 (the MCS-50T data base described in the next section), and the exposure estimates were based on the 1977 Truck Inventory and Use Survey (TIUS). This is one of the few previous studies to have used sufficient quantities of accident data to overcome the small-sample-size criticism. However, MCS-50T data are severely limited in their ability to provide reliably representative accident information. The 50T reports cover only interstate motor carriers who report their accidents. Studies completed since 1981 have indicated that only 30 to 60 percent of accidents that should be reported are reported. There is evidence of widely varying bias depending on geographic region, size of motor carrier, and other factors. The potential wide variations in reporting rates between singles and multis negate the accuracy of the findings. Even if there were identical reporting rates between singles and multis, however, the differences between the configurations in ratios of interstate to intrastate carriers would introduce another level of uncertainty (*5*).

Glennon in 1981 (*6*) found twin-trailer vehicles to be involved in accidents only 6 percent more frequently per mile traveled than single-trailer vehicles. The study has been faulted in legal proceedings concerning twin-trailer trucks because the procedure used to select matched pairs unnecessarily excluded some of the available semitrailer travel and accident data. The study apparently failed to attain the minimum possible statistical uncertainty in its estimates because of the small amount of data available, but the procedure did not necessarily bias the comparisons either for or against twins. The use of entirely self-reported data raises many questions as to potential bias, as does the use of a single motor carrier.

In a 1978 study in California, Yoo, Reiss, and McGee (*7*) found twin-trailer vehicles to have close to the same injury and fatal accident rates as single-trailer vehicles. The accident data were derived from 1974 State Highway Patrol reports. Exposure estimates were based on the relative proportions of singles and twins in limited observations at 15 counting stations. The traffic counts were far too few to properly account for the high degree of temporal and locational variation in travel, rendering the accident rate estimates highly uncertain. The possible differences in the predominant operational environments for the two truck configurations were also not investigated, although the extensive use of twins in California may make such differences insignificant.

In 1983 FHWA found fatal accident involvement rates of double-trailer vehicles to be 20 percent higher than involvement rates of single-trailer vehicles (*8*). Injury accident involvement rates were only 9 percent higher for twins. The data were collected from 12 motor carriers that reported miles of travel and accident data for a 12-year period. Because none of the data were closely scrutinized, there could have been bias in the self-reported data. In addition, because both double usage and overall accident rates changed during the 12-year period, bias is likely to be inherent in such a long time period. Finally, there are likely to be regional and operating-characteristics biases because of the areas and highway systems on which twins operate.

Graf and Archuleta in 1985 found doubles to be involved in accidents 12 percent more often than singles on rural highways and 21 percent less often on urban highways (*9*). Doubles were found to have a 23 percent greater chance of being involved in fatal accidents than are singles. Both travel and accident data were for 18 highway segments. In this sense, the sample design was good, because it limited comparison between twins and singles to similar operating environments. Unfortunately, the sample sizes were far too small to make significant conclusions. In addition, travel data were collected at only one location and during one time period for each highway segment, even though some of the segments had multiple entries and exits. All segments could have had differential growth in doubles and singles traffic, making the actual involvement rates uncertain.

It can be seen, then, that none of the five studies given qualified endorsements by TRB provides conclusive accident rates. Each has serious flaws. Since the 1986 TRB study, there have been three other safety studies worth reviewing here.

Jovanis et al. (*10*) used travel and accident data supplied by several large LTL motor carriers to conclude that doubles were safer than singles. Using paired comparisons, doubles were shown to have significantly lower accident rates in 1983 and 1985 and significantly higher rates in 1984. Because data from only a few motor carriers and from highways having

both doubles and singles operations were considered, the authors claimed to have controlled for roadway, traffic, and environmental variables.

The authors used data supplied by trucking companies with well-established safety programs that were known to make a good-faith effort to comply with federal safety laws. This raises many issues concerning the degree to which the results can be generalized to other companies. Also, the atypical operations among some of the participating companies (using fixed-location team drivers, for example) would cause bias if these atypical companies used doubles more or less frequently than other participating companies. Finally, the small sample sizes by themselves render any conclusions questionable and explain the major differences from year to year in relative safety of the configurations.

An FHWA study (*11*) consists of a voluntary reporting program in which several states collect travel data for selected portions of their highway systems and report corresponding accident involvements. During 1988, four states reported some data on the rural Interstate system, although during the period from 1983 to 1988 a total of 13 states reported data for between 6 months and 6 years. An unweighted average for all reporting states over the entire time period indicates that doubles have a 10 percent lower fatal accident involvement rate than singles on the rural Interstate system, a 20 percent higher rate on other rural principal arterials, and more or less random variation on the other systems, all of which have few reported data.

Although state-reported data covering all motor carriers are inherently less biased than data reported by only a few motor carriers, there are three problems with this study. First, sample sizes are far too small, are not designed to represent the national highway system, and vary greatly from year to year depending on the whim of each participating state. Second, severe limitations on state-reported accident and travel data, discussed in the following section, create substantial uncertainty in results derived from these sources. Finally, FHWA makes no attempt to analyze, adjust, evaluate, or make consistent the data submitted by each volunteer state.

In 1988 Campbell et al. (*12*) used data from the 1980 to 1984 Trucks Involved in Fatal Accidents (TIFA) data base and the 1985 National Truck Trip Information Survey from the University of Michigan. They found double-trailer fatal accident involvements to be 7 percent less than single-trailer fatal involvement rates. When adjustment for travel patterns is made by accounting for road type and time of day, however, doubles have 10 percent higher fatal involvement rates. This adjustment provides an interesting finding, but the small sample size used to estimate travel data (only 5,000 trucks of all types) makes validity of the results questionable. The biggest problem with the study, however, is that the use of accident data from one time period and travel data from another negates the validity of the results if there is differential growth among vehicle classes—a prospect that appears highly likely, because doubles were rapidly expanding during this time period. If doubles usage did grow faster than singles, a relative downward adjustment in prior-year travel estimates for doubles should be made, resulting in a relative increase in their accident rate.

In 1988 Jones and Stein (*13*) used case-control data gathered from Interstate highways in Washington State from 1984 to 1986. They found doubles to have 2.5 to 3 times the accident involvement rate of singles. The study has subsequently been criticized because sample traffic counts taken by the state produced estimates of the proportion of singles and doubles travel that did not agree with the implicit proportional estimates derived from the case-control study. Our assessment is that neither travel study used sufficient quantities of data to prove or refute the other travel estimate and that widely varying estimates of accident rates are to be expected when such small samples are used.

STUDY METHOD

Calculation of an accident or fatality involvement rate requires accurate counts of the number of accidents or fatalities as well as the miles traveled for each category of vehicle for which rates are desired. The available sources of each type of information were considered in this study, and the best ones were used. As most previous studies have found, there are severe limitations in current data related to both accidents and miles traveled by vehicle category. The most recent study to reaffirm this lack of adequate data was TRB's *Special Report 228: Data Requirements for Monitoring Truck Safety* (*14*). Thus, an important first step in the study was to consider and select the best available accident and travel data.

Choice of Accident Data Sources

Most states have established uniform accident reporting forms for use throughout their state, but wide variations exist among states. Only 22 states have any vehicle classification scheme on their accident reporting form, and only 10 of these states distinguish between doubles and other combination vehicles. Nine states have a blank space in which to enter vehicle type, with no guidance as to what classification scheme to use. The other 20 do not mention vehicle type on the form but rely on the narrative description of the accident to supply a vehicle description. The inconsistencies and gaps resulting from these varying reporting methods and classification schemes make it difficult to aggregate accident data on the national or multistate level.

One alternative to using state accident data is to use accident data reported by motor carriers. This alternative was discarded for three reasons: (*a*) even several years of data reporting by dozens of volunteer motor carriers could not produce sufficient data to produce statistically reliable results; (*b*) comparisons would not be valid because of wide variations in types of operations by various carriers, who would presumably use doubles in varying proportions; and (*c*) self-reported data are prone to inadvertent or intentional bias.

Because neither state nor self-reported data bases were deemed adequate, the use of federal data bases was thoroughly explored. The alternatives are (*a*) the MCS-50T data base of accident reports filed by interstate motor carriers for accidents involving an injury, fatality, or more than $4,400 worth of property damage (26,000 such reports were received in 1987); (*b*) the Fatal Accident Reporting System (FARS) data base consisting of all fatal highway accidents (42,000 in 1988); (*c*) the National Accident Sampling System (NASS)

consisting of accidents occurring at 50 sites nationwide (about 12,000 accidents per year); and (*d*) the TIFA program, which is not strictly a federal system but attempts to combine data from the 50T and FARS systems, supplemented by additional information.

The 50T data base covers only 30 to 60 percent of interstate truck accidents and a smaller portion of overall truck accidents. Because there is demonstrable reporting bias by carrier size, carrier type, and accident severity, the data base cannot be used to develop estimates of relative accident rates, the primary objective of this study, even though it could be used for numerous other related investigations. The NASS system has far too few heavy truck accidents to provide a statistically meaningful comparison of accident characteristics by configuration. It was not found to be useful for this study.

Both FARS and TIFA were chosen for use in this study. FARS includes a reasonably complete set of fatal highway accidents and much better configuration information than is available from the police accident reports, but still includes uncertainty as to whether some of the involved vehicles are multitrailer or single-trailer combinations. TIFA successfully matches only about one-third of the reported heavy truck fatal accidents with 50T accidents and is several years behind, but the matching process and follow-up interviews give it the best available configuration information.

Choice of Travel Data

Limitations in the current knowledge of vehicle miles of travel (VMT) are comparable with the severe limitations of accident data compilations, in which only fatal accidents are comprehensively compiled at the national level. Direct collection of VMT by the federal government is limited to the Bureau of the Census's TIUS, which surveys more than 100,000 owners of heavy vehicles at 5-year intervals. The 1987 national survey results were published and the data tape was made available in September 1990.

TIUS provides an excellent source of national travel data, with the best available vehicle configuration information and the largest, best-designed sample. One problem, however, is that travel is not reported by state or highway type. Another is that the survey covers only power units. Although tractors may operate at different times with varying numbers and types of trailers, most operate consistently with the same number of trailers. It is estimated that approximately as many miles are traveled by normally doubles tractors with single trailers as are traveled by normally singles tractors with two or more trailers.

The major source of national travel data besides TIUS is FHWA's collection of state-compiled travel data, reported under the Highway Performance Monitoring System (HPMS). One of the HPMS forms required by FHWA asks each state for estimates of VMT for each class of highway, as well as the percentage breakdowns of this travel into each of 13 vehicle classes. Although the classes are not sufficient to distinguish triples or larger doubles from other multitrailer combinations, it is possible to derive overall estimates of multitrailer miles traveled. All states but Oklahoma submit these estimates regularly, most of them annually, but a few biannually.

This set of data represents the best source of information from which to estimate travel in each state. Some limitations of the data are discussed later, but these limitations can be reasonably overcome by following FHWA's adjustment procedures and by carefully considering what types of configurations are included in each travel category.

Derivation of Vehicle Travel Estimates

As discussed, FARS collects information for each fatal highway accident from police accident reports supplemented by additional investigation by NHTSA-funded state employees. TIFA matches 50T and FARS data and contacts operators of involved vehicles. These are by a large margin the most usable and accurate large-scale accident data sets for use in determining the overall safety rates of various vehicle configurations. The FHWA-adjusted state-reported travel data and TIUS travel data are the best available sources of exposure information. This section of the report describes the use of these four sources to develop comparative fatality involvement rates. The latest available FARS data (1988) and the latest available TIFA data (1986) were used in this comparison, along with the 1986 HPMS and the 1987 TIUS travel data.

The first step in the analysis was to assess the validity of the HPMS state-reported travel data. Each state and the District of Columbia were asked more detailed information about how the estimates were derived, and 31 states responded. In addition, FHWA staff were asked numerous questions about how they assessed and adjusted the data. On the basis of the responses received, we concluded that the travel data collected by the states cannot be used in raw form, but must be adjusted to compensate for the sampling methodology used.

To begin with, states appear to substantially overreport combination truck travel. Thirty of the 31 states responding to the survey classify trucks only on weekdays and make no attempt to correct for the substantially lower truck percentages on weekends. FHWA attempts to adjust for this effect in some of these states by using the results of a week-long 1982 classification study in five states. The resulting adjustment results in only a slight reduction in combination truck travel rates. FHWA also adjusts overall VMT up or down for each highway type in each state to match its careful evaluation and calibration of statewide travel, while leaving truck percentages the same. This has a further effect on aggregate truck VMT, because percentage travel by trucks varies by highway system and state.

No attempt is made by FHWA to adjust for multitrailer travel estimates independently of single-trailer travel estimates because neither the 1982 classification study nor any other study provides any data with which to make this separate adjustment.

Besides the day-of-week errors, another potential source of error is in the classification methodology itself. Most states use a combination of manual and automatic vehicle counting and classification. Manual counting is subject to human error, in which "odd" vehicle classes (such as multitrailer vehicles) are subject to greater percentages of misclassification than the more common classes, but there is not necessarily systematic bias. Automatic classification, however, is subject to substantial systematic bias. Closely spaced vehicles are commonly counted as multitrailer vehicles. There is little calibra-

tion between manual and automatic methods of classification, and what there is usually looks at overall error rates, rather than error rates for individual classes. Thus an overall error rate of, say, 1 percent appears good. However, if much of this error is concentrated in doubles classes, which in all states make up less than 1 percent of total travel, the error rate could be substantial. Several states have suggested that the classification procedures commonly used result in systematic overestimation of doubles VMT.

There are no specific data on how much to adjust multitrailer counts to overcome the probable bias resulting from current classification procedures. Because we could not adjust the state-reported proportions, it is likely that our estimates of doubles travel are too high in many states. This results in a lower estimated accident rate for doubles than actually occurs. As described later, this hypothesized systematic overcounting of doubles is borne out by the TIUS travel figures. Future improved vehicle classification counts are thus likely to raise estimates of multiunit combination vehicle accident rates derived from count data.

Instead of attempting to derive independent estimates of large truck overcounting, we adjusted state-reported data to match FHWA-published figures. FHWA figures are based on what we believe to be partial compensation for some of the systematic sources of bias mentioned earlier. The state-reported proportions of travel for each vehicle configuration were applied to the travel in each functional class in each state as published in Table VM-1 of the 1986 and 1988 *Highway Statistics* reports (*15*). This process revealed an obvious problem for New Mexico's 1988 data, which was related to the implementation of new equipment and procedures. The problem was sidestepped by obtaining advance estimates of New Mexico's 1989 data and replacing its 1988 estimates with an average of 1987 and 1989 estimates (*16*).

The next step involved matching national control totals for vehicle group travel. Although FHWA does not publish breakdowns of travel by state and vehicle group, Table VM-2 in *Highway Statistics* contains estimates of travel by highway type and vehicle group that are derived by adjusting the state-reported figures to compensate for their sampling procedures (as discussed earlier). Each group of vehicles was proportionally adjusted to simultaneously match both the state highway class and the national vehicle type totals. This process maintained the same overall proportion of multitrailer to single-trailer combination travel as reported by each state for each functional highway class (this breakdown is not published by FHWA but can be purchased in spreadsheet form).

Table 1 gives the adjusted 1988 VMT by state for four categories of vehicles: passenger vehicles (including automobiles, motorcycles, buses, and light trucks and vans), single-unit trucks (six tires and larger), single-trailer combination vehicles, and multitrailer combination vehicles. The national travel by multitrailers is less than 0.3 percent of all highway travel. Only New Mexico and Wyoming show estimates of multitrailer travel above 1 percent of total highway traffic.

Considering the assumptions necessary for use of FHWA data, use of TIUS data is easier. In addition, the better configuration information allows a better match with accident data, as will be seen later. Several adjustments or refinements, however, are necessary and desirable.

The first adjustment concerns year of travel. The 1987 TIUS was actually conducted in early 1988 and asked each of 104,606 truck operators how many miles they traveled during calendar year 1987. To match the resulting 1987 travel estimates with the 1986 TIFA and the 1988 FARS, we adjusted the survey mileage up or down to match the average annual growth rates by vehicle configuration shown between 1982 and 1987. Table 2 gives the published estimates of miles traveled from the 1982 and 1987 TIUS reports for several vehicle configurations, the average growth rates, and the resulting projections of 1987 traffic to 1986 and 1988 (*17*). The 1982 TIUS did not distinguish between full and partial trailers on trucks, so a single growth rate was derived for and applied to the 1987 truck-trailer miles.

These unadjusted TIUS estimates are used for one set of accident and fatality rate calculations described later. It is also desirable, however, to adjust for three other phenomena: the overrepresentation of low-mileage vehicles in TIUS, the inclusion of off-road mileage, and the absence of government-owned vehicles. Using the Census-supplied computer data tapes, it is possible to compensate for the first two factors.

A number of TIUS respondents reported very low annual mileage. One common hypothesis is that many of these respondents answered in hundreds or thousands of miles rather than actual miles traveled. This would result in underestimates of travel for each truck type. One could compensate for these possible poor responses by replacing all mileage estimates below a certain level with the average miles traveled for each particular truck type. The upward adjustments in travel resulting from applying a lower threshold of 2,200 mi per year would be 16.06 percent for single-unit trucks, 10.47 percent for truck-trailers, 5.74 percent for single-trailer combinations, and 0.89 percent for multitrailer combinations.

Each TIUS respondent also reports the percentage of off-road miles traveled. Removal of off-road miles reduces travel of single units by 6.19 percent, truck-trailers by 4.24 percent, single trailers by 1.26 percent, and multitrailers by 0.89 percent. The net combined adjustments leave multitrailer mileage unchanged but increase single-unit mileage by 9.87 percent, truck-trailer mileage by 6.23 percent, and single-trailer mileage by 4.48 percent. These adjustments are reflected in the "adjusted TIUS mileage estimates" in the accident and fatality rate tables below.

It was not possible to estimate government truck travel, but it appears that governments have many more single-unit than combination trucks. The error of excluding them is estimated to be negligible, but on the side of underestimating the accident and fatality rates of single-trailer and multitrailer combinations.

Compilation of Accident and Fatality Data

The fatality involvement data for 1988 were taken directly from FARS using the body type and number of trailing units fields. Using the number of trailing units field alone overestimates fatality rates for combination vehicles, because it includes light vehicles with trailers. Using body type allowed us to distinguish between truck-trailers and tractor-trailer combination vehicles. Unfortunately, FHWA travel data do not separate truck-trailer travel, and it is mixed among all three

TABLE 1 STATE-REPORTED VMT FOR 1988 ADJUSTED TO MATCH VM-1 AND VM-2

	Psgr Veh	Sngl Unit	1 Trlr Comb	2 Trlr Comb	All Veh
ALABAMA	36484.	1103.	2051.	47.	39684.
ALASKA	3700.	97.	40.	5.	3841.
ARIZONA	30783.	1394.	1868.	203.	34247.
ARKANSAS	17314.	430.	1405.	71.	19219.
CALIFORNIA	229254.	3979.	6759.	1582.	241575.
COLORADO	25809.	911.	876.	68.	27665.
CONNECTICUT	24380.	607.	1045.	30.	26062.
DELAWARE	5929.	205.	261.	9.	6404.
DIST. OF COLUMBIA	3338.	59.	8.	0.	3405.
FLORIDA	99515.	2362.	3403.	39.	105319.
GEORGIA	58441.	1403.	2304.	114.	62262.
HAWAII	7196.	181.	36.	6.	7419.
IDAHO	7302.	351.	406.	69.	8127.
ILLINOIS	73770.	1525.	3075.	114.	78483.
INDIANA	45859.	1330.	3829.	106.	51124.
IOWA	19768.	641.	1443.	55.	21907.
KANSAS	19452.	586.	1067.	56.	21161.
KENTUCKY	29087.	1005.	1476.	47.	31614.
LOUISIANA	31489.	1328.	1865.	0.	34682.
MAINE	10640.	433.	328.	0.	11401.
MARYLAND	35180.	1102.	1192.	23.	37498.
MASSACHUSETTS	41620.	667.	1019.	28.	43334.
MICHIGAN	73819.	1500.	2317.	263.	77899.
MINNESOTA	34301.	887.	1196.	62.	36447.
MISSISSIPPI	19885.	420.	1677.	62.	22043.
MISSOURI	41464.	1073.	2886.	148.	45570.
MONTANA	7263.	495.	328.	53.	8138.
NEBRASKA	12163.	382.	815.	47.	13407.
NEVADA	8262.	264.	388.	76.	8989.
NEW HAMPSHIRE	8991.	294.	221.	0.	9507.
NEW JERSEY	55226.	1575.	1867.	3.	58671.
NEW MEXICO	12431.	929.	1724.	200.	15283.
NEW YORK	98809.	1735.	3029.	119.	103692.
NORTH CAROLINA	53230.	2103.	2531.	79.	57943.
NORTH DAKOTA	5207.	238.	312.	9.	5765.
OHIO	75852.	2240.	3742.	157.	81990.
OKLAHOMA	29920.	816.	1560.	92.	32388.
OREGON	23254.	691.	1058.	202.	25204.
PENNSYLVANIA	74809.	2786.	3532.	111.	81238.
RHODE ISLAND	5419.	165.	266.	3.	5853.
SOUTH CAROLINA	29665.	597.	1439.	59.	31759.
SOUTH DAKOTA	6204.	184.	237.	9.	6634.
TENNESSEE	40869.	932.	2263.	130.	44193.
TEXAS	144258.	4093.	7884.	223.	156458.
UTAH	12356.	260.	527.	120.	13263.
VERMONT	5188.	223.	142.	0.	5553.
VIRGINIA	53613.	1630.	2165.	46.	57453.
WASHINGTON	38975.	1031.	1493.	313.	41813.
WEST VIRGINIA	12650.	511.	696.	27.	13884.
WISCONSIN	39155.	1253.	1996.	54.	42458.
WYOMING	4658.	233.	686.	80.	5658.
All States	1884206.	51231.	84730.	5418.	2025586.

TABLE 2 TRAVEL DATA AND GROWTH RATES FOR SELECTED TRUCK TYPES FROM 1982 AND 1987 TIUS (MILLIONS OF MILES TRAVELED)

	Single Unit	1-Trlr Comb	2+ Trlr Comb	Truck w/ Full Trl	Truck w/ Partial	All Trk Trlr
1987 Travel	38770	57056	2692	1476	2325	3801
1982 Travel	36276	46075	1939			3294
Annual Growth	1.3%	4.4%	6.8%			2.9%
1986 Travel	38258	54668	2521	1434	2259	3694
1988 Travel	39289	59548	2875	1519	2393	3911

other truck types (single unit, single-trailer combination, and multitrailer combination). This difficulty can be sidestepped by using TIUS data, which distinguish and describe truck-trailers.

Table 3 gives the number of fatalities in each state in which each type of vehicle was involved. The "unknown and miscellaneous" category includes farm vehicles, combination vehicles with an unspecified number of trailing units, and vehicles for which the FARS investigator could not obtain information. About half of these unknown vehicles are known to be heavy trucks but were not classifiable among the three potential heavy truck classes.

Truck-trailers presented a special difficulty when using FHWA travel data, because some are widely considered to be doubles, whereas others would be more properly classified as single-trailer combinations or as single-unit trucks, depending on the nature of the power unit and the trailer. Unfortunately, no information is available from FARS on the nature of the trailing unit, so additional data sources must be used to attempt to place the vehicle in the class in which it would have been counted by the state in which the accident occurred. If the trailing unit were a full trailer, most states either intentionally or unintentionally would have classified the vehicle as a multitrailer combination in their travel esti-

TABLE 3 FATALITIES INVOLVING VEHICLES OF EACH TYPE, BY STATE (FATALITIES COUNTED ONCE FOR EACH INVOLVED VEHICLE)

	Psgr Veh	SU Truck	1-Trlr	Trk-trl	Doub+	Unknown	Total
ALABAMA	1366	39	126	0	0	16	1023
ALASKA	125	1	2	0	0	4	97
ARIZONA	1273	28	68	5	10	45	944
ARKANSAS	824	21	121	0	2	9	610
CALIFORNIA	7570	167	306	21	124	118	5390
COLORADO	670	10	44	1	0	6	497
CONNECTICUT	672	14	21	0	1	13	484
DELAWARE	235	8	18	0	0	4	160
DIST. OF COLUMBIA	74	0	1	0	0	8	60
FLORIDA	4354	168	209	18	2	92	3078
GEORGIA	2148	46	190	1	0	126	1653
HAWAII	208	5	3	3	0	3	148
IDAHO	309	6	23	1	5	8	257
ILLINOIS	2652	82	197	3	3	25	1837
INDIANA	1518	40	132	9	4	31	1101
IOWA	750	27	63	0	3	16	557
KANSAS	679	13	49	1	2	9	483
KENTUCKY	1153	54	61	3	0	14	838
LOUISIANA	1279	29	100	3	0	15	925
MAINE	316	19	29	0	0	4	255
MARYLAND	1114	56	49	0	0	21	782
MASSACHUSETTS	944	24	13	0	0	49	725
MICHIGAN	2463	57	119	4	15	48	1704
MINNESOTA	852	18	52	4	1	15	612
MISSISSIPPI	968	122	2	0	0	15	722
MISSOURI	1490	53	81	2	3	24	1103
MONTANA	250	1	12	1	2	1	198
NEBRASKA	330	15	34	2	0	6	261
NEVADA	367	11	14	0	5	5	286
NEW HAMPSHIRE	235	21	3	0	0	3	166
NEW JERSEY	1456	49	88	0	0	0	1051
NEW MEXICO	623	4	28	0	6	16	487
NEW YORK	2963	144	110	9	3	58	2255
NORTH CAROLINA	2199	50	183	7	2	32	1573
NORTH DAKOTA	130	4	8	0	0	1	104
OHIO	2358	87	210	1	8	49	1763
OKLAHOMA	875	10	68	4	5	11	634
OREGON	969	26	62	2	9	10	677
PENNSYLVANIA	2656	94	268	4	3	22	1931
RHODE ISLAND	175	5	3	0	0	0	125
SOUTH CAROLINA	1418	44	95	8	6	31	1034
SOUTH DAKOTA	177	8	6	1	0	6	147
TENNESSEE	1783	49	105	4	5	22	1266
TEXAS	4474	84	361	4	6	110	3393
UTAH	403	6	33	0	1	8	297
VERMONT	159	10	6	1	0	10	129
VIRGINIA	1413	87	67	0	0	14	1071
WASHINGTON	1085	24	46	3	7	8	778
WEST VIRGINIA	606	20	44	0	2	3	460
WISCONSIN	1092	51	74	1	1	12	807
WYOMING	181	4	31	0	7	0	155
All States	64383	2015	4038	131	253	1176	71996

mates. Partial trailers would have been variously classed as single-unit trucks, single-trailer combinations, or multitrailer combinations, depending on the state.

On the basis of a review of each state's practice and TIUS-based estimates of the relative prevalence of truck-trailer configurations of each type, estimates were made of how truck-trailers would have been classified in each state. Truck-trailer fatalities were apportioned among the three truck classes according to these estimates. Unclassifiable vehicles were not included in the estimates.

A better, but not as up-to-date, source of fatal accident data is the TIFA program. The 1986 fatal accident involvements given in Table 4 were taken directly from this source, which does not publish results by state (*18*). The configurations were derived by matching 50T and FARS data, as reported earlier, supplemented by telephone interviews when necessary to clarify information. There is a possible bias toward undercounting doubles accidents, because each report showing multitrailer involvement initiated telephoned verification that the vehicle was actually a double. No similar screening was done for single trailers, so it is reasonable to expect some multitrailers to have been mistakenly considered single-trailer vehicles and not corrected. Thus it is likely that the actual number of fatal accidents involving doubles and triples is higher than given in Table 4, although no adjustments were made in this study.

RESULTS

Six different estimates of fatality or fatal accident rates could be developed using the three travel estimates (FHWA, TIUS, and adjusted TIUS) and two accident data sources (FARS and TIFA). Four of the six are presented here.

The 1988 FARS and FHWA travel data indicate a fatality involvement rate for multiunit vehicles that is 22 percent higher than for single-trailer combination vehicles, 49 percent higher than for single-unit trucks, and 72 percent higher than for passenger vehicles (see Table 5). FARS and FHWA travel are the two sources that together allow estimates of individual state fatality rates, and they are presented here mostly for that reason, because the other data sources overcome the most important difficulties associated with each of them.

The wide variation in fatality rates by state, especially among states with lower levels of doubles travel, illustrates the random variation in accidents and the inherent uncertainty associated with use of smaller data sets. Nearly all previous studies have used smaller samples than any single state presented here, so the range of results in previous studies should not be surprising.

California, which has by far the largest amount of travel by multitrailer units of any of the states, has an involvement rate for multitrailers of 9.0 fatalities per 100 million mi traveled, which is much higher than the national average. The rate for single-trailer combinations of 4.6 is slightly below the national average. Thus double-trailers in California (there are no triples) have a 98 percent higher fatality involvement rate than single-trailer combinations.

California has used doubles for many years, in contrast to many other states where they are a relatively recent addition to the traffic stream. Drivers of doubles have much experience with them. Police officers are familiar with them and know what to call them on accident forms. Their use in California is similar to the use of single-trailer combinations (although they are still used more on safer roads such as Interstate highways, and the rates would probably be even more disparate if correction were made for this phenomenon). This tends to confirm the validity of the hypothesis that, as multitrailer vehicles become used for more general as opposed to special purposes, their accident rates will increase even above their current levels.

The next comparison combines 1986 FHWA travel data with 1986 TIFA accident data. TIFA has greatly improved determination of vehicle configuration and shows an even more pronounced trend than does FARS with the same travel data. As indicated in Table 6, fatal accident rates for multitrailer vehicles are 47 percent higher than for single-trailer vehicles and 118 percent higher than for single-unit trucks. This phenomenon tends to confirm the hypothesis that many doubles involved in accidents are mistakenly reported as other types of vehicles or are classified as "unknown" types for lack of coherent classification methodology. Although TIFA did not verify that each vehicle reported as a single-trailer combination was not actually a double, at least it decreased the number of "unknown" vehicles, resulting in more doubles being identified. An even more thorough investigation than was performed by TIFA is likely to further increase the disparity between multitrailer and single-trailer fatal accident rates.

Although the bias in the TIFA verification process lowers multitrailer accident rates by an undetermined amount, the TIFA data base is more reliable than FARS because of its extra verification of vehicle configuration. It was first paired with FHWA data to isolate the effect of improving accident data from the effect of improving travel data. The final two comparisons, given in Table 7, use TIFA data in combination with the travel estimates derived from the 1987 TIUS as described earlier. The first fatal accident rate in the table is calculated on the basis of the year-interpolated published TIUS figures for 1987 and 1982. The second set of rates is based on additional tabulations of the TIUS data tape to account for low-reported-mileage vehicles and off-road travel.

TABLE 4 FATAL ACCIDENT INVOLVEMENTS BY VEHICLE COMBINATION, 1986 (FROM TIFA REPORT)

Truck Type	No.	Pct.
01 Unknown	130	2.5
02 Straight Truck Only	1262	24.1
03 Bobtail Tractor	146	2.8
04 Straight Truck and Full Trailer	74	1.4
05 Straight Truck and Other Trailer	64	1.2
06 Tractor and Semitrailer	3273	62.4
07 Tractor and Other	23	0.4
08 Tractor and Semi and Full	235	4.5
09 Tractor and Semi and Other	6	0.1
10 Tractor and Three Trailers	3	0.1
11 Other	27	0.5
13 Straight and Two Trailers	1	0.0

TABLE 5 FATALITY INVOLVEMENT RATES BY STATE AND VEHICLE TYPE, 1988

	Psgr Veh	Sngl Unit	1 Trlr Comb	2 Trlr Comb	All Veh
ALABAMA	3.744	3.537	6.145	0.000	3.898
ALASKA	3.379	1.032	5.018	0.000	3.437
ARIZONA	4.135	2.045	3.641	7.140	4.173
ARKANSAS	4.759	4.888	8.614	2.835	5.084
CALIFORNIA	3.302	4.197	4.558	9.032	3.438
COLORADO	2.596	1.098	5.135	0.000	2.642
CONNECTICUT	2.756	2.308	2.009	3.327	2.766
DELAWARE	3.963	3.907	6.894	0.000	4.138
DIST. OF COLUMBIA	2.217	0.000	12.306	0.000	2.438
FLORIDA	4.375	7.111	6.354	32.856	4.598
GEORGIA	3.675	3.350	8.246	0.000	4.033
HAWAII	2.890	2.765	11.693	29.680	2.992
IDAHO	4.232	1.712	5.717	8.413	4.331
ILLINOIS	3.595	5.379	6.485	3.167	3.774
INDIANA	3.310	3.008	3.636	5.455	3.392
IOWA	3.794	4.215	4.365	5.493	3.921
KANSAS	3.491	2.218	4.685	3.562	3.558
KENTUCKY	3.964	5.375	4.296	1.278	4.065
LOUISIANA	4.062	2.184	5.522	0.000	4.112
MAINE	2.970	4.387	8.849	0.000	3.228
MARYLAND	3.167	5.081	4.110	0.000	3.307
MASSACHUSETTS	2.268	3.600	1.276	0.000	2.377
MICHIGAN	3.337	3.800	5.171	6.928	3.474
MINNESOTA	2.484	2.029	4.481	5.458	2.585
MISSISSIPPI	4.868	29.075	0.119	0.000	5.022
MISSOURI	3.593	4.940	2.835	2.844	3.627
MONTANA	3.442	0.202	3.784	4.938	3.281
NEBRASKA	2.713	3.930	4.270	2.531	2.887
NEVADA	4.442	4.172	3.612	6.563	4.472
NEW HAMPSHIRE	2.614	7.141	1.355	0.000	2.756
NEW JERSEY	2.636	3.112	4.714	0.000	2.715
NEW MEXICO	5.012	0.431	1.625	3.002	4.430
NEW YORK	2.999	8.298	3.751	7.067	3.170
NORTH CAROLINA	4.131	2.377	7.341	7.863	4.268
NORTH DAKOTA	2.497	1.682	2.566	0.000	2.480
OHIO	3.109	3.885	5.639	5.109	3.309
OKLAHOMA	2.924	1.226	4.461	8.032	3.004
OREGON	4.167	3.765	6.013	4.664	4.277
PENNSYLVANIA	3.550	3.374	7.634	4.848	3.751
RHODE ISLAND	3.229	3.035	1.127	0.000	3.127
SOUTH CAROLINA	4.780	7.371	7.048	12.937	5.044
SOUTH DAKOTA	2.853	4.347	2.701	6.356	2.985
TENNESSEE	4.363	5.688	4.640	3.856	4.453
TEXAS	3.101	2.053	4.630	2.686	3.221
UTAH	3.262	2.303	6.267	0.834	3.400
VERMONT	3.065	4.935	4.231	0.000	3.350
VIRGINIA	2.636	5.339	3.095	0.000	2.752
WASHINGTON	2.784	2.327	3.281	2.236	2.805
WEST VIRGINIA	4.790	3.917	6.323	7.303	4.862
WISCONSIN	2.789	4.070	3.758	1.860	2.899
WYOMING	3.886	1.717	4.516	8.709	3.941
All States	3.417	3.946	4.835	5.876	3.554

Whereas arguments could be made to favor either of these sets of estimates, both are more reliable than any other estimates of relative fatal accident involvement. Note the even more striking differences between single-trailer and multitrailer vehicles, and especially between both types of combinations and single-unit trucks. Multitrailers have a fatal accident rate 58 to 66 percent higher than that for single-trailer combinations and more than three times as high as that for single-unit trucks.

TABLE 6 COMPARISON OF FATAL ACCIDENT RATES (FROM 1986 TIFA AND FHWA)

	Accidents	Million VMT	Rate/ 100 M
Single-Unit Trucks	1408	48413	2.91
Single-Trlr Coms	3360	77672	4.33
Multi-Trlr Combs	319	5024	6.35

These estimates should be considered to be better than the FARS-FHWA or TIFA-FHWA estimates for two main reasons: the better configuration information on TIUS and the superior sampling of TIUS. As described earlier, TIUS distinguishes between triples, doubles, tractor-trailer combinations, and truck-trailer combinations comparably with TIFA and much better than either FHWA or FARS. This eliminates the need to apportion truck-trailer accidents among the other truck classes to match likely traffic-counting categories. Also, the careful sample design and method of stratification elimi-

TABLE 7 COMPARISON OF 1986 FATAL ACCIDENT RATES FROM TIFA AND TIUS

Vehicle Type	Accidents	TIUS Miles (Millions) Deflated	Rate / 100 M	Adjusted TIUS Miles (Millions)	Rate / 100 M
Single-Units	1262	38258	3.299	42034	3.002
Truck/ Partial Trlr.	64	2259	2.833	2400	2.667
Truck/ Full Trlr.	74	1434	5.159	1523	4.859
Single-Trailers	3436	54668	6.285	57119	6.015
Multi-Trailers	251	2521	9.956	2521	9.956

nate the systematic errors of current state traffic classification practices. Together, these important advantages significantly increase the probable accuracy of TIUS-based travel estimates and the corresponding accuracy of fatal accident involvement rates.

Accidents involving tractors without trailers attached were apportioned to single-trailer and multitrailer combinations in proportion to travel, because TIUS data are derived from power unit travel estimates. In the FHWA data comparisons, which were classification-based travel, these accidents were placed in the single-unit category. In addition, the estimates for trucks with full and partial trailers are less reliable than the estimates for the other three categories because of sample sizes and operational uncertainties. They are included for completeness but have no direct bearing on this study's conclusions.

CONCLUSIONS

1. When the fatal accident rate of all current multitrailer operations is compared with the fatal accident rates of other trucks, multitrailers are shown to be much more dangerous than either single-unit trucks or single-trailer combinations.
2. As indicated in Table 8, which is arranged in order of increasing data quality, the apparent fatal accident overrepresentation of multitrailers increases as the data improve. Use of the best available sources indicates that multitrailers are more than 1.5 times as dangerous as single-trailer combinations and more than 3 times as dangerous as straight trucks.
3. The much higher rates for multitrailers would be expected in similar operations because of their inferior operating characteristics.
4. Most previous studies have also shown markedly higher fatality or fatal accident rates for doubles. The fact that this study found higher differences in fatal accident rates than most previous studies can be explained by small sample sizes and other errors in previous studies, as well as likely deterioration of doubles rates with their increasing usage.
5. TIFA is superior to FARS for assessing doubles accidents. The error rates in truck configuration reporting in FARS, though not great for most vehicle types, are unacceptably high for multitrailer vehicles.
6. The year-to-year variations, small samples, and systematic biases in travel data reported by states to FHWA require significant adjustments before the travel data can be considered adequate.
7. No reliable source of national accident data for nonfatal accidents is available, and the number of annual fatal accidents precludes the desirable disaggregation of accidents by region, state, and motor carrier type.
8. In assessing the safety implications of proposed changes in allowable truck configurations, one must consider not only the differences in existing accident rates but also the likely changes in rates that would result from more widespread use.

TABLE 8 COMPARISON OF INVOLVEMENT RATIOS DERIVED FROM VARIOUS DATA SOURCES

Data Sources	Multi-Trailer to Single-Unit Truck	Multi-Trailer to Single-Trailer
FARS/FHWA	1.49	1.22
TIFA/FHWA	2.18	1.47
TIFA/TIUS	3.02	1.58
TIFA/TIUS (Adj.)	3.32	1.66

ACKNOWLEDGMENT

This paper uses results of a study sponsored by the Association of American Railroads.

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DISCUSSION

William D. Glauz
Midwest Research Institute, 425 Volker Boulevard, Kansas City, Mo. 64110.

The authors are to be commended for addressing an ongoing question by using available large-scale data bases. They faced the attendant difficulties of trying to achieve a consistency that is often not inherent in the data bases. The result was a laudable paper. However, the final conclusion, that double-trailer trucks were overinvolved in fatal crashes compared with single-trailer trucks by a ratio of 1.66, was a surprise to me. I have studied the same issue on several occasions.

It was possible to reexamine some of the analyses in the paper, which we did in an attempt to explain the authors' findings. The state-by-state data presented in Tables 1, 3, and 5 were the focus of the reanalysis. Table 3 contains FARS data, one of the two fatal accident data bases used by the authors. Unfortunately, TIFA data on a state-by-state basis were not included in the paper, so this discussion is limited to the FARS data analysis.

It is evident in Table 3 that the fatal doubles accidents are dominated by those in California. The data were reanalyzed to examine this domination. The reanalysis included reassigning "Trk-trl" accidents to the other truck categories on a state-by-state basis in the same way used by the authors. The resulting multitrailer to single-trailer fatal accident involvement ratios are as follows: all states, 1.215; California, 1.982; all but California, 0.939.

The apparent conclusion is that in California, doubles are twice as likely to be involved in fatal accidents as singles, but in the rest of the country doubles are slightly "safer." The authors suggest that the reason for this is that they have been in general use for many years in California, as opposed to special uses, and that therefore their accident rate will increase in the rest of the country as they become more common.

We believe that there is another explanation, which suggests both why the California rate is so high and that the doubles rate elsewhere is not likely to approach the California rate. Glauz and Harwood (*1*) analyzed accidents of doubles and singles in California on the basis of Caltrans data for an 18-month period, July 1976 through December 1977. One of the variables examined was the cargo area configuration. The findings in that study for all accident-involved doubles (not just fatal accidents) are given in the following table:

Configuration	*Number*	*Percent*
Fully enclosed (vans)	62	32
Platform (flatbed)	74	38
Tank	30	15
Bulk commodity or dump	24	12
Other	6	3
Total	196	100

It is evident that less than one-third of the accident-involved doubles were of the van type, which is the configuration used almost exclusively in the rest of the country. The remainder are intrastate haulers of special freight, such as fruits and vegetables from farms to packing plants, petroleum products from refineries to wholesalers and retailers, rock and earth from excavations to landfills, and so forth. These trucks tend to make short trips and probably use off-Interstate routes more often than interstate vehicles. (Nonfreeways generally have higher accident rates than freeways, so this factor alone tends to increase the accident rate of doubles in California. The authors voiced the opposite view.)

The suggested alternative hypothesis is that these specialized trucks are overinvolved in accidents and thus inflate the doubles accident rate in California. Furthermore, it is unlikely that these specialized trucks will be widely adopted elsewhere in the United States, because their use in California resulted from pre-1973 state legislation that allowed such configurations to operate at higher weights than singles. The use of these specialized doubles has an economic incentive in California because the freight they carry is heavy. The van-type doubles, which dominate doubles activity outside California, typically haul less-than-truckload freight that is less dense, so the extra space they provide is an incentive for their use.

In conclusion, the overinvolvement of double-trailer trucks in fatal accidents relative to single-trailer trucks that the authors found is likely to be primarily because of their high overinvolvement in California. Furthermore, the high doubles accident rate in California is associated with truck configurations unique to that state; they have not been adopted by industry in other states, nor are they likely to be under current state and federal laws.

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AUTHORS' CLOSURE

Mr. Glauz raises some intriguing points in his analysis of fatal accident involvements of various trailer types in California. We must disagree, however, with both of his conclusions.

We used two sources of accident data and two sources of travel data in our calculation of fatal accident and fatality rates. In each case, the weaker source of data included state-by-state breakdowns, whereas the more reliable source did not. In each case, the more reliable source of the pair indicated that multitrailer combinations have a higher fatal involvement rate relative to single-trailer combinations than did the weaker source. One of the main findings of our study, in fact, is the increasing clarity of the trend as the quality of the data increases.

Mr. Glauz's first conclusion (that only in California are doubles more dangerous, whereas they are safer in the rest of the country) can only be supported by using the weakest of the four possible pairs of data sources. This pair of sources indicates an involvement rate ratio for multitrailers relative to single trailers of 1.22. Other pairs of sources presented in our paper yield corresponding ratios of 1.47, 1.58, and 1.66. Clearly, it takes more than California to explain differences of the last three magnitudes.

As for premises leading to his second conclusion (that California-type vehicles will not spread to other states), Mr. Glauz in our view correctly attributes the prevalence of tanker, dump, and flatbed doubles in California to the weight incentives created long ago by the California legislature. Let us suppose that Bridge Formula B were enacted nationally in place of the current 80,000-lb limit. The formula would allow doubles to operate at higher weights than existing singles and would create precisely the same sort of incentives to use these "unique" trailer types (the ones Mr. Glauz considers to be more dangerous than vans). We cannot agree, therefore, that such vehicles would be confined to California if size and weight laws were modified.

Our paper concluded that doubles are a special case, operating on the average under better conditions than single-trailer vehicles. Because of this, national comparisons of singles and doubles unfairly make doubles appear safer relative to singles than if similar operations of each were considered. We identified traffic conditions and types of operations as two factors across which controls are needed. Mr. Glauz's analysis suggests that body type is another desirable stratification variable, and with that we agree. If the data were available, we could certainly get better results by using all of these stratifications. It is equally certain, however, that the failure to be able to do so favors doubles (not singles), and that the comparable-condition disparity between doubles and singles is even greater than the condition-ignoring 1.66 ratio found in our paper.

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

Differential Truck Accident Rates for Michigan

RICHARD W. LYLES, KENNETH L. CAMPBELL, DANIEL F. BLOWER, AND POLICHRONIS STAMATIADIS

Major changes in the trucking industry have resulted from federal legislation that relaxed the regulation of trucks in interstate commerce, allowed the use of double-trailer combinations nationwide on Interstate highways, and required states to regulate trailer length instead of overall length. Because Michigan has long had extremely liberal truck size and weight regulations, its experience with truck safety is of significant interest. A project by the University of Michigan and Michigan State University was undertaken to develop statistical information on accidents, travel, and the risk of accident involvement for Michigan-registered trucks in Michigan. The study objective was to calculate disaggregate truck accident rates by road class, day or night, and urban or rural operating conditions for tractors without trailers (bobtails) and in single- and double-trailer configurations. Major findings included the following: bobtails consistently have the highest accident rates; all-accident and casualty rates for single and double configurations are similar to one another; the most significant and consistent factor associated with truck accident rates was the roadway class (highest rates on the "local" road system, lowest on limited-access highways); urban accident rates were lower than rural rates; night rates were higher than day rates for casualty accidents but lower for all accidents; and tractor drivers aged 19–20 have an accident rate five times the average. The findings indicate that differences in truck safety by roadway class are more important than those between singles and doubles. Discussion and recommendations concerning improvements in truck accident and exposure data as well as further work on the relationship between truck accidents and geometry are included.

Major changes have taken place in the trucking industry during the past decade. In 1980, federal legislation significantly relaxed the regulation of trucks in the interstate segment of the industry. The 1982 Surface Transportation Assistance Act allowed the use of double-trailer combinations on Interstate highways nationwide, required states to regulate trailer length instead of overall length, and established the Motor Carrier Safety Assistance Program. More recently, the Commercial Motor Vehicle Safety Act of 1986 established national standards for commercial driver licenses.

Not all of the national changes had the same impact on Michigan as on other states, because it has long had some of the most liberal truck size and weight regulations in the United States. For example, double-trailer combinations weighing up to 164,000 lb have operated legally in Michigan for many years. The use of double trailers and the experience of other combinations operating in Michigan is of significant interest both within the state and nationally.

Whereas truck regulations for the most part are seen as becoming more liberal, at the same time it is generally perceived that large trucks are not very safe. There are lingering questions about the safety of these vehicles and what, if anything, should (or can) be done to make them safer. In Michigan, accidents involving large trucks increased 81 percent from 1982 to 1986, but they decreased in 1987 and 1988. For the entire period from 1982 to 1988, the number of truck accidents increased by 64 percent, whereas all motor vehicle accidents increased by about 40 percent. During the same period, economic conditions improved substantially in the state, and truck travel increased. In the face of so many changes, the problem is to identify the significant factors associated with the risk of truck accidents while controlling for variations in the exposure of trucks to the possibility of an accident.

Despite the interest in truck safety, there are still significant gaps in the current knowledge about truck accident rates and the causal factors involved—both nationally and in Michigan. This is reflected to some degree in, for example, recent publications that decry the lack of consistent data concerning truck use (*1*) and, implicitly, the capability to produce reasonable accident involvement rates. In this context, a joint project by the University of Michigan's Transportation Research Institute (UMTRI) and Michigan State University's (MSU's) Department of Civil and Environmental Engineering was undertaken to develop statistical information on accidents, travel, and the risk of accident involvement for Michigan-registered trucks in Michigan (*2*). Operationally, the objective of the study was to calculate disaggregate truck accident rates [in terms of accident involvements per million vehicle miles of travel (VMT)] for combinations of the variables shown in Table 1.

In general, MSU was responsible for the accident data, and UMTRI was responsible for exposure data. Both the accident and travel data spanned the 12-month study period beginning in May 1987 and ending in April 1988. The following sections are addressed, in turn, to discussion of truck accidents, truck travel, the development of truck accident rates, and, finally, the findings, implications, and conclusions of the Michigan study.

R. W. Lyles and P. Stamatiadis, Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Mich. 48824-1226. K. L. Campbell and D. F. Blower, University of Michigan Transportation Research Institute, Ann Arbor, Mich. 48109-2150.

TRUCK ACCIDENTS IN MICHIGAN

Because the reporting threshold for traffic accidents in Michigan is $200 of damage, virtually all accidents that occur on

TABLE 1 STRATIFYING VARIABLES FOR DISAGGREGATE TRUCK ACCIDENT RATES

truck types	1. bobtails--tractors without trailers,
	2. singles--tractor and semitrailer combinations, and,
	3. doubles--tractor, semitrailer, and full-trailer combinations;
roadway types	1. limited--limited-access highways,
	2. major--principal and other through highways and other four-lane divided highways (not included in 1), and,
	3. other--all other streets and roads;
rural/urban	1. rural--population code of 2,500-5,000 or less
	2. urban-population code greater than 5,000; and,
day/night	1. day--6:00 AM-9:00 PM
	2. night--9:00 PM-6:00 AM

public roads are supposed to be reported on a common form (UD-10, Traffic Accident Report) by the investigating officer. The data from these forms are then further interpreted (e.g., road classification codes are added) and entered in a computerized file, which is maintained by the Michigan Department of State Police (MSP). These files are public and made available by both MSP and the Michigan Department of Transportation (MDOT). MDOT has several versions of the file (e.g., one has physical location data), which are available for researchers and others.

Assembling and preparing the accident data for the study year required a considerable manual effort because of significant coding errors that occurred when trucks were classified by type. This happened as a result of confusion in interpreting the instructions for coding truck accidents on the UD-10. Numerous tractor-semitrailer combinations were coded as bobtails (tractors without trailers). Thus, a copy of the UD-10 for each truck-involved accident was manually reviewed. The type of truck was verified using codes entered by the investigating officer and the illustration and narrative describing the accident. The manual review also included coding the vehicle's state of registration, which is recorded on the UD-10 but not captured for the computerized data base. The review indicated that the involvement of singles had been underreported by approximately 20 percent, whereas involvement of single-unit (straight) trucks had been overreported by about the same amount.

During the 12-month study period, there were approximately 21,900 reported accidents that involved a truck larger than a pickup or panel truck. Of these, just over 10,000 involved bobtails, singles, or doubles [the rest involved single-unit trucks (straight trucks) for which no rates were calculated]. Some of the findings regarding truck accident frequencies in Michigan are summarized as follows. The frequencies indicate the magnitude of the truck accident problem relative to all traffic accidents. Findings based on accident rates, which identify configurations and operations with higher associated risks, are discussed later.

- Overall findings: About 5 percent of all accidents in Michigan involve a truck larger than a pickup or panel truck. These accidents are classified by type of truck involved in Table 2. Straight (single-unit) trucks (trucks with a cargo body mounted on the power unit chassis) are involved in about half of the truck accidents in Michigan. The other half are tractor configurations (bobtail, single, and double).

TABLE 2 DISTRIBUTION OF TRUCK AND ALL ACCIDENTS IN MICHIGAN FOR STUDY YEAR

truck type	accidents	percent
straight	10,993	2.7%
bobtail	458	0.1%
single	8,883	2.2%
double	678	0.2%
all trucks	21,827	5.3%
all accidents	408,066	100%
Source: Michigan State Police accident reports supplemented by manual review		

- Types of accidents: Trucks are more likely than nontrucks to be involved in multiple-vehicle accidents—79 percent of truck-involved accidents involved two or more vehicles versus about 57 percent of non-truck-involved accidents. Single-vehicle truck accidents are less likely to occur at night (about 25 percent of all truck-involved accidents) than single-vehicle nontruck accidents (about 50 percent). Conversely, a higher percentage of truck-involved multivehicle accidents (46 percent) occurred during non-rush-hour daytime hours (9:00 a.m.–3:00 p.m.) than non-truck-involved multivehicle accidents (32 percent).
- Severity of accidents: Trucks appear to be overrepresented in both fatal and property-damage-only (PDO) accidents. Whereas the absolute number of fatal accidents involving trucks is low (a total of 179 in 1988 for all types of trucks), the proportion of accidents that result in fatalities is about twice as high for accidents involving trucks as it is for non-truck-involved accidents.
- Driver age: In general, drivers of doubles are older than singles drivers, who are in turn older than the drivers of straights. (This finding is based only on the ages of drivers who are involved in accidents.)
- Roadway type: In general, truck-involved accidents were more likely to occur on US- and state-numbered routes than on city streets and county roads.

A summary of accident involvements by Michigan-registered trucks in Michigan is given in Table 3 (top). The involvements are stratified by truck type, roadway type, time of day, and whether the accident occurred in an urban or rural area.

TRUCK TRAVEL IN MICHIGAN

To develop truck accident rates, accurate exposure data as well as accurate accident frequencies are needed. VMT was selected as the measure of travel for this study. Although MDOT collects vehicle count data at numerous counting stations, it is impossible to accurately disaggregate these data according to truck configuration, road type, area of operation, and time of day. To address this need, UMTRI initiated a program to collect travel information with enough detail to calculate the required accident rates, the Michigan Truck Trip Information Survey (*3*).

TABLE 3 TRAVEL AND ACCIDENT INVOLVEMENT DISTRIBUTIONS OF MICHIGAN-REGISTERED TRUCKS IN MICHIGAN

Accident Involvement in Michigan by Michigan-registered trucks						
	bobtail		single		double	
category	# involv	%	# involv	%	# involv	%
limited day rural	17	5.41	768	14.83	86	16.90
limited night rural	9	2.87	200	3.86	25	4.91
major day rural	41	13.06	971	18.75	112	22.00
major night rural	8	2.55	182	3.51	17	3.34
other day rural	69	21.97	948	18.30	86	16.90
other night rural	14	4.46	89	1.72	6	1.18
limited day urban	40	12.74	455	8.79	66	12.97
limited night urban	4	1.27	63	1.22	4	0.79
major day urban	36	11.46	445	8.59	41	8.06
major night urban	0	0.00	64	1.24	5	0.98
other day urban	65	20.70	926	17.88	53	10.41
other night urban	11	3.50	68	1.31	8	1.57
TOTALS	314	100.00	5179	100.00	509	100.00

Travel in Michigan by Michigan-registered trucks						
	bobtail		single		double	
category	10^6miles	%	10^6miles	%	10^6miles	%
limited day rural	2.096	20.26	204.434	26.79	23.163	25.90
limited night rural	0.237	2.29	41.949	5.50	9.473	10.59
major day rural	2.099	20.29	128.647	16.86	15.040	16.82
major night rural	0.067	0.65	17.642	2.31	2.401	2.68
other day rural	0.258	2.50	31.765	4.16	3.207	3.59
other night rural	0.058	0.56	1.289	0.17	0.224	0.25
limited day urban	2.627	25.39	177.251	23.23	21.163	23.67
limited night urban	0.372	3.59	29.884	3.92	3.474	3.88
major day urban	0.930	8.99	59.822	7.84	5.530	6.18
major night urban	0.068	0.66	6.839	0.90	0.460	0.51
other day urban	1.439	13.91	59.731	7.83	4.952	5.54
other night urban	0.093	0.90	3.775	0.49	0.341	0.38
TOTALS	10.346	100.00	763.029	100.00	89.427	100.00

The survey was conducted between May 1987 and April 1988, the same period covered by the accident file. The sampling universe consisted of truck tractors with an empty weight of more than 6,000 lb—virtually all medium and heavy-duty truck tractors in Michigan. The sampling frame included trucks registered under the International Registration Plan with Michigan as the base state. A stratified random sample of 1,556 cases was drawn from registration files maintained by the Michigan Department of State. Of the sampled cases, 301 were determined to be either expired registrations or not a truck according to the definition of the survey protocol. Of the remaining 1,255 cases, 1,055 were completed, for a completion rate of 84 percent.

With 1,055 cases, the sampling fraction is substantial. When allowances are made for expired registrations and nontrucks incorrectly registered as trucks, estimates from the survey data indicate that there were 34,577 truck tractors registered in Michigan. Almost 10,000 of the tractors were registered to gross over 80,000 lb.

The objective of the survey was to collect detailed information about the actual travel of Michigan-registered tractors on Michigan roads. The operators of each truck were contacted by telephone four times over the course of the study year for a detailed description of the activities of the truck during the 24 hr of a randomly sampled day. If the truck was not used on that day, the day of the truck's last use was substituted. [The procedure for calculating the weights when a year's travel is estimated is described elsewhere (*3*).] Information gathered about the truck's use included the total travel for the day, the number and type of trailers pulled, the actual route driven by the truck, and the time of operation as well as other data. The route for the day was plotted on a map, and the accumulated mileage was recorded for each combination of road type, time of day, and area type. Both vehicle description and route data were reviewed and edited by experienced personnel so that problems with vehicle descriptions or the routes traveled were identified and subsequently clarified through additional calls.

Interviews for 8,464 trips on 3,603 sample days were completed. (The number of trips is higher than the number of sample days because a new "trip" started whenever a truck's configuration, loading, or driver changed. This allowed the desired disaggregation of VMT by the study variables noted.) The truck tractors in the study traveled 470,017 mi on those days. The routes for 96.1 percent of those miles were described in sufficient detail to be broken down by road type, time of day, and area type. Additional technical detail on the procedure used for this study is provided elsewhere (*2,3*) as are other applications (e.g., *4*).

Findings concerning the travel patterns of Michigan-registered trucks in Michigan are summarized in the following and in Table 3.

Travel Characteristics

On the basis of the survey, it is estimated that Michigan-registered tractors traveled approximately 883 million mi within

the state during the study period—an average of approximately 25,500 mi annually in Michigan. Tractors with semitrailers (singles) account for more than 88 percent of the estimated total travel, doubles account for 10.4 percent, and bobtails just 1.2 percent.

Approximately half the total travel by singles is on limited-access highways during the day—which are split between rural (54 percent) and urban (46 percent) roads. Another 25 percent of the total travel by singles is on major highways during the day (68 percent rural and 32 percent urban). The highest percentage of night travel (by highway and area type) is on limited-access highways in rural areas (5.5 percent of the total travel). Overall, about 59 percent of the singles travel was on limited-access roadways.

The distribution of travel by doubles is similar to that of singles, with the principal exception that about 11 percent of total travel by doubles is on limited-access highways in rural areas at night. Overall, approximately 64 percent of the total travel by doubles was limited-access highways—about 5 percent more than the comparable figure for singles. Conversely, doubles log about 3 percent less of their travel on local streets and roads than singles.

Classification of the travel of all tractors by approximate gross combination weight of the vehicle indicates that the 20,000- to 40,000-lb group (virtually all empty, or nearly empty, singles) accounts for about 39 percent of all travel, the 40,000- to 80,000-lb group accounts for about 43 percent, and about 14 percent of all travel is at weights in excess of 80,000 lb.

For singles, nearly 44 percent of travel is while empty or very lightly loaded. About 20 percent each is in the 40,000- to 60,000-lb and 60,000- to 80,000-lb ranges, and about 10 percent occurs at weights over 80,000 lb. For doubles, the distribution of travel by weight is somewhat different. Whereas about 43 percent of the travel is while empty, the percentages are lower (relative to singles) for intermediate weights, rising gradually to 26 percent in the 140,000- to 160,000-lb range. This indicates that doubles are more likely to run fully loaded in one direction and return empty—a typical pattern for the commodities (e.g., gravel) carried by very heavy trucks in Michigan.

Driver Characteristics

The distribution of truck drivers by age indicates that only 3.5 percent are 24 or younger, about 14 percent are 25 to 29, and 18 percent are 30 to 34. The percentages then drop gradually until 50 to 54, which accounts for 10.5 percent, and then more abruptly. Only 6 percent are 55 to 59, about 2 percent are 60 to 64, and less than 0.5 percent are over 64.

Only about 15 percent of the drivers definitely had driver training consisting of a combination of classroom and on-the-road training, whereas about 54 percent did not. It was not known whether the remaining 31 percent had any formal training. (The drivers themselves were not always interviewed, and this information was often unknown to the actual respondents.)

Of the 15 percent of drivers who had training, about two-thirds received it from either the current or a previous employer, about 18 percent from a truck-driving school, and less than 10 percent from the military. In other words, less than 3 percent of all drivers surveyed had definitely received training at a truck-driving school. For-hire haulers and companies that operate in interstate commerce may have a higher proportion of trained drivers, but the large amount of missing data makes firm conclusions impossible.

TRUCK ACCIDENT RATES IN MICHIGAN

The accident involvement and exposure data were combined to produce differential truck accident rates for various combinations of the stratifying variables described earlier (Table 1). Because the exposure survey covered only travel in Michigan by Michigan-registered tractors, only accident involvements of Michigan-registered tractors were used for the rate calculations. About 62 percent of the tractors involved in accidents in Michigan were registered in Michigan. The summaries of mileage and accident involvements are given in Table 3.

In addition to the rates based on all combinations of the stratifying variables and all accidents in Michigan by Michigan-registered tractors, rates were also calculated for (only) casualty accident involvements. The calculated rates for all police-reported, Michigan-registered tractor accident involvements, in their most disaggregate form, are given in Table 4. The rates are presented as accident involvements per million miles traveled and are shown with approximately 95 percent confidence intervals. The variance of the accident rates was calculated from the variances of the numerator (accidents) and denominator (travel) on the basis of the assumption that they are independent. Although the accidents are a census of all police-reported accidents during the study period, they were assumed to follow a Poisson distribution, and a variance assigned accordingly. Calculation of the variance of the travel estimates follows directly from the sample design, a stratified simple random sample. Ninety-five percent confidence intervals are approximated as plus and minus twice the standard error of the rate.

In comparing any two rates (e.g., Table 4), if the respective confidence intervals overlap, the rates are not significantly different. In general, the confidence intervals reflect the sample size and the observed variability in accidents and travel. Rates with large confidence intervals are usually based on relatively small samples of accidents or travel. Principal findings based on the accident rates are summarized as follows:

- In virtually all instances, bobtail accident involvement rates are far higher than those for singles and doubles, although the differences are not always statistically significant.
- Rates for doubles are generally somewhat lower than those for singles. This is the case regardless of whether all, one-vehicle, or multivehicle accidents are considered (the breakdown by number of vehicles involved is not shown in Table 4).
- Although there are just over 300 bobtail involvements, the highest rates tend to be at night, generally in rural areas, and, most clearly, on the lowest class of roadway.
- Singles involvement rates are always higher for lower classes of roadways—rates for major highways are typically 2 to 3 times higher than for limited-access highways; rates for other highways (local streets and roads) are typically 7 to 10 times higher than for limited-access highways.

TABLE 4 OVERALL TRUCK ACCIDENT RATES* (ALL INVOLVEMENTS) FOR MICHIGAN-REGISTERED TRUCKS ON MICHIGAN ROADS IN STUDY YEAR

urban/ rural	day/ night	road class	bobtails rates ± 2sd	singles rates ± 2sd	doubles rates ± 2sd
rural	day	limited	8.11 ± 5.02	3.76 ± 0.35	3.71 ± 1.09
		major	19.53 ± 10.38	7.55 ± 0.80	7.45 ± 2.38
		other	267.21 ±138.73	29.84 ± 4.15	26.81 ±11.20
rural	night	limited	38.00 ± 74.57	4.77 ± 0.86	2.64 ± 1.35
		major	118.69 ±153.57	10.32 ± 2.32	7.08 ± 4.96
		other	239.79 ±347.57	69.04 ±24.98	26.78 ±24.78
urban	day	limited	15.23 ± 6.37	2.57 ± 0.28	3.12 ± 0.94
		major	38.71 ± 16.66	7.44 ± 0.87	7.41 ± 2.98
		other	45.16 ± 14.19	15.50 ± 1.56	10.70 ± 4.15
urban	night	limited	10.76 ± 14.32	2.11 ± 0.58	1.15 ± 1.22
		major	---- ± ----	9.36 ± 2.89	10.88 ±10.82
		other	118.35 ± 93.08	18.01 ± 6.10	23.47 ±19.49
		OVERALL	**30.35 ± 5.89**	**6.79 ± 0.22**	**5.69 ± 0.55**

* rates are accidents per million vehicle-miles ± 2 std dev

- Singles involvement rates for rural, night conditions are, at worst, about twice as high as for daytime conditions. The difference between night and day is not as distinct for urban areas. However, urban rates are generally lower than rural rates regardless of roadway class.
- Although limited by sample size, doubles rates are lower than singles rates in most instances—the principal exception (from Table 4) is on urban, limited-access roads during the day.
- Further analysis indicated that doubles rates were higher than singles rates in some specific situations, such as one-vehicle involvements on rural limited-access highways during the day, multivehicle involvements on rural major roadways during the day, and urban limited-access roadways during the day. The higher one-vehicle accident rate is primarily due to rollover accidents, an accident type for which doubles are well known.

Rates considering only casualty accidents are given in Table 5. These results and those from related analysis (not shown here) can also be summarized (subject to the same caveats concerning confidence intervals and sample size as noted earlier).

- Although there is an even greater scarcity of bobtail data (relative to Table 4), bobtail rates are higher than those for either singles or doubles. The ratio of the rates is about the same as it was when all (casualty and noncasualty) accidents were considered.
- In contrast to the all-involvement rates, when only casualty accidents are examined, the overall doubles rate is higher than the singles rate. More specifically, it appears that doubles rates are higher than singles rates for day conditions in both rural and urban situations and regardless of roadway class.
- Also in contrast to Table 4, when only casualty accidents are considered, nighttime rates are generally higher than daytime rates. This finding is somewhat stronger in rural than urban areas.

Whereas the disaggregated casualty accident rates shown in Table 5 are of considerable interest, the sample sizes are small in many instances. However, the accident and travel

TABLE 5 OVERALL TRUCK CASUALTY ACCIDENT RATES* FOR MICHIGAN-REGISTERED TRUCKS ON MICHIGAN ROADS IN STUDY YEAR

urban/ rural	day/ night	road class	bobtails rates ± 2sd	singles rates ± 2sd	doubles rates ± 2sd
rural	day	limited	3.34 ± 2.83	0.92 ± 0.14	0.91 ± 0.44
		major	5.72 ± 4.12	1.87 ± 0.29	2.06 ± 0.91
		other	85.20 ± 53.44	6.30 ± 1.18	8.11 ± 4.30
rural	night	limited	8.44 ± 19.63	1.50 ± 0.41	1.16 ± 0.79
		major	---- ± ----	3.46 ± 1.06	2.08 ± 2.14
		other	119.89 ±185.22	17.07 ± 8.83	8.93 ±13.21
urban	day	limited	3.43 ± 2.47	0.60 ± 0.12	0.61 ± 0.36
		major	4.30 ± 4.46	1.54 ± 0.34	1.99 ± 1.30
		other	4.86 ± 3.79	1.98 ± 0.39	3.43 ± 1.91
urban	night	limited	---- ± ----	0.77 ± 0.33	0.29 ± 0.58
		major	---- ± ----	2.78 ± 1.37	---- ± ----
		other	43.04 ± 48.21	5.03 ± 2.60	17.60 ±16.29
		OVERALL	**7.15 ± 2.01**	**1.51 ± 0.09**	**1.61 ± 0.28**

* rates are accidents per million vehicle-miles ± 2 std dev

data can also be aggregated by the key variables to yield marginal rates, such as daytime rates for different truck types regardless of roadway class and urban-rural classification. The results of calculating such aggregated rates are discussed below in summary form. All rates are given in accidents per million vehicle miles.

The rates in Table 6 highlight the fundamental differences between the different types of trucks and the impact of including PDO accidents in the rate calculation. The bobtail rates are significantly higher than those for combination trucks for both casualty and all involvements. When PDOs are included, the singles rate is significantly higher than the doubles rate. When only casualty accidents are considered, the doubles rate is higher, but not significantly.

The aggregated urban and rural rates (regardless of roadway type and time of day) in Table 7 indicate that rural rates are generally higher than those for urban areas (regardless of truck type and whether PDOs are included). The bobtail rates are still far higher than combination truck rates for both urban and rural conditions. The rates for singles and doubles are similar. PDO accidents tend to "drive" the overall rates. Similarly, singles dominate when rates are aggregated across configuration. In general, the subgroups with large sample sizes dominate the overall rate.

The differences between day and night rates given in Table 8 are less clear than the other aggregated rates. When all accidents are considered, the night rates are lower than the day rates, except for bobtails. For combination trucks, there is more of a difference for doubles than for singles (i.e., the night doubles rate is much lower than the day rate). However, when only casualty accidents are considered, the night rates are higher for both bobtails and singles. The doubles rate is still lower at night than during the day. The "overall" rate shows that when only casualty accidents are considered, combination trucks tend to have higher night rates—this is, however, driven by bobtails and singles.

The aggregated rates by roadway type (Table 9) indicate a clear and consistent trend: the lower the road class, the higher the accident rate, regardless of truck type or whether all accidents or only casualty accidents are considered. The rates for singles and doubles are also similar, although there is some divergence between the two when the lowest road class is considered.

TABLE 6 RATES* BY TRUCK CONFIGURATION, ALL ACCIDENTS AND CASUALTY ACCIDENTS

truck type	all accidents	casualty accidents
bobtails	30.35 ± 5.89	7.15 ± 2.01
singles	6.79 ± 0.22	1.51 ± 0.09
doubles	5.69 ± 0.55	1.61 ± 0.28

* rates are expressed as accidents per million vehicle-miles ± 2sd

TABLE 7 RATES* BY TRUCK CONFIGURATION AND URBAN OR RURAL AREA, ALL ACCIDENTS AND CASUALTY ACCIDENTS

	all accidents		casualty accidents	
truck type	urban	rural	urban	rural
bobtails	28.21 ± 6.16	32.81 ± 9.20	4.34 ± 1.89	10.38 ± 3.79
singles	5.99 ± 0.29	7.42 ± 0.31	1.12 ± 0.12	1.82 ± 0.14
doubles	4.93 ± 0.78	6.20 ± 0.77	1.34 ± 0.39	1.79 ± 0.38
overall	6.22 ± 0.26	7.54 ± 0.25	1.19 ± 0.11	1.90 ± 0.13

* rates are expressed as accidents per million vehicle-miles ± 2sd

TABLE 8 RATES* BY TRUCK CONFIGURATION AND TIME OF DAY, ALL ACCIDENTS AND CASUALTY ACCIDENTS

	all accidents		casualty accidents	
truck type	day	night	day	night
bobtails	28.36 ± 5.85	51.37 ± 30.55	6.45 ± 1.97	14.52 ± 11.00
singles	6.82 ± 0.23	6.57 ± 0.63	1.43 ± 0.10	2.04 ± 0.31
doubles	6.08 ± 0.64	3.97 ± 1.13	1.63 ± 0.31	1.53 ± 0.65
overall	7.02 ± 0.19	6.55 ± 0.47	1.51 ± 0.09	2.06 ± 0.26

* rates are expressed as accidents per million vehicle-miles ± 2sd

TABLE 9 RATES* BY TRUCK CONFIGURATION AND ROAD TYPE, ALL ACCIDENTS AND CASUALTY ACCIDENTS

	all accidents		
truck type	limited	major	other
bobtails	13.13 ± 4.40	26.86 ± 9.11	85.99 ± 18.04
singles	3.28 ± 0.18	7.80 ± 0.44	21.03 ± 1.14
doubles	3.16 ± 0.50	7.47 ± 1.26	17.54 ± 3.09
total	3.37 ± 0.16	8.02 ± 0.37	21.87 ± 0.90
	casualty accidents		
truck type	limited	major	other
bobtails	3.38 ± 1.78	5.06 ± 2.85	21.63 ± 7.46
singles	0.84 ± 0.09	1.94 ± 0.20	3.72 ± 0.41
doubles	0.80 ± 0.24	2.01 ± 0.60	5.85 ± 1.69
overall	0.86 ± 0.08	1.99 ± 0.18	4.20 ± 0.40

* rates are expressed as accidents per million vehicle-miles ± 2sd

DISCUSSION OF PRINCIPAL FINDINGS

Discussion of the principal findings of this project is organized by truck type and then by the other variables that were isolated (e.g., roadway type).

Bobtails

The bobtail configuration clearly has the most serious problem safely negotiating the highway system. It had the highest rates for every road type, area type, time of day, or combination of those variables. This was true regardless of whether all accidents or only casualty accidents were considered (see Tables 4 and 5). Though the differences were not always statistically significant, the bobtail rates were always the highest. The only exceptions were for cells that had no accidents. Moreover, for the overall (marginal) rates, the increased risk of bobtails over singles and doubles is highly significant for both casualty and all accidents.

This finding is consistent with vehicle design considerations. The handling, braking, and other systems for tractors are all designed to pull single or double configurations. Without a trailer attached, the handling properties of the tractor are significantly degraded, which must account for at least some of the rate differential. Though some manufacturers have recently introduced "brake proportioning" valves to improve tractor braking when no trailer is being pulled and drivers may compensate when driving bobtails, these factors are apparently insufficient to produce accident rates similar to other tractor configurations.

Singles and Doubles

There is a growing literature that compares the safety of singles and doubles. Estimates of the relative safety of doubles range from somewhat lower rates than for singles to rates two to three times as great (*1*). The statistics presented here for Michigan, which are based on a census of police-reported accidents and a statistically valid survey of actual travel, indicate that the performance of singles and doubles is generally similar in terms of overall safety. For all accidents, the doubles rate is significantly lower than the singles rate (5.69 versus 6.79), but for casualty accidents the rates are virtually identical.

When the rates are disaggregated by road class, time of day, and area type, other differences are apparent. Considering all accidents, the rates for doubles are the same or lower for all road types. For "other" roads, the rate for doubles is 17.54 versus 21.03 for singles (this difference is not significant at the 95 percent confidence level). However, for casualty accidents, doubles have a statistically significant higher rate (5.85 versus 3.72) on these same roads. Doubles accidents on such roads are more likely to involve injury or death than singles accidents.

The same pattern holds for area type: doubles rates are lower in both rural and urban areas when all accidents are considered. However, when only casualty accidents are considered, the rates are about the same in rural areas, and doubles rates are slightly higher in urban areas. This is consistent with the typical usage patterns for doubles—they accumulate a higher proportion of their travel on inherently safer limited-access roads. On the other hand, an accident involving doubles is more likely to involve a casualty, which offsets some of the doubles' advantage due to road type.

Similarly, the overall accident rate for doubles is lower than for singles for both day and night conditions, although for casualty accidents, doubles do somewhat worse during the day and significantly better at night. This is consistent with doubles use at night being on limited-access roads.

Road Type

The most significant and consistent effect on accident rates appeared to be due to the type of road. Accident rates for all types of trucks were highest on "other" roadways (local streets and roads) and lowest on limited-access highways. This was true in every case, when controlling for other variables, and for both casualty and all accidents. The effect of road type is so large that it must be taken into account in any analysis of truck accident rates, or it may mask the effects of other variables.

Area Type and Time of Day

Accident rates were generally lower in urban areas than in rural areas, regardless of combination type. The effect is not as great as that of road type, but it is consistent across the other variables in the study. For all accidents, the day rate was higher than the rate for night. However, when only casualty accidents were considered, the night rate was 2.06 versus 1.51 for day, with the difference being statistically significant. The explanation for these differences is probably that PDO accidents occur primarily during the day and are a function of traffic density, which is higher during the day and in urban areas. Casualty accidents are more likely to be associated with fatigue, higher speeds, and shorter sight distances due to darkness, which would lead to higher rural night rates.

Driver Age

Accident rates for truck drivers in Michigan are strongly associated with driver age. Drivers under the age of 25 and over 60 had much higher accident rates than average—drivers aged 19 and 20 had rates 5 times higher than the average, and drivers over 60 had rates 1.5 times greater than average. This is consistent with previous work, which has indicated that younger drivers generally have higher rates for passenger cars and higher fatal rates in large trucks (*5,6*).

IMPLICATIONS FOR FUTURE WORK AND RECOMMENDATIONS

This work has attempted to advance both the quality and level of detail in the data on the study of truck safety. The accident data represented a census of 1 year of accidents involving Michigan-registered trucks operating in Michigan. The travel data similarly came from a survey of the actual travel of a representative sample of Michigan tractors. In both files a

level of detail was achieved that allowed the calculation of rates for groups determined by the cross-classification of several factors of interest. Rates can be examined not just by one or two factors at a time but by several (e.g., casualty accidents involving singles on limited-access roads in urban areas at night). This has allowed a significantly increased level of understanding of the complex interaction of the many factors associated with the risk of truck accidents.

It is clear that detailed accident and travel data are essential to useful safety analysis, but such data are not widely or readily available. For example, a recent report (*7*) indicated that there is no current national consensus on either the number of trucks involved in accidents or their annual travel. Moreover, whereas the quality of the data in the Michigan accident file is as good as any, extensive manual review of hard copies of the police reports was required to identify Michigan-registered trucks and to correct coding errors. Even then, no data were available on cargo body type, virtually none on loading, and only the most basic on truck configuration. Reliable Michigan travel data were simply unavailable from existing sources.

To answer detailed questions about truck safety, detailed data are required. The results here indicate that analyses must be able to control at least for road type, area of operation, and time of day. The TRB Committee on Truck Safety Data Needs has recommended important steps toward improving the quality of data available for truck traffic safety research. Moreover, implementation of the National Governors Association supplemental truck accident form would improve the amount of information available about vehicle configurations and hazardous cargo. Whereas the supplemental form contains many of the data elements used in this study, an urban/rural code is not included. Partially in response to the results of the study reported here, Michigan has implemented a supplemental truck accident report, which, in combination with the computerized accident file, provides considerable data for more thorough analysis.

The provision of better accident data is not, however, sufficient for the analysis that needs to be done. Exposure data are equally important but appear to command less attention despite the difficulty of collection. The TRB committee's recommendations on travel data would improve the situation, although it is not clear that even that is sufficient. Exposure data must be collected at the same level of detail as the accident data to calculate differential accident involvement rates and to allow examination of the interactions between variables of interest. Thus, a system of vehicle counts supplemented by descriptive information from random safety inspections may not produce adequate travel information. However, it produces timely and continuous data, which are crucial in an industry as dynamic as trucking.

Many important safety-related questions that could not be addressed during this study are logical extensions of this approach. The impact of carrier type, gross vehicle weight, and trailer cargo body are among the opportunities for further work. In an era of deregulation, differences in safety records of various categories of truck operators will be of increasing interest. The transport of hazardous cargo and pressure to increase the productivity of trucking by allowing heavier and longer combinations also raise important safety questions (*8*). Addressing them will require weight and length information as well as operating weight, cargo type, and cargo body.

One of the original objectives of this study was to explore the relationship between roadway geometry and truck type. As noted earlier, problems with data reduction limited the scope of the work. However, the study has clearly confirmed that restrictive geometry, as measured by road class, is a serious problem in truck safety. Examination of some truck accidents indicated that even the relatively low crash rates for limited-access highways may be overstated. A sizable number of one-vehicle accidents involving doubles resulted from overturns on ramps. These accidents were attributed to limited-access roads even though they occurred on the low-design-speed components of that system.

More work is required to identify the geometric characteristics specifically related to truck accidents. Not only the characteristics of the accident sequence and roadway but also truck loading and travel characteristics should be included. The accident risk on ramps, for example, is related not only to the interaction between truck type per se and ramp geometry, but also to the specifics of the trailer type, number of axles, cargo body style, and loading.

This sort of inquiry is of continuing importance as, for example, pressure is applied to allow triples in more states and other truck configurations are proposed. Whereas accurate prediction of the safety impact of new configurations or operating weights would be best (*8*), it is imperative that the data and analytical process be in place to allow accurate assessment of the effects of such policies. Some of the research techniques and methodologies to make such assessments have been demonstrated by this study.

ACKNOWLEDGMENT

More details on the study reported on here are contained in the final report on this project (*2*).

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The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the Michigan Office of Highway Safety Planning, FHWA, or NHTSA.

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