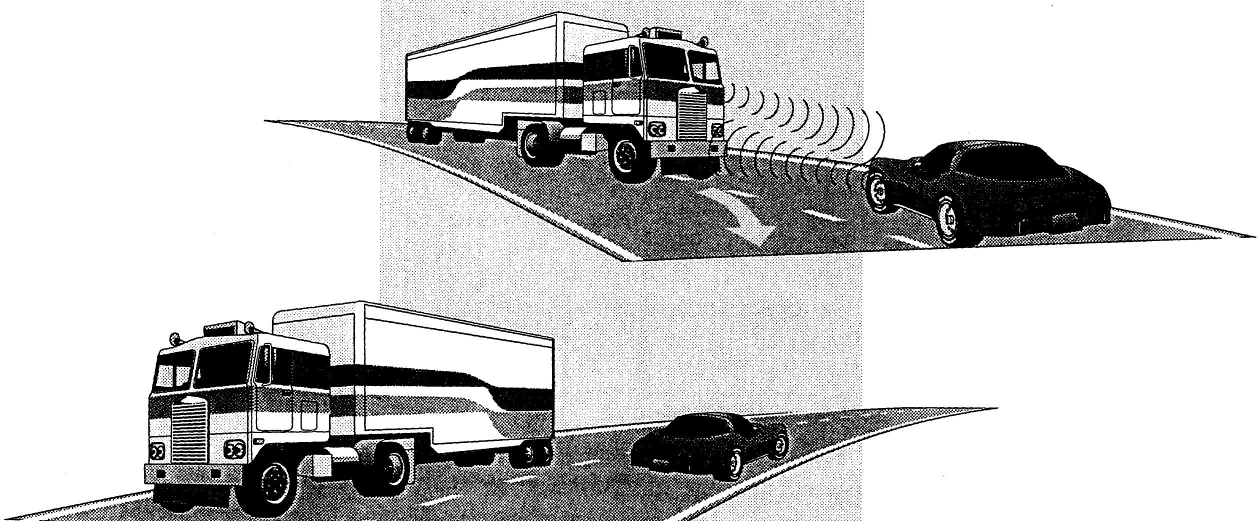
FINAL REPORT

ADVANCED TECHNOLOGIES FOR IMPROVING LARGE-TRUCK SAFETY ON TWO-LANE SECONDARY ROADS



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16. Abstract

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Although several studies have been conducted to determine the effects of large trucks on safety on multilane primary and interstate highway systems, the effects on two-lane secondary roads have been largely ignored. This study identified the causal factors and predominant types of large-truck crashes on two-lane secondary roads in Virginia and compared the large-truck crash rates for two-lane secondary roads and two-lane primary roads. The study also identified advanced technologies associated with intelligent transportation systems (ITS) that can be used to minimize the causal factors of large-truck crashes on these roads.

The results showed that large-truck crash rates are significantly higher on two-lane secondary roads than on two-lane primary roads, with the predominant types of crashes being angle, rear end, sideswipe same direction, and sideswipe opposite direction. The study identified several ITS technologies that can be used to mitigate the predominant causal factors and recommends a pilot study to test the effectiveness of one such system.

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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The results showed that large-truck crash rates are significantly higher on two-lane secondary roads than on two-lane primary roads, with the predominant types of crashes being angle, rear end, sideswipe same direction, and sideswipe opposite direction. The study identified several ITS technologies that can be used to mitigate the predominant causal factors and recommends a pilot study to test the effectiveness of one such system.

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INTRODUCTION

Supporters of the Surface Transportation Assistance Act (STAA) of 1982 and the Tandem Truck Safety Act (TTSA) of 1984 claimed that passage of these two acts would reduce the overall vehicle miles of travel (VMT) of large trucks (trucks having six or more wheels in contact with the road and having a gross weight greater than 4535.9 kg [10,000 lb]) since fewer of the longer and wider trucks would be needed for the transportation of goods in the United States. Supporters also believed that the increased use of twin-trailer trucks (truck-tractors pulling two trailing units) would have little overall effect on highway safety because the reduction in truck VMT would approximately offset the small possible increase in crash involvement per mile traveled.[1]

The predicted reduction in large-truck VMT, however, has not occurred. Apparently, increasing the size of the trucks has simply reduced the expense of distribution. Consequently, more businesses have begun using this mode of transporting goods, thus increasing the number of large trucks using the highway system and the annual VMT. In fact, their use has steadily increased over the years to the point where large trucks now account for over 50% of vehicle traffic on some highways in Virginia. Projections now forecast that large-truck travel will grow at twice the rate of personal vehicle travel in the near future.[2] This will probably result in increasing numbers of large-truck crashes, particularly on two-lane secondary roads, as motorists move from the congested interstate and primary roads onto the secondary road system.

Several studies have been conducted to determine the effect of large-truck operation on multilane primary and interstate highway systems. However, two-lane secondary roadways have been largely disregarded under the assumption that crash characteristics and crash rates for large trucks are the same for these roads as for multilane and interstate highways. In fact, geometric characteristics of two-lane secondary routes often limit maneuverability and visibility for large vehicles, thereby increasing the risk of a crash involving a large truck. One study determined that collisions between passenger cars and large trucks on undivided rural roads are more severe than on divided roads under all conditions. This disparity is even more predominant during nighttime hours.[3] These results pertain particularly to secondary roads, which tend to be undivided and, more often than not, two lane. Sharp curves, steep grades, and limited sight distance are common on secondary roads throughout the United States and are particularly abundant in certain areas of Virginia where mountains and other natural land features have dictated many of the road locations and designs. These limitations can lead to more large-truck crashes and traffic delays on these two-lane secondary roads than on multilane highways.

Other pertinent factors with regard to secondary roads are the wide variations in their physical characteristics and average annual daily traffic (AADT). For example, lane width varies from about 2.44 m (8.0 ft) to 3.66 m (12.0 ft), and AADT can be as low as 30 and as high as 30,000.

Since statistics suggest that large-truck traffic will continue to increase on two-lane secondary roads, and their inherent geometric characteristics will not change, suitable countermeasures must be identified that will reduce the risk of large trucks being involved in crashes on these roads. Most often, a large-truck crash is caused by driver error or inattention rather than a problem with the highway environment. Traditional improvements to the roadway such as geometric changes, increased/improved signing, and altered/improved pavement markings cannot counter driver error significantly, or have not appeared to be effective to this point. It is, however, feasible that advanced technologies, particularly those associated with intelligent transportation systems (ITS), which consist of a number of technologies including information processing, communications, control, and electronics, could be used to minimize the effect of the lower geometric standards and other causal factors of large-truck crashes on two-lane secondary roads.

Toward this end, the Virginia Transportation Research Council (VTRC) conducted this study to determine the crash characteristics and identify the causal factors of large-truck crashes on secondary roads and identify ITS and other advanced technologies that would eliminate or minimize the effect of the identified factors. In addition, the study contributed to achieving the Virginia Department of Transportation's (VDOT's) fundamental objective to use ITS technology to enhance safety.

PURPOSE AND SCOPE

The purpose of this project was to identify the predominant collision types and the principal causal factors of large-truck crashes on two-lane secondary roads in Virginia through fault tree analysis and then identify existing or future ITS and other advanced technologies that could be used to develop appropriate countermeasures to eliminate or reduce the detrimental effects of the identified factors. The specific objectives were:

1. Determine the characteristics of crashes involving large trucks on two-lane secondary roads.

2. Determine whether large-truck crash rates for two-lane secondary roads are significantly different from those for two-lane primary roads.

3. Determine whether large trucks are overrepresented in crashes on two-lane secondary roads.

4. Identify predominant causal factors for large-truck crashes on two-lane secondary roads.

5. Identify existing or proposed ITS and other advanced technologies that could be used to develop countermeasures that would minimize or eliminate large-truck crashes on two-lane secondary roads.

LITERATURE REVIEW

Sources for identifying information relevant to this study included the Transportation Research Information Service (TRIS), the VTRC Library, and the University of Virginia libraries. Completed studies over the past 15 years relating to this project were identified and their reports reviewed. In addition, reports on ITS and other advanced technologies were continuously reviewed in order to ensure inclusion of the most up-to-date material on this ever-changing field. The materials reviewed were classified under the following subheadings:

- large-truck crash characteristics on two-lane primary roads
- large-truck crash characteristics on secondary roads
- large-truck access laws
- large-truck safety
- ITS and other advanced technologies.

Large-Truck Crash Characteristics on Two-Lane Primary Roads

Several reports have been published by the Transportation Research Board relating to the impact of the STAA of 1982 and the TTSA of 1984 on traffic safety on two-lane highways. For example, Hedlund[4] reported that large-truck crashes are more likely to result in a fatality on two-lane primary roads than on four-lane primary roads. Hedlund attributed this finding to the increased likelihood of high-speed, head-on collisions on two-lane primary roads. On the other hand, low-speed crashes, with less severe effects, predominated in residential and business areas.

Preliminary analysis of large-truck crashes on two-lane primary highways in Virginia indicated that large trucks have higher rates of injury crashes, property damage crashes, and overall crashes than passenger cars.[5] Between 1988 and 1990, large-truck fatality rates increased significantly for two-lane primary roads whereas overall vehicle fatality rates declined.[5] The greatest percentage of crashes were rear-end collisions and fixed-object-off-the-road crashes.[5]

Cleveland et al.[6] examined the influence of geometric characteristics and traffic variables on crash rates on rural two-lane highways by grouping them into compatible classes based on their geometric and traffic characteristics. A total of 21 models were tested with different combinations of the variables within each class. These models were able to explain between 30% and 75% of the variation in crashes, and the most significant variable was found to be the average daily traffic (ADT) of the roadway. They concluded that the geometric characteristics of the roadway were relatively insignificant. However, their analysis was based on all crashes, not just on those involving large trucks.

Large-Truck Crash Characteristics on Secondary Roads

Roads classified as secondary roads in the United States can be grouped into two categories: those that were formally under the federal-aid system, consisting of 398,000 miles of rural major collector roads linking towns and smaller communities with the primary system,[7] and those that are off the federal-aid system, consisting of about 2.6 million miles of two-lane rural highways. These secondary roads account for 80% of all U.S. road miles.[8] In addition, roads in mountainous and rolling terrain account for more than two-thirds of the secondary two-lane mileage.[8] The roads that traverse these types of terrain are characterized by steep grades and sharp curves. Within the secondary system, geometric design standards vary considerably, the use of traffic control devices is limited, and estimates indicate that 68% of rural travel and 30% of all travel occur on the rural two-lane system.[8] In addition, 80% to 90% of two-lane crashes occur in this rural environment and certain crash categories including passing maneuver, run-off-the-road, and railroad crossing crashes are predominant among them.[8] In Virginia, the total mileage of secondary roads is about 45,710.

The literature review revealed no specific study on large-truck crashes on two-lane secondary roads.

Large-Truck Access Laws

The access of large trucks onto secondary roads is governed by both federal and state laws. Although a state's regulations cannot reduce the restrictions called for by federal regulations, they can further restrict large-truck access over and above that of the federal regulations. This in some cases results in litigation. For example, prior to 1988, Virginia had state regulations in effect that prevented single pup trailer units 2.6 m (102 in) wide from reaching local customer

Table 1. Federal and Virginia Codes Regulating Large-Truck Access

Statute	Pertinent Language
Federal Regulations	
49 U.S.C.S. Appx. §2311(a) (1992)	No state shall impose regulation on tractor-trailer combinations of less than 48 ft [14.6 m] or semi-trailers of less than 28 ft [8.5 m]
49 U.S.C.S. Appx. §2311(b)	Federal regulation is limited to only trailers
49 U.S.C.S. Appx. §2311(i)	The Governor can petition the Department of Transportation for any road to be exempted from federal length regulation for purely safety reasons
49 U.S.C.S. Appx. §2312(b)	States can impose reasonable regulations on trailers less than 28.5 ft [8.7 m] for purely safety reasons
49 U.S.C.S. Appx. §2316(a)	Prohibits state regulation of trailers less than 102 in [2.6 m] wide (does not include safety devices in measurement)
49 U.S.C.S. Appx. §2316(e)(1)	The Governor can petition the Department of Transportation for any road to be exempted from federal width regulation for purely safety reasons
Virginia Regulations	
Va. Code Ann. §46.2-1109 (1993)	Limits commercial vehicles to 102 in [2.6 m] wide and trailers to 28.5 ft [8.7 m] long
Va. Code Ann. §46.2-112 (1993)	Vehicle load combinations must be less than 60 ft [18.3 m] and tractor-trailer combinations must be less than 48 ft [14.6 m]

points of loading and unloading on two-lane secondary roads. In 1988, as a result of *A.B.F. Freight System, Inc. v. Suthard,* 681 F.Supp. 334 (1988), the Virginia statutes were found to prohibit "reasonable access" guaranteed for single pup trailers in 49 U.S.C.S. Appx. §2312 and were struck down. A summary of the current federal and state laws relevant to large-truck access in Virginia is given in Table 1, and a summary of the size and weight requirements is given in reference 9.

Large-Truck Safety

Truck crashes are complex events; several factors interact to contribute to their occurrence: the vehicle, the driver, the environment, or another vehicle. Evidence indicates that the driver contributes most significantly to truck crashes since driver action or inaction can frequently precipitate or prevent the occurrence of a crash. Driver factors (i.e., fatigue, inattention, driving under the influence of drugs or alcohol, driving at an excessive speed for prevailing conditions, and poor judgment) have contributed to a large portion of truck crashes investigated by the National Transportation Safety Board.[10] Nevertheless, as with most vehicle crashes, commercial vehicle crashes are caused by the interaction of human, environmental, and vehicle factors. Although most crashes are attributed to driver error, this classification often obscures the fact that safety enhancements along the roadway and integrated into the vehicle can decrease the probability that a driver will make a serious error and a crash will occur.[11]

With the introduction of the longer and wider tractor-trailers, questions have arisen about the safety of these vehicles. Many secondary roadways have lane widths of only 3.1 m (10 ft) or less.[7] These roads were not designed for and are not able to carry the larger, heavier trucks that now dominate the trucking industry. A study[12] conducted by the Highway Safety Research Center at the University of North Carolina and the Scientex Corporation found that on high-speed rural two-lane and multilane roads, the tractor-trailers 2.6 m (102 in) wide encroached on lane edges and operated slightly closer to the center line than did those 2.4 m (96 in) wide. In another study,[13] Donaldson concluded that the operation of long, wide trucks, especially on two-lane, two-way roads with substantial geometric deficiencies, significantly compromised the safety of automobile motorists.

Gericke and Walton[10] stressed that prospective increases in the length of trucks will correspondingly increase aborted passing maneuvers of automobiles and will thereby increase safety hazards. Olsen et al.[11] also found that for controlled stops in which the truck driver modulates his or her brakes to prevent spinning or jackknifing and maintains steering control, trucks require stopping distances that are approximately 1.4 times those required for automobiles. Two studies[13,14] concluded that many curves with lanes less than 3.7 m (12 ft) wide on two-lane two-way roads cannot be properly and safely negotiated by a large truck even when it is traveling at the posted speed.

A 1992 study by Garber and Patel[14] showed that large-truck crash rates are significantly higher when lane widths are 3.1 m (10 ft) or less on multilane highways and that steep grades and narrow lanes also increase the probability of crashes on multilane roads. For example, during 1987 to 1989, the crash rate of tractor-trailers with trailer widths greater 2.4 m (96 in) in Virginia was 584 per 100 million VMT on a sample of primary roads having lanes 3.1 m (10 ft) wide and only 203 per 100 million VMT on similar roads having lanes 3.7 m (12 ft) or wider.[14] These statistics are of particular importance for two-lane secondary roads when it is noted that 88.9% of these roads in Virginia have lane widths of 3.1 m (10 ft) or narrower.

There are also intrinsic characteristics of large trucks that increase the potential of these vehicles to be involved in crashes, particularly on two-lane secondary roads. For example, the stopping sight distance given in AASHTO guidelines for crest vertical curves are much shorter than the actual stopping distance for trucks while maintaining directional control.[15] The primary factors that contribute to the longer stopping distances are inferior truck tire properties on poor, wet roads; poor braking efficiencies of heavy trucks; and poor driver control efficiencies in modulating the brakes to avoid wheel lock. Fancher concluded that vertical curves designed for speeds of 60 mph or more in accordance with AASHTO guidelines are adequate only for trucks traveling 52 mph or less.[15] The majority of the secondary roads in Virginia have a legal speed limit of 55 mph.

Another issue is the comparison of the crash rates of large trucks with those of other vehicles. Based on the results of previous studies,[5,13,14] there is no consensus as to whether the crash rate of large trucks is significantly higher or lower than that of all other vehicles. Most truck crash studies, nevertheless, appear to indicate that the fatal crash rate of large trucks is much higher than that for passenger cars. For example, from 1988 to 1990, large-truck fatal crash involvement in Virginia increased 2.1% whereas automobile fatal crash involvement decreased 0.8%.[16] These statistics raise questions regarding the overall safety of large trucks on U.S. highways, especially on secondary roads where standards for geometric characteristics are usually lower than those for primary and interstate highways.

ITS and Other Advanced Technologies

ITS technologies are based on the integration of the elements of surface transportation systems (the vehicle, the infrastructure, and the traveler) into a single system through communication, information, and control functions. ITS technologies use state-of-the-art microelectronics to achieve this integration. These technologies are capable of a wide variety of functions. Examples of advanced technologies that have been implemented for safety reasons are antilock brakes and airbags. ITS technologies currently in use or being developed that could affect traffic safety include weigh-in-motion of large trucks, automatic vehicle identification, collision warning and/or avoidance, traveler information, traffic condition reporting, alternate route selection, and incident management. Research is being initiated to determine if these technologies are economically, technically, socially, and politically feasible.

Current ITS Technologies Available

Current literature on ITS technologies indicates that research is underway or being planned that will lead to the development of different types of equipment that would have a significant impact on the highway system. It is envisioned that by the year 2000 these will include the following:[17]

- longitudinal and lateral collision avoidance systems
- "smart" traffic signal systems that genuinely maximize the efficient use of roads, reducing stops and delays

- aids to tell drivers where they are when traveling in unfamiliar areas and show the location of their destinations

- driver information systems that display congestion information and assist the driver in selecting the best route

- a general facility for providing a variety of information to travelers that is tailored to their locations and needs as ITS comes to constitute an information utility

- devices to sense lapses in driver performance and aid in driving tasks (e.g., cruise control that responds to changes in speed and distance of the vehicle ahead)

- systems to help police, fire, ambulance, and transit services dispatch their vehicles as quickly as possible to where they are most needed (e.g., enhanced 911)

- systems to improve the efficiency of truck operations, reducing paperwork and delays and thereby helping to reduce the cost of all goods shipped by truck

- "may day" systems that will speed emergency response to accidents in rural areas.

Visions of the Future

Researchers have indicated that ITS can reduce traffic fatalities by 8% by the year 2011.[18] That percentage translates to 3,300 lives saved and 400,000 injuries prevented each year at current traffic levels. These figures, however, could prove to be quite conservative. Future advanced technology could "ensure the driver's own state of fitness, enhance driver perception on a continuous basis, give warning of impending danger, intervene with emergency control if a crash is imminent, and perhaps eventually automate the driving process on specialized roads."[18] For example, the next generation cruise control system will automatically slow the vehicle to maintain a safe headway from the vehicles ahead. Further, impending departure from the roadway will be predicted by on-board electronics using a lane tracking system and the driver will be alerted in time to recover. Also, a cooperative intersection will communicate data on the state of the traffic signal and the presence of conflicting traffic so as to avoid intersection collisions.[18]

Summary

The literature review showed how little is known about large-truck safety on two-lane secondary roads. An important result that has been shown from some studies is that large trucks are overrepresented in crashes on two-lane roads and that the severity of a crash involving a large truck is usually greater than a similar crash involving a passenger car on a two-lane road. The literature also speculates that ITS and other advanced technologies can be used to increase the safety of these large trucks.

METHODOLOGY

Data Collection

The data collection task consisted of two subtasks: collection of field data on truck percentages within the traffic streams, and extraction of the relevant crash data on secondary highways from VDOT's computerized data files.

Sample Size, Site Selection, and Collection of Field Data

Currently, there are very limited data available on large-truck AADT on secondary roads in Virginia. This deficiency necessitated the collection of data on vehicle classification and total volumes on these secondary roads as this information was needed for the computation of crash rates. Unfortunately, it was not feasible for data to be collected on each of the approximately 7,000 secondary roads in the state. A representative sample of roads was therefore selected for which data were obtained.

The secondary roads in each VDOT district were grouped into clusters, with each cluster consisting of all roads having AADTs within a specific range. It was originally intended to collect data at a statistically selected sample of roads from each cluster, but due to the large variation in large-truck percentages found between routes in different districts within the same cluster, the authors determined that the cluster methodology would not be suitable for analysis. For example, the tractor-trailer percentages on routes in the 0-1000 AADT cluster varied from 0.0% to 5.3% and had a standard deviation of 1.77. This large standard deviation was unacceptable since the average tractor-trailer percentage was only 1.35%. Therefore, the data collection and statistical comparison were carried out for each district rather than for the different clusters based on the AADTs. The authors believed that this analysis procedure was better than the original procedure based on AADT clusters as effects of variations in land use and topography are minimized by considering needs within each district. Consequently, the required sample size for each district was then determined for a $\pm$1% tolerance level and a 95% confidence level using the following equation:

$$n_i = \frac{t^2_{(1-\alpha/2)} \times \frac{S_i^2}{d^2}}{[1 + (\frac{1}{n}) \times [t^2_{(1-\alpha/2)} \times \frac{S_i^2}{d^2}]} \qquad \textbf{(1)}$$

where:

n_i = sample size for district i

$t_{(1-\alpha/2)}$ = standard two-tail t value at level of confidence $(1-\alpha)$

S_i^2 = variance of truck percentages on two-lane highways in district i

d = tolerance level (1%)

n = total number of elements in population.

The sample size calculated and the actual sample size used for each district are shown in Table 2.

A random selection of the calculated number of study roads required for each district was then made, and data on volume and vehicle classification were collected for each of those roads. A total of 124 roads were randomly selected, and data were collected for at least a 48-hour period on large trucks and passenger cars, vans and pickups separately using Streeter Amet electronic counters. These percentages were then used to determine actual truck volumes from the AADT on each secondary road, which in turn were used to determine truck VMT on each road.

Table 2. District Sample Sizes

District	Calculated Based on Single-Unit Truck Percentage	Calculated Based on Tractor-Trailer Percentage	Actual Sample Size Used
Bristol	10	6	10
Salem	7	2	13
Lynchburg	11	3	12
Richmond	7	3	18
Suffolk	8	11	12
Fredericksburg	10	5	11
Culpeper	9	6	21
Staunton	7	3	9
Northern Va	11	3	18

Due to the lack of available data and time, seasonal variation of the large-truck AADTs was not investigated. The authors believed that this limitation would have a minimal effect on the results of the study since the AADT data were mainly used to estimate the crash rates for comparison purposes and for identification of large-truck crash trends rather than for calculation of absolute crash rates. In addition, the monthly variation of the number of large-truck crashes was small, and all counts were made during the summer months of June and August. Further, in order to determine the predominant causal factors from which the countermeasures were identified, fault tree analysis was used. This methodology is based on the proportion, not the rate, of different types of crashes occurring under specific conditions and was the primary tool used to identify the applicable ITS countermeasures.

Compilation of Accident Data

Data on crashes in Virginia were obtained from the crash report forms that are completed by police officers for each crash involving a fatality, personal injury, or property damage exceeding a specified dollar amount. This amount was \$500 between July 1988 and June 1989, and \$750 between July 1989 and June 1992, and is currently \$1,000. Information on these reports is stored in computerized files and was available from VDOT. Crash data for 1988 through 1990 were extracted from these computerized files, compiled for each secondary road, and categorized with respect to vehicle type. Specific information on type of crash, severity, number of vehicles involved, and causal factor was obtained for each crash from the crash data files.

The width and length of a large truck involved in a crash were not recorded in the crash report and were, therefore, not available for analysis purposes. This study, therefore, determined the crash rate based on truck type (single-unit truck or tractor-trailer) and not on truck width or length.

Computation of Accident Rates

The first step was to compute the VMT on each road for each vehicle type using the following equation:

$$VMT_i = LENGTH \times P_i \times AADT \times 365 \tag{2}$$

where:

VMT_i = VMT for vehicle type i (single-unit trucks, tractor-trailers, or passenger vehicles)

Length = length of road segment

P_i = percentage of vehicle type i in the traffic stream

$AADT$ = average annual daily traffic on the road.

The VMT computed for each road was then used in the second step to compute crash rates by type and severity in number of crashes per 100 million VMT. These crash rates were computed for each vehicle type separately and for all vehicles together. Existing data on truck VMT and crashes were used to determine the large-truck crash rates for two-lane primary roads.

Statistical Analysis

The t test and proportionality test were used to find significant differences at $\alpha = 0.05$. The t test was used to test the following null hypotheses:

1. Large-truck total (fatal, injury, and property-damage-only [PDO]) crash rates for two-lane primary roads and for two-lane secondary roads were not significantly different.

2. Large-truck fatal crash rates for two-lane primary roads and for two-lane secondary roads were not significantly different.

3. Total (fatal, injury, and PDO) crash rates for two-lane secondary roads for large trucks and passenger cars were not significantly different.

4. Fatal crash rates for two-lane secondary roads for trucks and passenger cars were not significantly different.

The proportionality test was used to test the following null hypotheses:

5. The proportion of each collision type of large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion on two-lane primary roads.

6. The proportion of each collision type of large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion for passenger car crashes on two-lane secondary roads.

7. The proportion of each crash severity level in large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion on two-lane primary roads.

8. The proportion of each crash severity level in large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion in passenger car crashes on two-lane secondary roads.

The results of these analyses indicated to what extent large-truck crash characteristics on secondary roads were different from those on primary roads and to what extent large-truck crash characteristics were different from those for passenger cars on secondary roads.

Identification of Significant Causal Factors

In this study, the "fault tree" approach, which is an application of the branched-events chain theory, was used to identify the predominant crash causes. The branched-events chain theory is based on the assumption that the likelihood of a crash occurring can be determined if the pathway leading to the crash can be identified. Branched-event theory is logically adaptable to traffic crashes, and it describes a crash phenomenon as a chain of events leading to the top event. A *fault tree* is a model that graphically and logically represents the various combinations of possible events occurring in a system that leads to the *top event*. The *top event* is an undesired outcome of some process, which in this case was the occurrence of a large-truck crash.

The paths of the fault tree were used to identify the sequences and relationships between basic events and the top event. The objective of the analysis was to determine the shortest failure path for each type of truck crash, thereby identifying the predominant causal factors. These shortest failure paths are known as *minimum cut sets*. A *cut set* is a set of events whose occurrence leads to the occurrence of the top event. A *minimum cut set* is obtained when a cut set cannot be reduced further and the occurrence of the top event is still ensured.

The significant causes were identified by first calculating the probability of the top event on all minimum cut sets. The minimum cut set associated with the highest probabilities for the top event contained the significant causes.

In order to determine the probabilities of the minimum cut set, the Boolean representation used for coherent structure by Birnbaum et al.[19] is used. The probabilities are calculated as follows:

$$\Psi = \begin{cases} 1 \text{ if basic event } i \text{ occurs} \\ 0 \text{ otherwise} \end{cases} \quad \textbf{(3)}$$

Let $Y = (Y_1, Y_2, \ldots, Y_n)$ be the vector of basic event outcomes

Define:

$\Psi(\underline{Y}) = 1$ if the top event occurs

$= \;\; 0$ otherwise

Ψ is the Boolean indicator function for the top event.

The Boolean indicator function is determined from either the minimum cut sets or the minimum path sets. The following notation is used for clarity:

$$\coprod_{i=1}^{m} = 1 - \prod_{i=1}^{m}(1-Y_i) \tag{4}$$

Minimum cut representation: Let $K_1, K_2, \ldots, K_n$ be the minimum cut sets of basic events for a specified fault tree. Then

$$\Psi(\underline{Y}) = \coprod_{s=1}^{k} \prod_{i \in K_s} Y_i \tag{5}$$

is the minimum cut representation for Ψ.

To calculate the probability of the top event, let

$$P[Y_i=1] = E(Y_i) = q_i \tag{6}$$

then

$$P[Top\ Event] = E\Psi(Y). \tag{7}$$

Since, in this analysis, there are no event replications, the probability of the top event for the minimum cut set is given as:

$$P\ [Top\ event] = \coprod_{1 \le s \le k} \ \Psi q_i \quad {}_{i \in K_s} \tag{8}$$

Minimum path representation: Let $P_1, P_2, \ldots, P_n$ be the minimum path sets of basic events for a specified fault tree. Then

$$\Psi(\underline{Y}) = \prod_{r=1}^{p} \coprod Y_I \tag{9}$$

The probability of the top event for the minimum path representation is given as

For minimum cut sets:

$$P\,[Top\ event] = \coprod_{1 \le s \le k} \prod_{i \in K_s} q_i \tag{10}$$

For minimum path sets:

$$P\,[Top\ event] = \prod_{1 \le r \le p} \coprod_{i \in P_r} q_i \tag{11}$$

Identification of ITS and Other Advanced Technologies

ITS technologies are classified into five main categories: (1) advanced traffic management systems (ATMS), (2) advanced traveler information systems (ATIS), (3) commercial vehicle operations (CVO), (4) advanced vehicle control systems (AVCS), and (5) advanced public transportation systems (APTS). The capabilities of ITS have recently been classified into 28 "user services" grouped into the following six general categories: (1) travel and traffic management, (2) public transportation management; (3) electronic payment services, (4) commercial vehicle operations, (5) emergency management, and (6) advanced vehicle safety systems.[20]

The user services that are considered to be related to this study are two in the commercial vehicle category, i.e., automated roadside safety inspection and on-board safety monitoring, and all services in the advanced vehicle safety systems category, i.e.,

- longitudinal collision avoidance
- lateral collision avoidance
- intersection collision avoidance
- vision enhancement for crash avoidance
- safety readiness
- pre-crash restraint deployment
- automated vehicle operation.

A brief description of these services follows.

- *Automated roadside safety inspection.* This service will facilitate roadside inspection and provide for real-time access to the safety performance record of carriers, vehicles, and drivers. This in turn will aid in the identification of those vehicles and/or drivers that will be stopped for inspection. Also, sensors and diagnostics will be used to rapidly and accurately check vehicle systems and driver fitness for duty. Technologies under this service will aid in significantly reducing large-truck crashes on two-lane secondary roads in Virginia if vehicle failure is identified as a predominant causal factor of these crashes.

- *On-board safety monitoring.* This will involve the continuous monitoring of the vehicle and driver at mainline speeds. Vehicle monitoring will entail the collection and analysis of data on the condition of critical vehicle components, such as brakes, tires, lights, and the determination of thresholds of warnings and countermeasures. It is envisioned that the monitoring of the driver will involve the use of nonintrusive technologies to obtain driving time and alertness, which can be used as a basis to warn drivers or enforcement officers of critical driver conditions. These monitoring technologies may also be useful in reducing large-truck crashes on two-lane highways in Virginia if vehicle failure or, to a certain extent, driver failure is identified as a predominant causal factor of these crashes.

- *Longitudinal collision avoidance.* This will help prevent head-on and rear-end collisions by providing a means of sensing potential or impending collisions and then prompting the driver to take an avoidance action or temporarily control the vehicle. Technologies developed under this user service's group may be effective in reducing large-truck crashes on secondary roads in Virginia if head-on and rear-end collisions are predominant in these crashes.

- *Lateral collision avoidance.* This will help prevent sideswipe collisions, which often occur as a result of vehicles leaving their lane of travel, by providing crash warnings and controls for lane changes and road departures. If sideswipe collisions are identified as a predominant type of crashes of large trucks on secondary roads in Virginia, technologies in this group may be effective in reducing the large-truck crash rates.

- *Intersection collision avoidance.* This service will help prevent crashes at intersections by informing the driver of an imminent collision when he or she is approaching or crossing an intersection with a traffic control device or by alerting the driver when the right of way at the intersection is unclear or ambiguous. If large-truck crashes at two-lane secondary road intersections are overrepresented, technologies in this area may significantly reduce large-truck crashes on two-lane secondary roads in Virginia.

- *Vision enhancement for crash avoidance.* This service will improve the driver's ability to see more clearly the roadway and any obstacles on or along it. Technologies in this area may aid in significantly reducing large-truck crashes on two-lane roads in Virginia if environmental factors such as fog, heavy storms, snow, nighttime, etc., that inhibit driver vision are found to be predominant causal factors for these crashes.

- *Safety readiness.* This service will help prevent crashes that are mainly due to driver fatigue by the installation of in-vehicle equipment that could unobtrusively gauge a driver's condition and provide a warning if he or she is drowsy or otherwise impaired. The service can also be used to monitor critical elements of a vehicle internally and detect unsafe road conditions, such as bridge icing and standing water on the roadway, and then warn the driver of these conditions. Technologies in this area may significantly reduce large-truck crashes in Virginia if driver conditions such as fatigue and/or environmental conditions such as ice and wet weather are found to be predominant causal factors of these crashes.

- *Pre-crash restraint deployment.* This service will provide technologies that will help reduce the severity of a crash rather than prevent one. These technologies will identify the velocity, mass, and dimensions of the vehicle and objects involved in a potential crash and deploy restraint features such as airbags, lap/shoulder belts, etc., at an optimal pressure.

- *Automated vehicle operations.* These technologies will provide a fully automated "hands off" operating environment. This is, however, a long-term goal of ITS and was not considered in this study.

By using the information obtained from the literature review and telephone interviews with several manufacturers, appropriate technologies that had been developed or proposed and were related to the user services considered in this study were identified and classified into sub-categories based on their proposed specific use in the field. A list of these technologies and their individual status are given in Appendix A.

Based on the predominant causal factors determined from the fault tree analysis and the predominant collision types identified, the appropriate user services were identified and suitable ITS technologies within these services were selected to eliminate or minimize the effect of these causal factors.

Since tests have not been completed, or in many cases not even begun, to evaluate the effectiveness of these technologies in reducing the number of crashes caused by an identified causal factor, this criterion could not be used in the selection process. The basis for selection of each technology was its current stage of development and perceived effectiveness.

RESULTS

Crash Characteristics

Percentage Distribution of Crashes by Time of Day

Figure 1 shows the percentage distribution of large-truck crashes on two-lane secondary roads by time of day. The information for passenger cars was included to aid in the interpretation of the data. For single-unit trucks, there was little difference in the percentage of crashes occurring throughout the daylight hours (7 A.M.–5 P.M.). However, a peak existed in the late afternoon (3 P.M.–4 P.M.). Tractor-trailer crashes showed two peaks: at 11 P.M. and at 3 P.M., with a wide variation in the percentage of crashes occurring during the hours between the two peaks. Crashes involving passenger cars, on the other hand, increased from about 9 A.M. to 5 P.M. and then dropped. A relatively low percentage of these crashes occurred during the night period, suggesting that poor visibility due to increasing darkness was not a significant causal factor of large-truck crashes on two-lane secondary roads. However, it is likely that the reduction in truck volumes resulted in a relatively lower number of crashes but a relatively higher crash rate at nighttime. Not enough information is available at this time, however, to draw this conclusion as the results shown in the graph are for percentages of crashes occurring and not for crash rates.

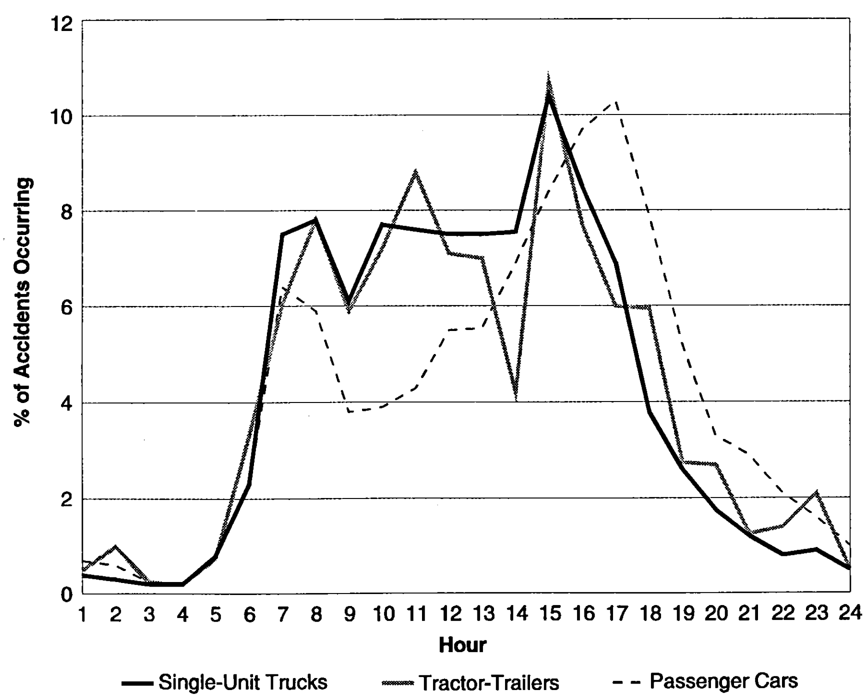


Figure 1. Percentage Distribution of Large-Truck Crashes on Two-Lane Secondary Roads by Time of Day

Percentage Distribution of Crashes by Month

Figure 2 shows the percentage distribution of crashes by month of occurrence for each vehicle type. This figure does not show any regular pattern of variation through the year for any of the vehicle types except that the highest percentage of crashes involving single-unit trucks occurred in June; October and June seem to be the worst months for tractor-trailers, and May and October seem to be the worst months for passenger cars. Due to the unavailability of large-truck VMT for each month of the year, it was not possible to calculate the crash rates for each month to see if the rates throughout the year varied more significantly than the number of crashes.

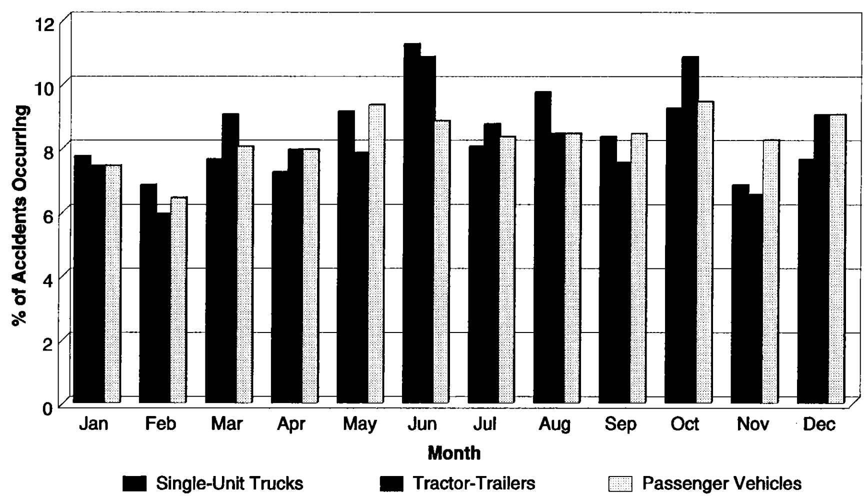
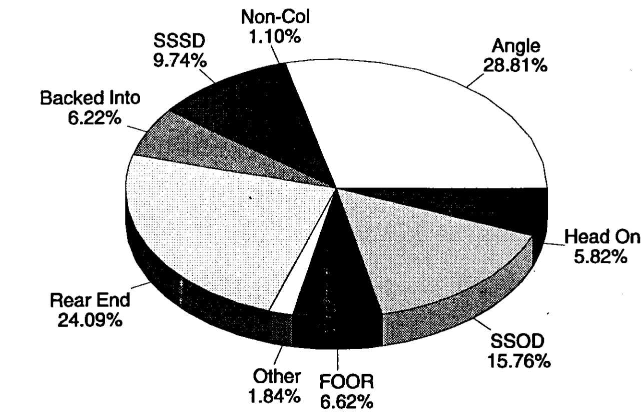


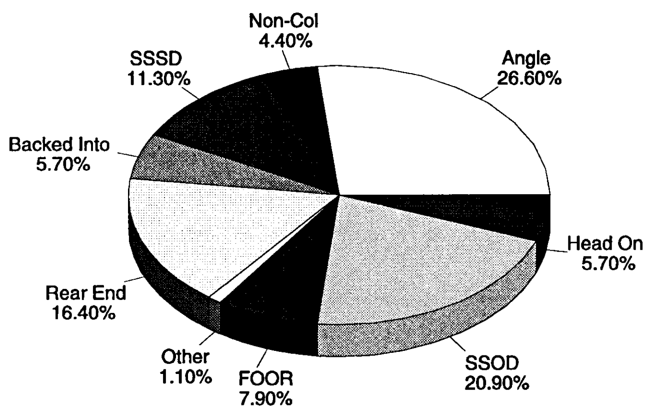
Figure 2. Percentage Distribution of Large-Truck Crashes on Two-Lane Secondary Roads by Month of Year

Percentage Distribution of Crashes by Collision Type

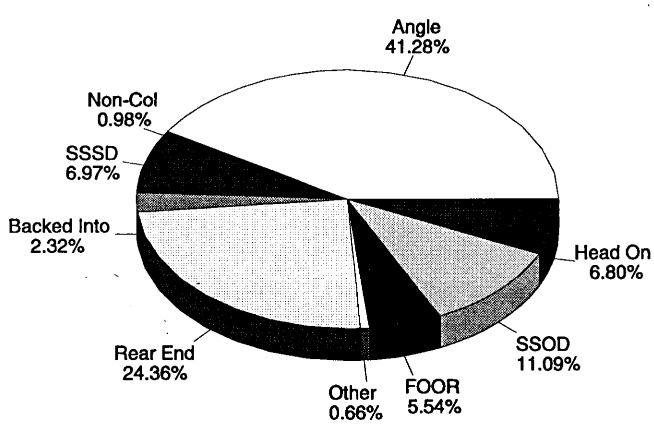
Figure 3 shows the percentage distribution of crashes by collision type for each vehicle type studied. Angle crashes, which are primarily intersection crashes, seemed to be the predominant collision type for all types of vehicles. The next order of predominance for passenger cars and single-unit trucks was rear end, sideswipe opposite direction (SSOD), and sideswipe same direction (SSSD), and for tractor-trailers was SSOD, rear end, and SSSD. These predominant collision types accounted for over 75% of crashes on two-lane secondary roads involving single-unit trucks and tractor-trailers. Technologies that can significantly reduce these types of crashes may significantly reduce the potential of large-truck crashes on two-lane secondary roads. The SSSD crashes are characteristic of passing maneuvers, whereas the SSOD crashes are characteristic of vehicles straying into the lane of the oncoming traffic, which in turn reflects the characteristic of a large vehicle traveling on a narrow road.



A. Single-unit trucks



B. Tractor-trailers



C. Passenger cars

SSOD - Sideswipe opposite direction
SSSD - Sideswipe same direction
FOOR - Fixed object off roadway

Figure 3. Percentage Distribution of Large-Truck Crashes on Two-Lane Secondary Roads by Collision Type

Percentage Distribution of Crashes by Severity

The percentage distributions of crashes by severity are shown in Figure 4. This figure shows that tractor-trailers have a higher percentage of fatal and injury crashes than both single-unit trucks and passenger vehicles. This finding coincides with what has been found on Virginia's primary highways.

Statistical Analysis

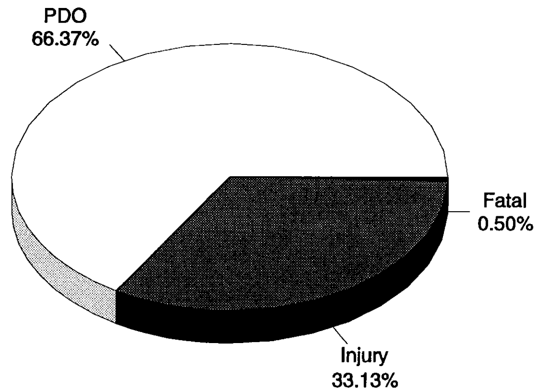
Tables 3 and 4 show the average crash rates by severity for each district for the secondary and primary roads, respectively. These crash rates were used to test null hypotheses 1 through 4 using the t test. The proportionality test was used to test null hypotheses 5 through 8. These tests were carried out to determine significant differences at a significance level of $\alpha = 0.05$.

Null Hypothesis 1: ***Large-truck total crash rates for two-lane primary roads and for two-lane secondary roads were not significantly different.***

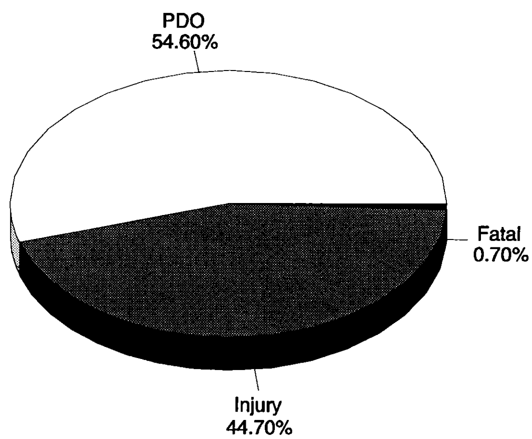
Table 5 shows the results of the analysis. When the crashes were considered using overall crash rates, the Richmond, Staunton, and Northern Virginia districts had significantly higher crash rates for the two-lane secondary roads than for the two-lane primary roads and there was no significant difference in the other districts. When the crash rates were considered for all

Table 3. Secondary Route Crash Rates for Large Trucks

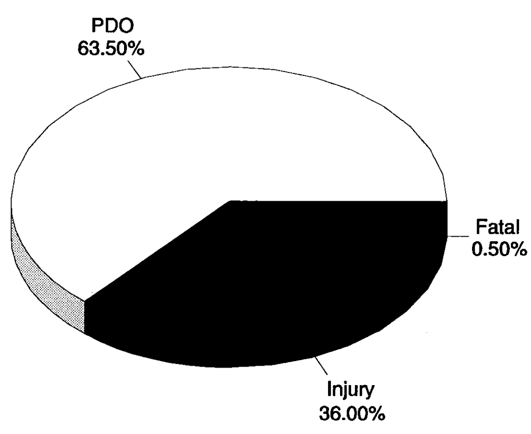
District	Crash Rate (per 100 million VMT)			
	Overall	Fatal	Injury	PDO
Bristol	276.8	5.7	22.2	248.6
Salem	917.5	0.0	293.4	624.0
Lynchburg	1859.7	13.1	144.6	1702.2
Richmond	1427.2	4.7	332.8	1095.6
Suffolk	120.5	3.5	23.7	91.7
Fredericksburg	1386.2	0.0	539.1	847.1
Culpeper	688.5	0.0	271.7	427.7
Staunton	1145.7	15.1	556.1	574.5
Northern Va	764.8	0.0	253.9	510.9
Average	951.1	3.8	268.2	681.5



A. Single-unit trucks



B. Tractor-trailers



C. Passenger cars

PDO - Property damage only

Figure 4. Percentage Distribution of Large-Truck Crashes on Two-Lane Secondary Roads by Severity

Table 4. Primary Route Crash Rates for Large Trucks

District	Crash Rate (per 100 Million VMT)			
	Overall	Fatal	Injury	PDO
Bristol	232.3	0.0	101.2	131.0
Salem	497.0	5.0	406.7	85.3
Lynchburg	647.1	0.0	297.6	349.7
Richmond	227.2	0.0	126.3	100.9
Suffolk	228.7	10.5	92.3	125.9
Fredericksburg	289.2	31.7	59.0	198.5
Culpeper	426.3	0.0	70.5	352.8
Staunton	103.3	0.0	65.3	38.0
Northern Va	232.4	0.0	100.2	132.2
Average	320.1	5.2	146.6	168.3

districts combined statewide, the results indicated that the large-truck crash rates for two-lane secondary roads were significantly higher than for two-lane primary roads. This significant difference was, however, due to the significant difference in PDO crashes. Null hypothesis 1 was therefore rejected when the entire state was considered. This was expected since it was already noted that large-truck crashes increased when the lane width fell below 3.1 m (10 ft).[14] For the two-lane primary roads in Virginia, only 7.5% of these roads have lane widths less than 3.1 m (10 ft). In contrast, 75.7% of the two-lane secondary roads have lane widths less than 3.1 m (10 ft). However, the significant variation found in the analysis was due primarily to significantly higher large-truck crash rates in the Richmond, Staunton, and Northern Virginia districts.

Null Hypothesis 2: ***Large-truck fatal crash rates for two-lane primary roads and for two-lane secondary roads were not significantly different.***

Table 5 shows the results of the analysis. It can be seen that when crashes were considered by severity, the fatal crash rates for two-lane secondary roads were not significantly different than for two-lane primary roads. Null hypothesis 2 could, therefore, not be rejected. This was also true in most cases for injury and PDO crashes with the exception of the Richmond District, where both injury and PDO crash rates were significantly higher; the Culpeper District, where the injury rate was significantly higher; and the Northern Virginia District, where the PDO rate was significantly higher.

Table 5. *t* Values for Large-Truck Crash Rates for Two-Lane Secondary vs. Two-Lane Primary Roads

District	*t* Value			
	Overall	**Fatal**	**Injury**	**PDO**
Bristol	0.34	1.44	-2.31	0.86
Salem	0.93	-1.00	-0.34	1.65
Lynchburg	0.76	1.00	-0.48	0.90
Richmond	**3.61**	1.00	**2.17**	**3.34**
Suffolk	-0.95	-0.65	-1.31	-0.39
Fredericksburg	1.19	-1.00	1.56	1.05
Culpeper	1.05	---	**2.25**	0.28
Staunton	**2.17**	1.00	1.28	1.70
Northern Va	**3.40**	---	2.03	**3.28**
Statewide	**3.24**	-0.34	1.83	**3.00**

Note: t values that are significantly higher at $\alpha = 0.05$ are shown in **bold**. $t_{crit} = 2.13$.

Null Hypothesis 3: ***Total crash (fatal, injury, and PDO) rates for two-lane secondary roads for large trucks and passenger cars were not significantly different.***

Table 6 shows that the crash rate for large trucks on secondary roads was significantly higher than for passenger cars on the same roads when the entire state was considered. Therefore, null hypothesis 3 was rejected. This significant difference is due to three of the nine districts, Richmond, Culpeper, and Northern Virginia, which had significantly higher crash rates for large trucks.

Table 6. *t* Values for Total Crash Rates for Large Trucks vs. Passenger Cars on Two-Lane Secondary Roads

District	*t* Value
	Truck
Bristol	-0.21
Salem	1.68
Lynchburg	0.87
Richmond	**3.26**
Suffolk	-1.84
Fredericksburg	0.07
Culpeper	**2.65**
Staunton	1.42
Northern Va	**2.74**
Statewide	**2.62**

Note: t values that are significant at $\alpha = 0.05$ are shown in **bold**. $t_{crit} = 2.13$.

Null Hypothesis 4: ***Fatal crash rates for two-lane secondary roads for trucks and passenger cars were not significantly different.***

The results shown in Table 7 indicate that large trucks did not have significantly higher fatal crash rates than passenger cars on two-lane secondary roads. Therefore, null hypothesis 4 could not be rejected. Although these results indicate no significant difference in the fatal crash rates between large trucks and passenger cars, it is feasible that the proportion of fatal crashes in large-truck crashes might have been significantly different than that for passenger cars. This was tested with null hypothesis 8.

Table 7. *t* Values for Fatal Crash Rates for Large Trucks vs. Passenger Cars on Secondary Roads

District	*t* Value
Bristol	1.27
Salem	-2.05
Lynchburg	0.42
Richmond	0.10
Suffolk	0.42
Fredericksburg	-1.59
Culpeper	-2.61
Staunton	0.44
Northern Va	-2.59
Statewide	0.22

Note: *t* values that are significant at $\alpha = 0.05$ are shown in **bold**. $t_{crit} = 2.13$.

Null Hypothesis 5: ***The proportion of each collision type of large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion on two-lane primary roads.***

Table 8 shows the results of this test. Based on these results, null hypothesis 5 was rejected for angle, head-on, SSOD, and backed-into large-truck crashes.

Null Hypothesis 6: ***The proportion of each collision type of large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion for passenger car crashes on two-lane secondary roads.***

Table 8 shows the results of this analysis. Based on these results, this null hypothesis was rejected for SSSD, SSOD, noncollision, miscellaneous, and backed-into collisions. The large-truck proportions of these collision types were significantly higher than those for passenger cars.

Null Hypothesis 7: ***The proportion of each crash severity level in large-truck crashes on two-lane secondary roads was not significantly different from the corresponding proportion on two-lane primary roads.***

Table 8. Results of Proportionality Test for Large-Truck Crashes on Two-Lane Secondary Roads by Collision Type

Collision Type	*Z* Value	
	Large Trucks Secondary vs Primary	**Large Trucks vs Passenger Cars Secondary Roads**
Rear end	-1.7361	-0.8808
Angle	**2.9193**	-7.2039
Head on	**3.3044**	-1.0658
SSSD	-0.2623	**3.1637**
SSOD	**5.5943**	**4.7015**
Fixed object on road	-2.3682	0.4155
Train	-0.5165	-0.1535
Pedestrian	-0.9896	0.4766
Other animal	-1.9347	-0.3493
Noncollision	-5.2609	**1.7289**
Backed into	**5.0577**	**6.6108**
Fixed object off road	-5.8220	1.5147
Deer	-2.5028	0.1189
Not stated	-0.7304	-0.4942
Miscellaneous	-2.2852	**4.1061**

Note: *Z* values that are significantly higher at the 95% confidence level are in **bold**. $Z_{crit} = 1.96$.

Table 9 provides the results of this analysis. Based on these results, null hypothesis 7 could not be rejected for fatal and injury but was rejected for PDO crashes.

Null Hypothesis 8: ***The proportion of each crash severity level in large-truck crashes on two-lane secondary roads was not significantly different from that for the corresponding proportion in passenger car crashes on two-lane secondary roads.***

Table 9. Results of Proportionality Tests for Large-Truck Crashes on Two-Lane Secondary Roads by Crash Severity

Severity	*Z* Values	
	Large Trucks Secondary vs Primary	Large Trucks vs Passenger Cars Secondary Roads
Fatal	-3.2288	**1.7914**
Injury	-3.9691	-1.8106
Property damage only	**4.8645**	1.5493

Note: Z values that are significantly higher at the 95% confidence level are in **bold**. $Z_{crit} = 1.645$.

The results of this test are shown in Table 9. They indicate that large trucks had a significantly higher proportion of fatal crashes on two-lane secondary roads than passenger cars. Consequently, null hypothesis 8 was rejected for fatal crashes and was not rejected for injury and PDO crashes. This suggests that although the fatal crash rates for large trucks were not significantly different from those for passenger cars as shown in testing hypothesis 4, there was a significantly higher proportion of large-truck crashes that were fatal in comparison with passenger cars on two-lane secondary roads.

Fault Tree Analysis

In developing the fault trees, the crashes were first categorized with respect to their major causal factor. The major causal factors associated with large-truck crashes can be categorized as driver related, vehicle related, and environment related (i.e., highway related and/or weather related). Results showed that driver-related failure was the leading cause of crashes as shown in Figure 5. Overall, the percentages of crashes by failure type were consistent across all vehicle types. Driver-related failures caused between 76% and 80% of the crashes. Environment-related failures accounted for 10% to 15%, and vehicle-related failures accounted for 1% to 4%, with single-unit trucks having the highest percentage. Figures 6, 7, and 8 show the percentage breakdown of crash severity by failure type and vehicle type. Tractor-trailer crashes had the highest fatality percentage when the crash was caused by a driver-related failure. In fact, tractor-trailers had higher percentages of severe crashes (i.e., fatal and personal injury) than both single-unit trucks and passenger cars for all failure types on two-lane secondary roads.

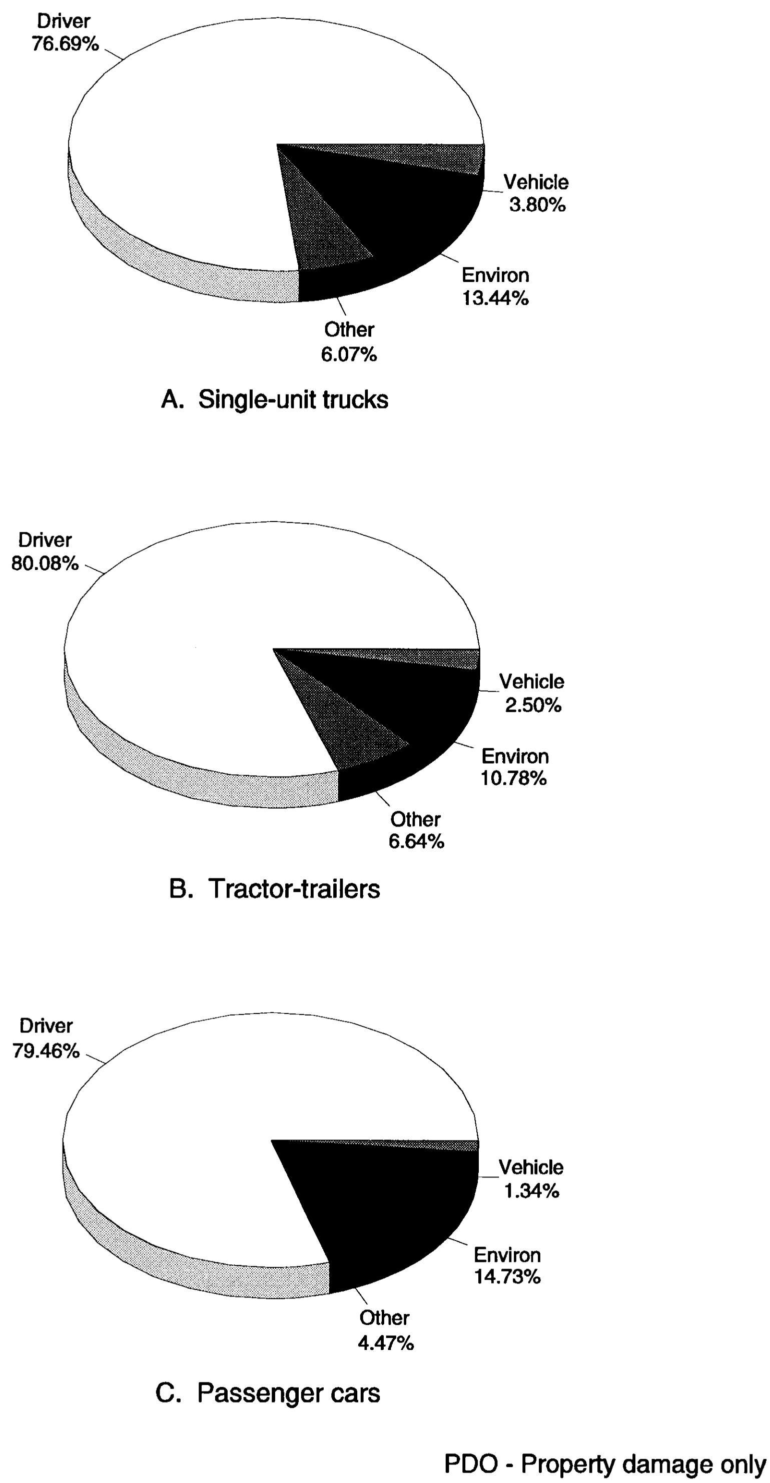


Figure 5. Percentage Distribution of Large-Truck Crashes on Two-Lane Secondary Roads by Failure Type

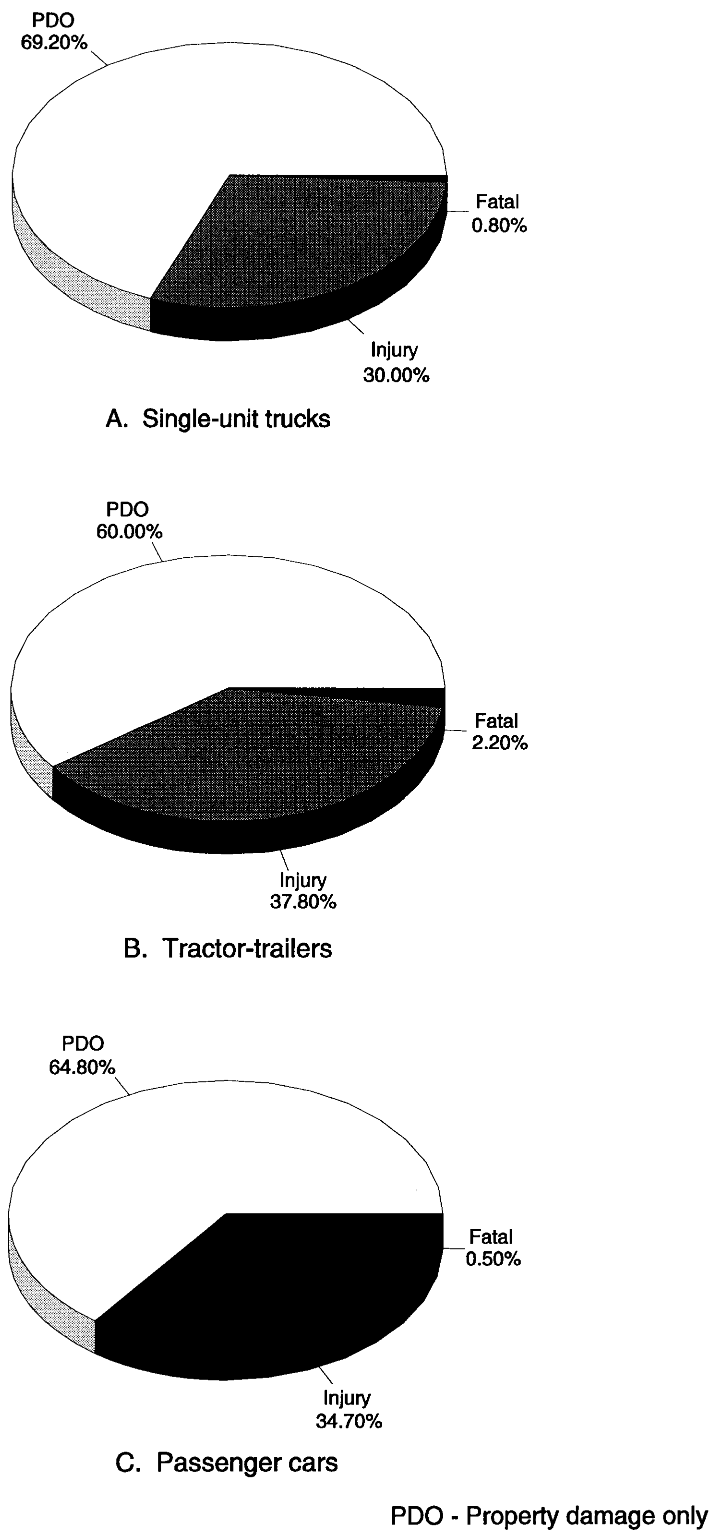


Figure 6. Percentage Distribution of Driver-Related Large-Truck Crashes on Two-Lane Secondary Roads by Severity

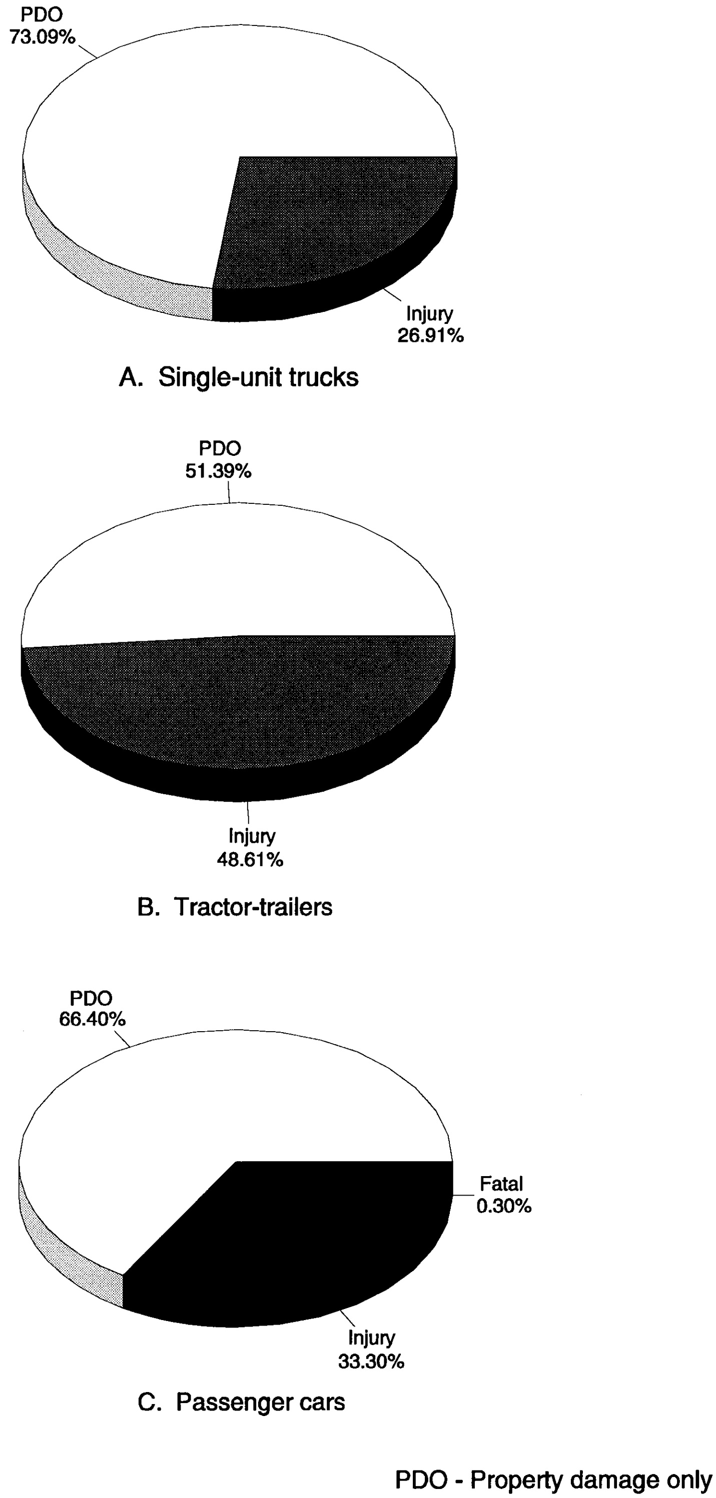
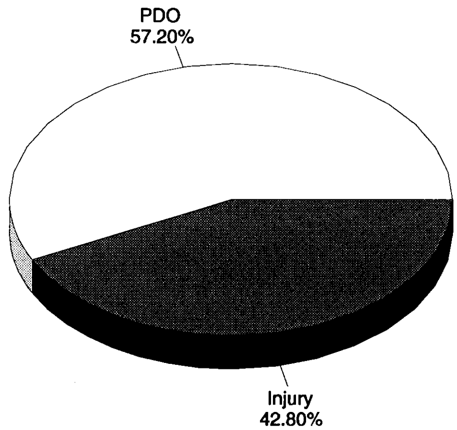
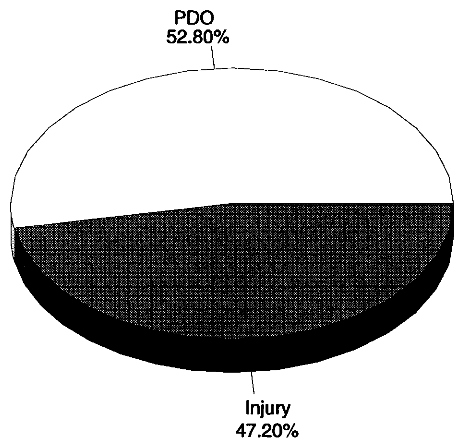


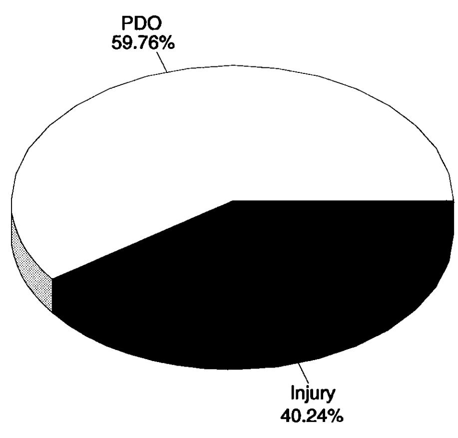
Figure 7. Percentage Distribution of Environment-Related Large-Truck Crashes on Two-Lane Secondary Roads by Severity



A. Single-unit trucks



B. Tractor-trailers



C. Passenger cars

PDO - Property damage only

Figure 8. Percentage Distribution of Vehicle-Related Crashes on Two-Lane Secondary Roads by Severity

Figures 9 and 10 show the fault trees for driver-related crashes involving single-unit trucks and tractor-trailers, respectively. The fault trees for vehicle- and environment-related crashes are shown in Appendix B. The minimum cut sets were identified and their probabilities calculated for each fault tree. The minimum cut sets for driver-related failures are shown in Tables 10 and

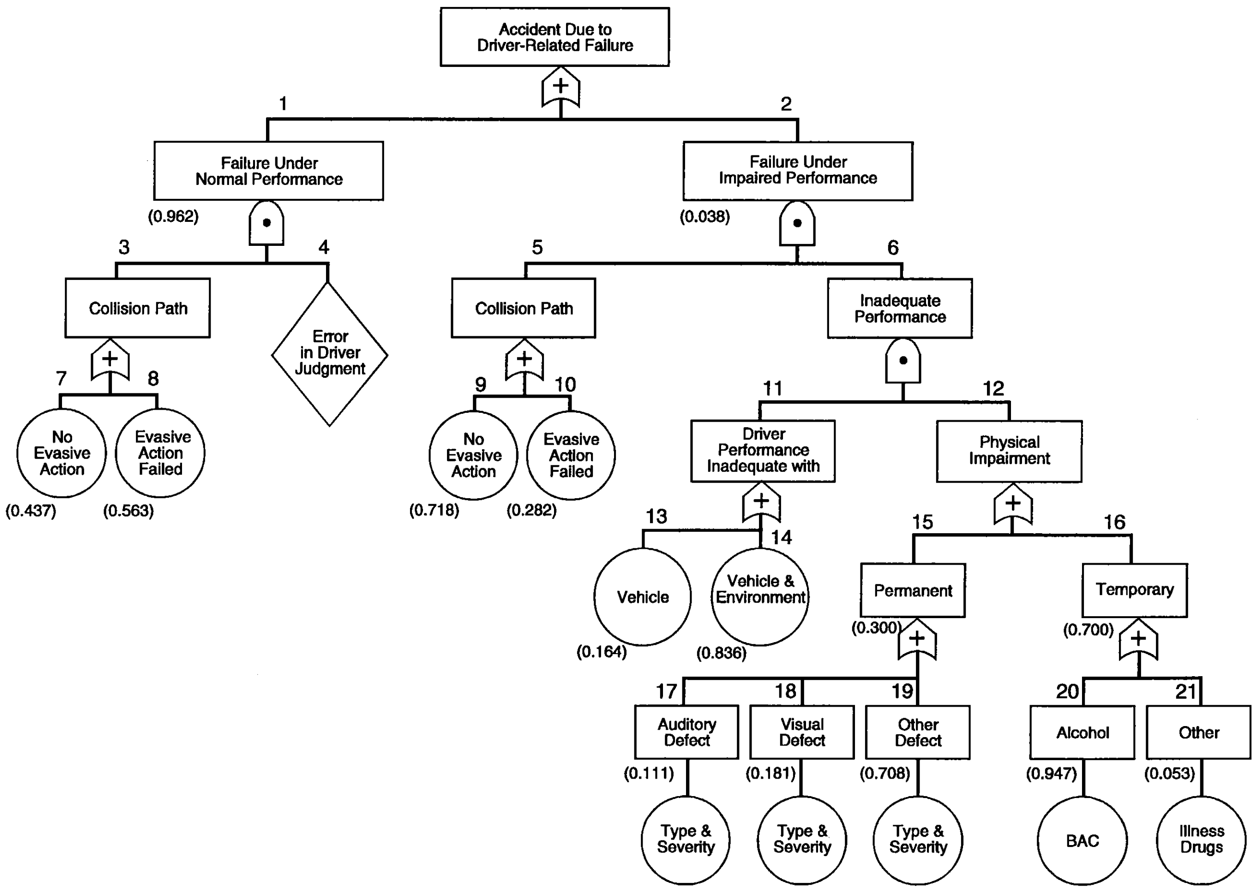


Figure 9. Fault Tree for Driver-Related Crashes Involving Single-Unit Trucks

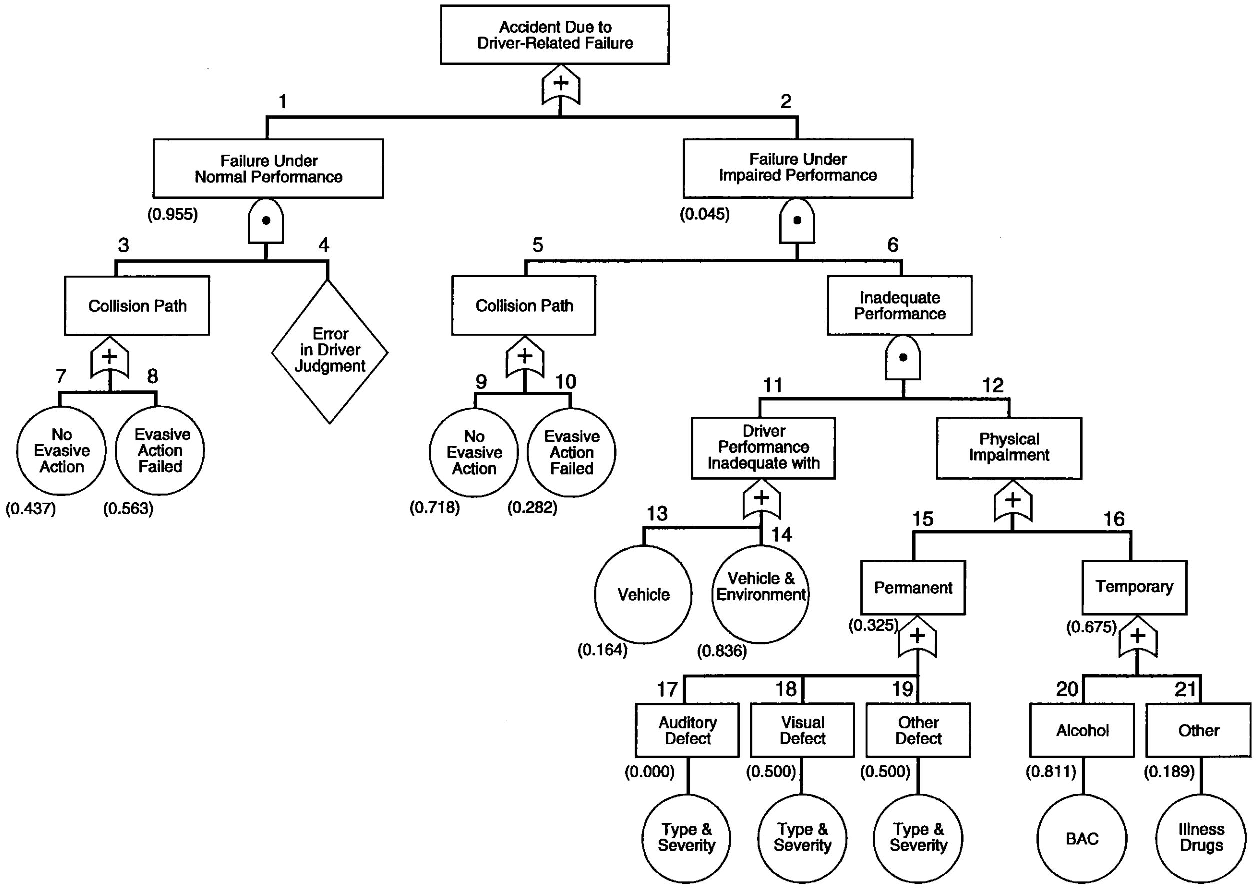


Figure 10. Fault Tree for Driver-Related Crashes Involving Tractor-Trailers

11 for single-unit trucks and tractor-trailers, respectively. Those for vehicle- and environment-related failures are shown in Appendix C.

Vehicle defects included items such as brake, tire, and light failures; environment-related failure conditions were categorized as adverse weather or surface defects. The type of surface defects was not specified in the Virginia crash data; therefore, this category could not be developed any further. Adverse weather conditions were more detailed in the reports and, consequently, could be further categorized as nonfreezing precipitation, freezing precipitation, and other lighting and weather problems.

Table 10. Minimum Cut Sets for Single-Unit Truck Crashes Due to Driver-Related Failure

Path	Probability
1→3→7 and 1→4	**0.4204**
1→3→8 and 1→4	**0.5416**
2→5→9 and 6→11→13 and 6→12→15→17	0.0001
2→5→9 and 6→11→13 and 6→12→15→18	0.0002
2→5→9 and 6→11→13 and 6→12→15→19	0.0010
2→5→9 and 6→11→13 and 6→12→15→20	0.0030
2→5→9 and 6→11→13 and 6→12→15→21	0.0002
2→5→10 and 6→11→13 and 6→12→15→17	0.0001
2→5→10 and 6→11→13 and 6→12→15→18	0.0001
2→5→10 and 6→11→13 and 6→12→15→19	0.0004
2→5→10 and 6→11→13 and 6→12→15→20	0.0012
2→5→10 and 6→11→13 and 6→12→15→21	0.0001
2→5→9 and 6→11→14 and 6→12→15→17	0.0008
2→5→9 and 6→11→14 and 6→12→15→18	0.0012
2→5→9 and 6→11→14 and 6→12→15→19	0.0048
2→5→9 and 6→11→14 and 6→12→15→20	0.0151
2→5→9 and 6→11→14 and 6→12→15→21	0.0008
2→5→10 and 6→11→14 and 6→12→15→17	0.0003
2→5→10 and 6→11→14 and 6→12→15→18	0.0005
2→5→10 and 6→11→14 and 6→12→15→19	0.0019
2→5→10 and 6→11→14 and 6→12→15→20	0.0059
2→5→10 and 6→11→14 and 6→12→15→21	0.0003

Bold indicates the minimum cut sets with the highest probabilities and thus the predominant causal factors.

The driver-related failure category was broken down into auditory, visual, and other permanent handicaps; driver inattention; fatigue; alcohol and drugs; illness; and driver error. Examples of driver error are improper passing, straying into the lane of oncoming traffic, improper turns, speeding, and tailgating. Of the specific driver factors involved, driver error had the highest frequency, followed by speeding, impairment due to drugs and/or alcohol, and driver

Table 11. Minimum Cut Sets for Tractor-Trailer Crashes Due to Driver-Related Failure

Path	Probability
1→3→7 and 1→4	**0.4173**
1→3→8 and 1→4	**0.5377**
2→5→9 and 6→11→13 and 6→12→15→18	0.0009
2→5→9 and 6→11→13 and 6→12→15→19	0.0009
2→5→9 and 6→11→13 and 6→12→15→20	0.0029
2→5→9 and 6→11→13 and 6→12→15→21	0.0007
2→5→10 and 6→11→13 and 6→12→15→18	0.0003
2→5→10 and 6→11→13 and 6→12→15→19	0.0003
2→5→10 and 6→11→13 and 6→12→15→20	0.0011
2→5→10 and 6→11→13 and 6→12→15→21	0.0003
2→5→9 and 6→11→14 and 6→12→15→18	0.0043
2→5→9 and 6→11→14 and 6→12→15→19	0.0043
2→5→9 and 6→11→14 and 6→12→15→20	0.0148
2→5→9 and 6→11→14 and 6→12→15→21	0.0034
2→5→10 and 6→11→14 and 6→12→15→18	0.0017
2→5→10 and 6→11→14 and 6→12→15→19	0.0017
2→5→10 and 6→11→14 and 6→12→15→20	0.0058
2→5→10 and 6→11→14 and 6→12→15→21	0.0014

Bold indicates the minimum cut sets with the highest probabilities and thus the predominant causal factors.

handicap (which includes fatigue, illness, and sleeping). The specific cause of driver error was not available; therefore, this category was an undeveloped event in the fault tree analysis.

Based on the probabilities of the minimum cut sets, the following were the most probable causes of large-truck crashes on two-lane secondary roads:

- *Driver-related failure.* For all large trucks, a crash most often occurred when the driver was not impaired but there was error in the driver's judgment and either no evasive action was taken or the evasive action failed. See Tables 10 and 11. These crashes represented about 74% of all single-unit truck crashes and about 76% of tractor-trailer crashes on two-lane secondary roads in Virginia. See Tables 12 and 13.

Table 12. Percentage of Crashes Involving Single-Unit Trucks on Two-Lane Secondary Roads Due to Causal Factors Identified

Type of Failure	Predominant Causal Factor	Probability of Crash Due to Predominant Causal Factor[1]	Percentage of All Single-Unit Truck Crashes Associated with Type of Failure	Percentage of All Single-Unit Truck Crashes Due to Predominant Causal Factor
Driver related	Driver not impaired, but error in driver judgment and no evasive action taken	0.4204[2]	76.68	32.3
	Driver not impaired, but error in driver judgment and evasive action failed	0.5416[2]	76.68	41.5
Vehicle related	Brake failure and evasive action failed or not taken	0.2154[3]	3.8	0.8
Environment related	Faulty highway component led to surface defects and driver evasive action either failed or was not taken	0.5900[4]	13.44	7.9

[1]See Figure 5.
[2]See Table 13.
[3]See Appendix C, Table C-1.
[4]See Appendix C, Table C-3.

Table 13. Percentage of Crashes Involving Tractor-Trailers on Two-Lane Secondary Roads Due to Causal Factors Identified

Type of Failure	Predominant Causal Factor	Probability of Crash Due to Predominant Causal Factor	Percentage of All Tractor-Trailer Crashes Associated with Type of Failure[1]	Percentage of All Tractor-Trailer Crashes Due to Predominant Causal Factor
Driver related	Driver not impaired, but error in driver judgment and no evasive action taken	0.4173[2]	80.07	33.4
	Driver not impaired, but error in driver judgment and evasive action failed	0.5377[2]	80.07	43.1
Vehicle related	Vehicle characteristics unfavorably interacted with driver and/or environment	0.3075[3]	2.50	0.8
Environment related	Faulty highway component led to surface defects and driver evasive action either failed or was not taken	0.5600[4]	10.78	6.0

[1]See Figure 5.
[2]See Table 13.
[3]See Appendix C, Table C-2.
[4]See Table C-4.

- *Vehicle-related failure*

  —For single-unit trucks, a crash most often occurred when there was brake failure and the evasive action failed. These crashes represented about 0.8% of all single-truck-involved crashes on secondary roads in Virginia. See Table 12.

  —For tractor-trailers, a crash most often occurred when the vehicle characteristics interacted unfavorably with the driver and/or the environment and no evasive action was taken. These crashes also represented about 0.8% of all tractor-trailer-involved crashes on secondary roads in Virginia. See Table 13.

- *Environment-related failure.* For all large trucks, a crash most often occurred when a faulty highway component led to surface defects and the driver's evasive action either failed or was not taken. These crashes represented about 8% of all crashes involving large trucks on secondary roads in Virginia (see Table 12) and about 6% of all crashes involving tractor-trailers on these roads (see Table 13).

Selected Advanced Technologies

Based on the most probable causal factors and the predominant collision types of large-truck crashes that were identified, the different categories of advanced technologies available or proposed that could eliminate or mitigate these causal factors and types of crashes were selected and are described below. It should be emphasized again that the selection of any specific technology was not based on a knowledge of its ability to eliminate or reduce these crashes, as no specific test for which the results are available has been conducted. The selection was based on the availability of equipment or its stage of development and its perceived effectiveness.

Technologies Based on Predominant Causal Factors

Driver-Related Failures

For driver-related failure, both single-unit trucks and tractor-trailers had the same major causal factors. For all large trucks, a crash most often occurred when there was an error in driver judgment and the evasive action failed or no evasive action was taken. The type of driver error was not specified in most cases in the crash data files. If it was specified, more often that not it was simply categorized as driver inattention. Traditional countermeasures to driver inattention or fatigue such as "alertness maintainers" (e.g., coffee and loud music) are not particularly effective countermeasures. In addition, operational rules regulating the hours of service for commercial drivers have not appeared to eliminate the problem. Consequently, a continuous status/performance monitoring system is needed. Technologies under the user services area of on-board safety monitoring may be effective in mitigating some of the effect of this causal factor.

Such a monitoring system could either sound an alarm to alert the driver of the need to return his or her attention to the roadway or send a warning to enforcement officers in order for them to deal with the problem.

Vehicle-Related Failure

Under vehicle-related failure, single-unit trucks and tractor-trailers had two different predominant causal factors. For single-unit trucks, a crash most often occurred when there was brake failure and the evasive action failed. The implementation of systems that will ensure that only single-unit trucks with adequate brakes are permitted on the two-lane highways or will identify imminent brake failure conditions and give adequate warning to the driver will result in a significant reduction in the number of single-unit truck crashes that are related to vehicle failure. The user services that are related to this causal factor are the automated roadside inspection and the on-board safety monitoring system in the commercial vehicle operations area. The automated roadside inspection system would ensure that only single-unit trucks with adequate brakes are permitted on the two-lane highways, and the on-board safety monitoring system would continually monitor the safety status of a vehicle, which will include the sensing and collection of data on critical components such as brakes, tires, and lights from which thresholds for warning and countermeasures will be determined. Although the concept of these technologies has been discussed, the authors are not aware of any specific systems that have been developed. This, however, is not a severe problem as less than 1% of single-unit truck crashes on two-lane secondary roads were due to this causal factor.

For tractor-trailers, a crash most often occurred when the interaction among the vehicle, driver, and environment was incompatible and no evasive action was taken. It is likely that these types of crashes were attributable to the incompatible physical and operational characteristics of a large truck with the characteristics of the two-lane secondary highway system, e.g., a long truck traveling on a narrow lane of a roadway. Again, the authors are not aware of any technologies available to mitigate the effect of this causal factor. This, however, is not a serious setback as less than 1% of tractor-trailer crashes on two-lane secondary roads were due to this causal factor.

Environment-Related Failures

Under environment-related failure crashes, both single-unit trucks and tractor-trailers had the same most probable causal factors. For all large trucks, a crash most often occurred when a faulty highway component led to surface defects and the driver's evasive action either failed or was not taken. The occurrence of these types of crashes can be reduced considerably if drivers are made aware of the defects in sufficient time before arriving at the defective location, thereby providing the driver the opportunity to take the appropriate evasive action in time. This may be achieved through a vision enhancement system for crash avoidance that improves the driver's ability to see the roadway and objects that are on or along the roadway. If the driver is aware of the defects in the roadway, then he or she will have more time to prepare for the situation and can consider the most effective evasive action available before it becomes necessary. One such system is that manufactured by the Jaguar Corporation in cooperation with Lucas Automotive. It is a computerized vision system that provides an early warning collision avoidance system for drivers. It uses a camera that converts the road scene into a computerized map, identifying road edges, white line objects, and road defects. It therefore has the ability to recognize the highway features and the trajectory of the driven vehicle. Based on these, potential difficulties are identified early and the driver can be warned to take corrective action.

Technologies Based on Collision Types

As stated earlier, the predominant collision types for both single-unit trucks and tractor-trailers are angle, rear end, SSOD, and SSSD. These collision types accounted for over 75% of large-truck crashes on two-lane secondary roads. The user service areas that would reduce these types of crashes are longitudinal collision avoidance, lateral collision avoidance, and intersection collision avoidance. A specific technology that has been developed to reduce these types of collisions is the vehicle on-board radar (VORAD) vehicle detection and driver alert system manufactured by VORAD. It is a high-frequency radar system that determines the speed and relative distance of objects from the vehicle. Upon sensing a potential hazard, such as a vehicle suddenly decelerating, VORAD emits a combination of lights and audible warning tones to give drivers additional time to apply the brakes or take evasive action. This system is currently in use.

Summary

Statistical Analysis

- Large trucks had significantly higher overall crash rates for secondary roads than primary roads in the Richmond, Staunton, and Northern Virginia districts.

- Large trucks had significantly higher statewide crash rates for two-lane secondary roads than for two-lane primary roads.

- There was no significant difference between the fatal crash rates of large trucks for two-lane secondary roads and two-lane primary roads.

- Large trucks had significantly higher injury crash rates for secondary roads than for primary roads in the Richmond and Culpeper districts.

- The Richmond, Culpeper, and Northern Virginia districts had significantly higher crash rates for large trucks than for passenger cars for two-lane secondary roads.

- Large trucks had significantly higher crash rates statewide than passenger cars for two-lane secondary roads.

- The crash rates for single-unit trucks were higher than the rates for tractor-trailers for two-lane secondary roads, although the difference was not significant.

- Large trucks did not have significantly higher fatal crash rates than passenger cars for two-lane secondary roads.

- The predominant collision types of large-truck crashes on two-lane secondary roads were angle, rear end, SSSD, and SSOD. These predominant collision types accounted for over 75% of large-truck crashes on two-lane secondary roads in Virginia.

- The proportions of angle, head-on, SSOD, and backed-into large-truck collisions were significantly higher on two-lane secondary roads than on two-lane primary roads.

- The large-truck proportions of SSSD, SSOD, noncollision, miscellaneous, and backed-into collision types were significantly higher than those for passenger cars on two-lane secondary roads.

- Large trucks had a significantly higher fatal crash proportion than passenger cars on two-lane secondary roads.

Fault Tree Analysis

- For single-unit trucks, a vehicle-related failure crash most often occurred when there was brake failure and the evasive action failed. Crashes in this category accounted for less than 1% of all single-unit truck crashes on secondary roads in Virginia.

- For tractor-trailers, a vehicle-related failure crash most often occurred when there was no observed vehicle defect but the interaction among the driver, vehicle, and environment was incompatible and no evasive action was taken. It is likely these crashes were due to the characteristics of the large trucks and the characteristics of the highway system. Crashes in this category also accounted for less than 1% of all tractor-trailer crashes on two-lane secondary roads in Virginia.

- For all large trucks, an environment-related failure crash most often occurred when a faulty highway component led to surface defects and the driver's evasive action either failed or was not taken. These crashes represented about 8% of all single-unit truck crashes and about 6% of all tractor-trailer crashes on two-lane secondary roads in Virginia.

- For all large trucks, a driver-related failure crash most often occurred when there was an error in driver judgment and the evasive action either failed or was not taken. These crashes represented over 70% of all large-truck crashes on secondary roads.

CONCLUSIONS

- The lack of adequate data on large-truck volumes by type on secondary roads makes it essential that a significant effort be made to obtain these data at regular intervals.

- The lack of data on the characteristics (width, trailer length, tractor length) of large trucks involved in crashes on two-lane secondary roads inhibits research in this area.

- Because SSSD, SSOD, and angle collisions are significant problems for large trucks on two-lane secondary roads, it is essential that a significant effort be made to reduce these types of collisions.

- Because large-truck crash rates for two-lane secondary roads were significantly higher than for two-lane primary roads in Virginia, the effort placed in reducing large-truck crashes on two-lane secondary roads must be at least the same as that put on primary roads.

- Because driver error was the single highest causal factor of large-truck crashes on two-lane secondary roads, significant effort must be placed in eliminating or reducing large-truck driver errors or mitigating the effect of such errors.

RECOMMENDATIONS

- Enforcement officers in Virginia should be better trained to provide more details on crash and vehicle characteristics in their crash reports to facilitate more in-depth analysis of large-truck crashes.

- A statistical sampling system for collecting traffic data, including vehicle classification on two-lane secondary roads, should be developed and implemented as soon as possible.

- As it has been shown that the predominant causal factors of large-truck crashes on two-lane secondary roads are driver related and the predominant types of crashes are angle, rear end, SSSD, and SSOD, a pilot study using an identified ITS technology should be conducted to evaluate the effectiveness of such a technology in reducing these types of large-truck crashes on these roads. The most appropriate technology identified is the VORAD system and should be used in the study. Such a test should be conducted under the cooperative effort of VDOT and the Department of Motor Vehicles in partnership with a selected number of private large-truck companies, under the sponsorship of the Federal Highway Administration and the National Highway Traffic Safety Administration. Data should be collected for a 3-year period on the characteristics of crashes involving different types of large trucks on two-lane highways in the Richmond, Staunton, and Northern Virginia districts, which had significantly higher crash rates for large trucks than for passenger cars on the secondary roads. Such a study should also evaluate the feasibility of public/private partnership in the implementation of ITS technologies.

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Appendix A

ADVANCED TECHNOLOGIES FOR LARGE-TRUCK SAFETY

Table A-1. Advanced Technologies for Large-Truck Safety

Crash Causal Factor	User Service	Advanced Technologies	Status
Vehicle equipment failure and evasive action failed or was not taken	Automatic roadside safety inspection	Automatic commercial vehicle operation safety inspection system	Operation test in progress ADVANTAGE I-75
	On-board safety monitoring	Vehicle monitoring systems: Automated bus diagnostic system, Michigan Mass Transit Authority	Operational test
Inattentive driver error	Safety readiness	Pattern recognition continuous driver status/performance monitoring system	Proposed
Impairment	Safety readiness	Galvanic skin detectors	Automobile manufacturers have the technology
		Steering wheel motion pattern recognition system	Proposed
Roadway hazardous conditions	Vision enhancement for crash avoidance	Hazard-mounted beacons	Proposed
		Infrared laser scanning system	Proposed
		Machine-vision guidance system	Operational test by U.S. Army
Interaction between vehicles	Longitudinal collision avoidance, lateral collision avoidance, and interaction collision avoidance	Headway detection system, VORAD, lateral encroachment warning system, ultrasound backing sensors	Available; operational test

Appendix B

FAULT TREE FOR VEHICLE- AND ENVIRONMENT-RELATED CRASHES

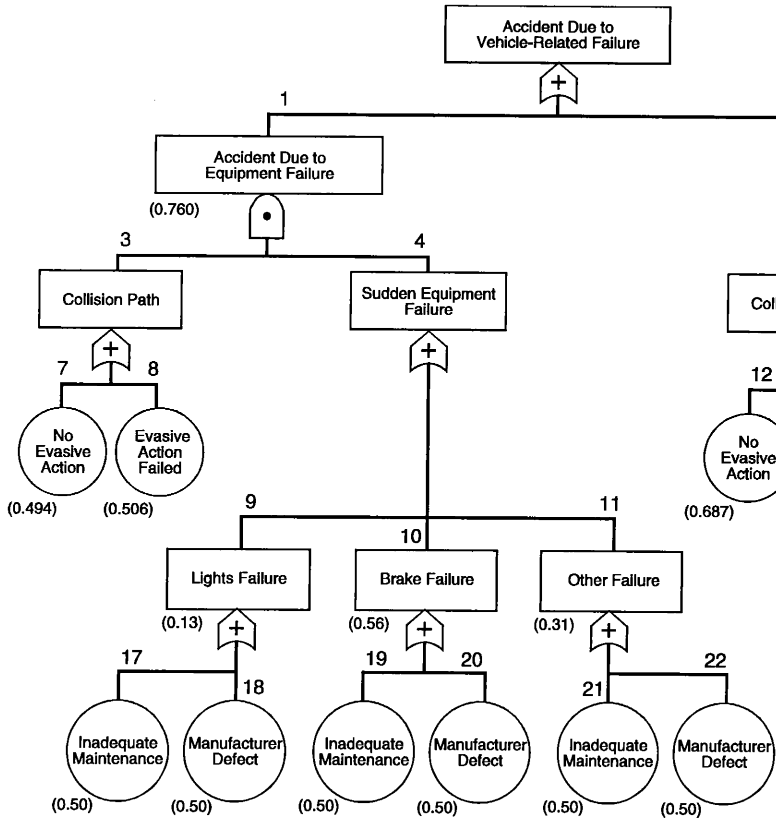

Figure B-1. Fault Tree for Vehicle-Related Crashes Involving Single-Unit Trucks

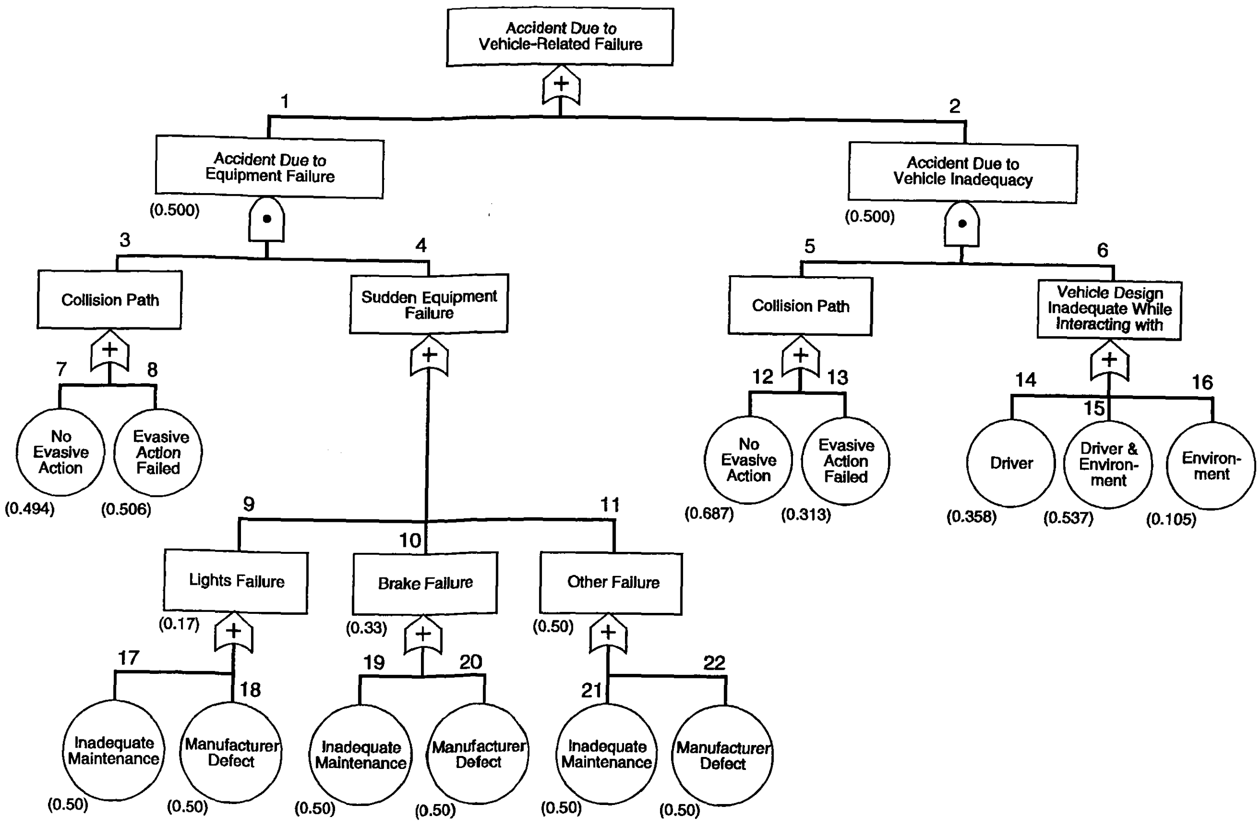

Figure B-2. Fault Tree for Vehicle-Related Crashes Involving Tractor-Trailers

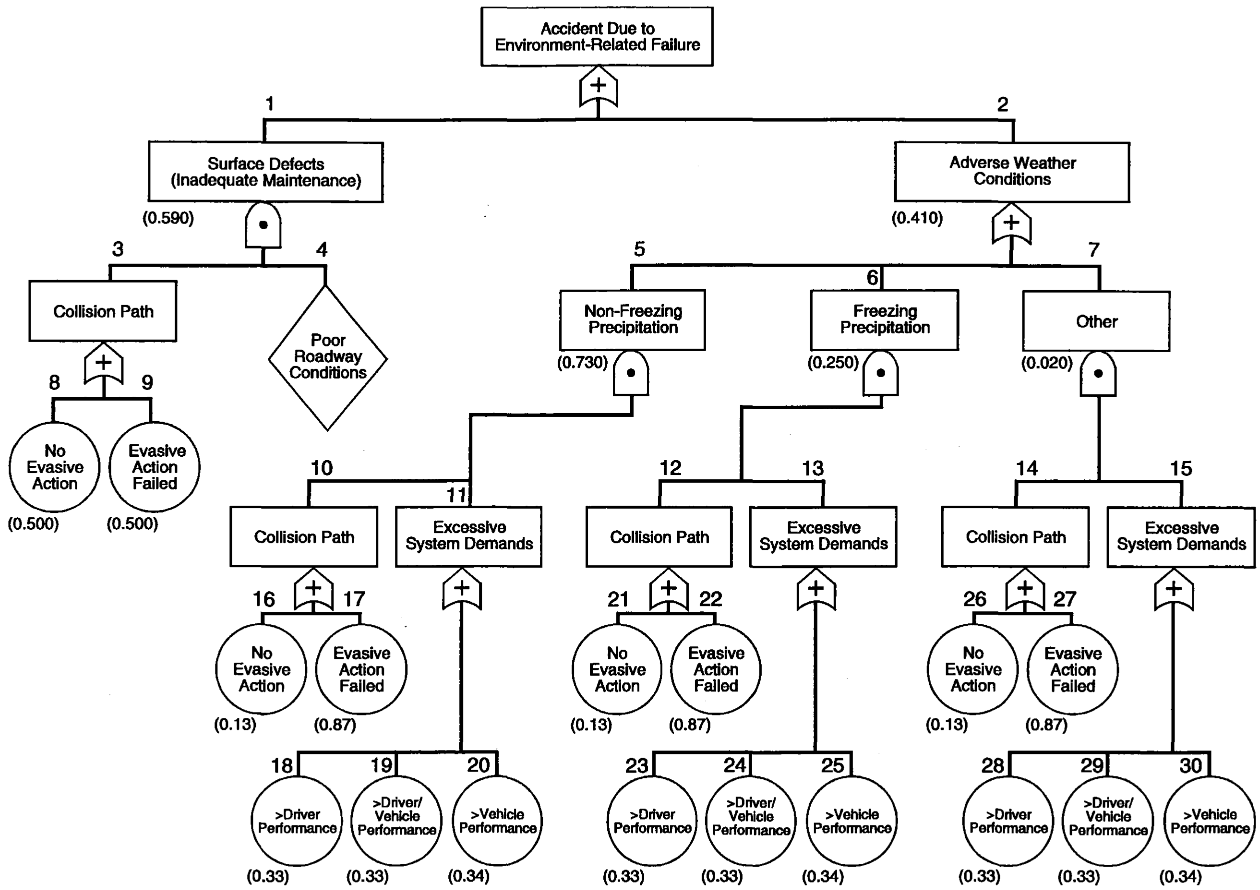

Figure B-3. Fault Tree for Environment-Related Crashes Involving Single-Unit Trucks

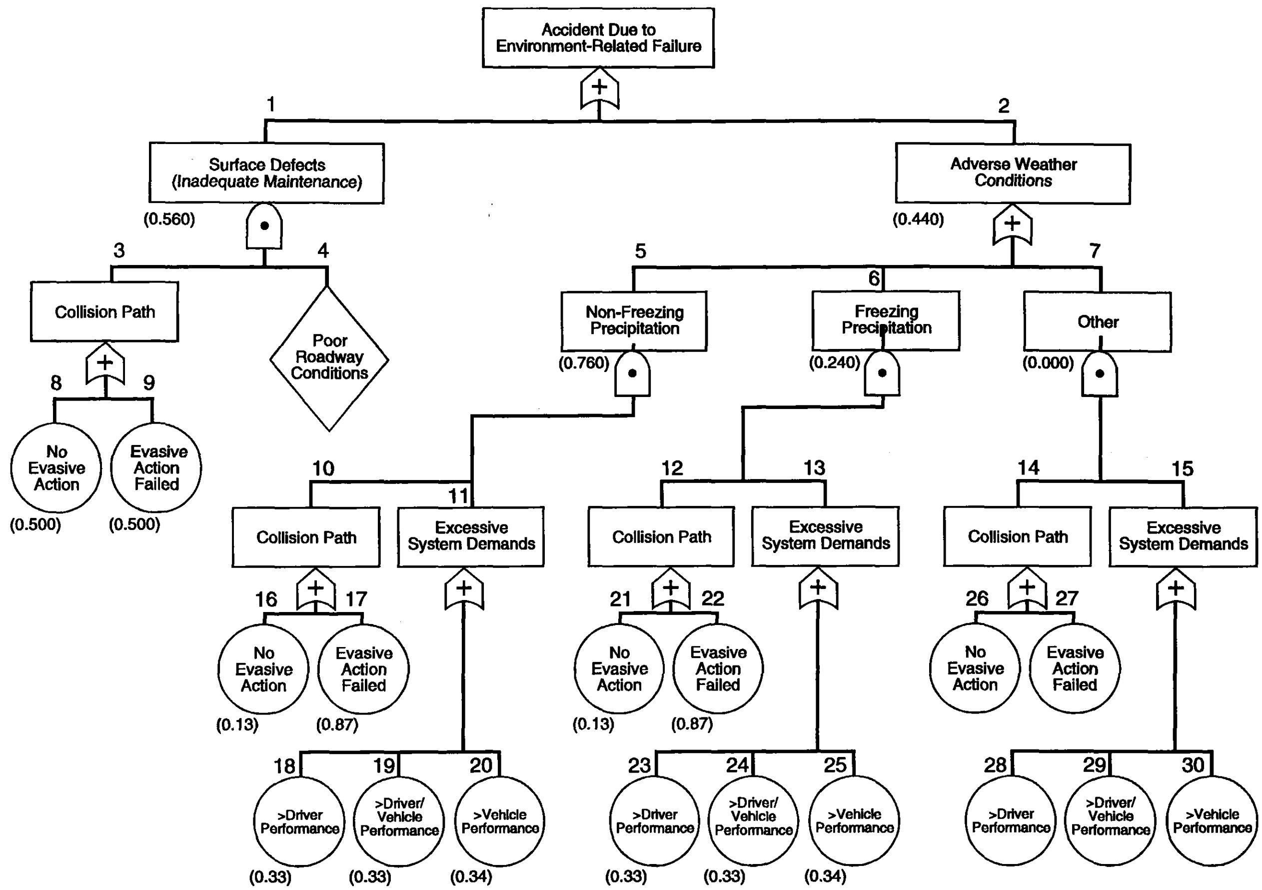

Figure B-4. Fault Tree for Environment-Related Crashes Involving Tractor-Trailers

Appendix C

MINIMUM CUT SETS AND THEIR ASSOCIATED PROBABILITIES

Table C-1. Minimum Cut Sets for Single-Unit Truck Crashes Due to Vehicle-Related Failure

Path	Probability
1→3→7 and 1→4→9→17	0.0244
1→3→7 and 1→4→9→18	0.0244
1→3→8 and 1→4→9→17	0.0250
1→3→8 and 1→4→9→18	0.0250
1→3→7 and 1→4→10→19	0.1051
1→3→7 and 1→4→10→20	0.1051
1→3→8 and 1→4→10→19	**0.1077**
1→3→8 and 1→4→10→20	**0.1077**
1→3→7 and 1→4→11→21	0.0582
1→3→7 and 1→4→11→22	0.0582
1→3→8 and 1→4→11→21	0.0596
1→3→8 and 1→4→11→22	0.0596
2→5→12 and 2→6→14	0.0590
2→5→12 and 2→6→15	0.0885
2→5→12 and 2→6→16	0.0173
2→5→13 and 2→6→14	0.0269
2→5→13 and 2→6→15	0.0403
2→5→13 and 2→6→16	0.0079

Bold indicates the minimum cut paths with the highest probability and thus significant causal factors.

Table C-2. Minimum Cut Sets for Tractor-Trailer Crashes Due to Vehicle-Related Failure

Path	Probability
1→3→7 and 1→4→9→17	0.0210
1→3→7 and 1→4→9→18	0.0210
1→3→8 and 1→4→9→17	0.0215
1→3→8 and 1→4→9→18	0.0215
1→3→7 and 1→4→10→19	0.0408
1→3→7 and 1→4→10→20	0.0408
1→3→8 and 1→4→10→19	0.0417
1→3→8 and 1→4→10→20	0.0417
1→3→7 and 1→4→11→21	0.0618
1→3→7 and 1→4→11→22	0.0618
1→3→8 and 1→4→11→21	0.0633
1→3→8 and 1→4→11→22	0.0633
2→5→12 and 2→6→14	**0.1230**
2→5→12 and 2→6→15	**0.1845**
2→5→12 and 2→6→16	0.0361
2→5→13 and 2→6→14	0.0560
2→5→13 and 2→6→15	0.0840
2→5→13 and 2→6→16	0.0164

Bold indicates the minimum cut paths with the highest probability and thus significant causal factors.

Table C-3. Minimum Cut Sets for Single-Unit Truck Crashes Due to Environment-Related Failure

Path	Probability
1→3→8 and 1→4	**0.2950**
1→3→9 and 1→4	**0.2950**
2→5→10→16 and 5→11→18	0.0128
2→5→10→17 and 5→11→18	0.0859
2→5→10→16 and 5→11→19	0.0128
2→5→10→17 and 5→11→19	0.0859
2→5→10→16 and 5→11→20	0.0132
2→5→10→17 and 5→11→20	0.0885
2→6→12→21 and 6→13→23	0.0044
2→6→12→22 and 6→13→23	0.0294
2→6→12→21 and 6→13→24	0.0044
2→6→12→22 and 6→13→24	0.0294
2→6→12→21 and 6→13→25	0.0045
2→6→12→22 and 6→13→25	0.0303
2→7→14→26 and 7→15→28	0.0004
2→7→14→27 and 7→15→28	0.0024
2→7→14→26 and 7→15→29	0.0004
2→7→14→27 and 7→15→29	0.0024
2→7→14→26 and 7→15→30	0.0004
2→7→14→27 and 7→15→30	0.0024

Bold indicates the minimum cut paths with the highest probability and thus significant causal factors.

Table C-4. Minimum Cut Sets for Tractor-Trailer Crashes Due to Environment-Related Failure

Path	Probability
1→3→8 and 1→4	**0.2800**
1→3→9 and 1→4	**0.2800**
2→5→10→16 and 5→11→18	0.0143
2→5→10→17 and 5→11→18	0.0960
2→5→10→16 and 5→11→19	0.0143
2→5→10→17 and 5→11→19	0.0960
2→5→10→16 and 5→11→20	0.0148
2→5→10→17 and 5→11→20	0.0922
2→6→12→21 and 6→13→23	0.0045
2→6→12→22 and 6→13→23	0.0303
2→6→12→21 and 6→13→24	0.0045
2→6→12→22 and 6→13→24	0.0303
2→6→12→21 and 6→13→25	0.0047
2→6→12→22 and 6→13→25	0.0312

Bold indicates the minimum cut paths with the highest probability and thus significant causal factors.