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Abstract

Recent trends indicate that vehicle miles traveled for large trucks is increasing at a higher rate than for other vehicles. The resulting competition between large trucks and other vehicles for highway space can be expected to result in more multivehicle collisions involving large trucks. The likelihood of these collisions causing severe injuries to vehicle occupants will also increase with the trend towards the use of smaller automobiles and heavier and larger trucks. In order to develop countermeasures that will alleviate this problem, it is first necessary to identify the characteristics of large-truck accidents and the role of traffic and geometric variables in such accidents. This study investigated the major factors associated with large truck accidents including the effect of highway facility type and highway geometry, and the development of mathematical models relating the factors with accident rates and probability of occurrence.

This first volume documents the methodology of the study, the results of a statistical analysis of large-trucks historical accident data, the results of a fault tree analysis.

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FINAL REPORT

TRAFFIC AND GEOMETRIC CHARACTERISTICS AFFECTING THE INVOLVEMENT OF LARGE TRUCKS IN ACCIDENTS

VOLUME I

ACCIDENT CHARACTERISTICS AND FAULT TREE ANALYSIS

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Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

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The research was performed under the general guidance and advice of the Research Task Force on Traffic and Geometric Characteristics Affecting the Involvement of Large Trucks in Accidents, consisting of

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ABSTRACT

Vehicle miles traveled for large trucks, which are defined here as trucks having six or more wheels in contact with the road and having a gross weight greater than 10,000 lb, have been steadily increasing during the past few years. On some sections of Virginia interstate routes, for example, the proportion of large trucks is as high as 50 percent. The resulting competition between large trucks and other vehicles for highway space can be expected to result in more collisions involving large trucks. An analysis of large-truck accidents in Virginia also indicated that driver-related factors are the primary associated factors for truck crashes. For example, driver error is associated with over 50 percent of fatal accidents involving large trucks, and fatal crashes for which driver error is listed as the primary factor occur predominantly on stretches of highways with vertical or horizontal curves and/or grades. In order to develop countermeasures that will alleviate this problem, it is necessary to identify the specific traffic and highway geometric characteristics that significantly affect the occurrence of large-truck crashes.

This study was therefore conducted by the Virginia Transportation Research Council with the objective of identifying appropriate countermeasures for highway geometrics to reduce large-truck crashes. The major factors associated with large-truck accidents, including the effect of highway facility type and highway geometry, were investigated. This study is reported in two volumes.

This volume presents the methodology of the study, the results of a statistical analysis of large-truck accident data, the results of a causal analysis of large-truck accidents through fault tree analysis, and a recommended list of preventive measures for reducing large-truck accidents.

FINAL REPORT

TRAFFIC AND GEOMETRIC CHARACTERISTICS AFFECTING THE INVOLVEMENT OF LARGE TRUCKS IN ACCIDENTS

VOLUME I

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INTRODUCTION

Large trucks, which are defined here as trucks having six or more wheels in contact with the road and having a gross vehicle weight greater than 10,000 lb, have now become a significant proportion of the vehicle fleet on the nation's highways. In Virginia, for example, the proportion of large trucks on some highways is as high as 50 percent. The vehicle miles of travel (VMT) of these large trucks on Virginia highways has continued to increase over the years, and, in 1983, for the first time, the rate of increase of large truck VMT surpassed that for passenger cars. Between 1979 and 1982, for example, the average annual rate of increase in the VMT of large trucks was less than 1 percent per annum, whereas that for passenger cars, vans, and pickups was about 2.6 percent. Between 1983 and 1988, however, the VMT of large trucks in Virginia increased at an average rate of 8.2 percent per annum, whereas that for passenger cars, vans, and pickups was about 6.3 percent per annum.

In addition to the increase in VMT of large trucks, both the maximum allowable size and axle weights have been increasing over the years. The Surface Transportation Assistance Act (STAA) of 1982 requires states to allow trucks of 80,000-lb gross weights and 102-in widths and prevents states from establishing limits on overall tractor trailer lengths (Appendix, Table A-1). These provisions apply to all interstate highways and other roads in the federal and primary systems that are so designated by the Secretary of Transportation. These roads are now commonly referred to as the "STAA designated and access system of highways."

Fatal accidents per 100 million VMT for all large trucks in Virginia increased from 3.81 to 5.88 between 1982 and 1984 (an increase of about 54 percent); that for tractor trailers increased from 2.81 to 5.36 (an increase of about 90 percent); and that for other vehicles (passenger cars, vans, and pickups) remained approximately constant at less than a 0.30 percent increase.

In order to arrest this trend of increasing fatal accident rates for large trucks, it is necessary to identify the crash characteristics and the factors that are associated with these crashes so that appropriate countermeasures can be identified and implemented. A study was therefore conducted with the objective of identifying appropriate countermeasures for highway geometrics to reduce large-truck crashes. The first part of this effort was to carry out a detailed analysis of the historical data on large-truck accidents in order to determine specific characteristics of these accidents, and the second part was to develop mathematical relationships between large-truck accidents and the significant associated traffic and geometric characteristics identified.

The study is reported in two volumes.

Volume I documents

- the methodology used in carrying out the study
- the results from a statistical analysis of large-vehicle historical accident data
- the results from a causal analysis of large-vehicle accidents through fault tree analysis
- a recommended list of preventive measures for reducing large-vehicle accidents.

Volume II gives

- a detailed description of the development of the multiple linear regression models relating large-vehicle accidents with the significant associated traffic and geometric factors
- the step-by-step development of the Poisson regression models.

PURPOSE AND OBJECTIVE

The purpose of this study was to identify the characteristics of large-truck accidents in Virginia and to identify the traffic and geometric variables that significantly affect large-truck involvement in accidents.

The specific objectives were

- to determine the distribution of large-truck accidents by weekday
- to identify the major causes of large-truck accidents
- to determine whether large-truck accidents are overrepresented in multi-vehicle accidents
- to determine the effect of the type of highway on large-truck accidents
- to determine the effect of road geometry on large-truck accidents

- to identify significant changes with time in large-truck accident characteristics in Virginia
- to develop models relating large-truck accidents with significant traffic and geometric characteristics.

LITERATURE REVIEW

A review of the literature was carried out to identify results obtained from recent studies similar to this project. Facilities of the University of Virginia, the Virginia Transportation Research Council, and the Transportation Research Information Service were used to identify and select appropriate publications for review. Information was sought on the characteristics of large-truck accidents particularly in relation to associated causal factors and the types and severity of accidents.

Factors Contributing to Large-Truck Accidents

The following factors have been identified in previous studies as contributing to truck accidents:

- driver-related factors
  - age, experience, training
  - drug use
  - medical condition
  - driver qualifications
  - fatigue
  - driver safety
  - alcohol use
  - motivation programs
- vehicle-related factors
  - vehicle design and weight
  - crashworthiness
  - large-truck dynamics and crash avoidance
- highway/environment-related factors
  - roadway type
  - stopping sight distance
  - interchanges/intersections

— roadside hazards

— grades

— speed differentials

— curves

— lighting and weather.

Driver-Related Factors

Driver error has been recognized as a major link in the causal chain in accidents involving large trucks. Shinar analyzed 161 in-depth accident investigations that involved large trucks and found that 8 of the 10 causes cited were most frequently related to driver error.[1] In a separate study in Washington on data based on police reports, inattention and negligence were identified as the most frequent causes involved in large-truck accidents with another vehicle.[2] The truck driver was the causal factor in 62 percent of the accidents compared to 31 percent for the other driver. Defective truck equipment was cited in 6 percent of the accidents.

The following paragraphs briefly summarize the results from numerous studies carried out to investigate the influence of driver-related factors on truck crashes.

- *Age, experience, and training*: A number of studies have yielded data and statistics on the distribution of large-truck accidents by age of the driver. The results of all the analyses in this area show a clear trend of high accident rates for the younger age group, low for the middle age group, and somewhat high again for the older age group.[3,4] A survey by Wyckoff indicated that drivers under the age of 25 appeared to take greater risks and a greater number of them are involved in accidents.[5] There is little information available on the influence of formal driver training on large-truck crashes; however, available data have revealed that many drivers involved in accidents have not had any formal driver education.[6] This situation has also been worsened by the influx of many inexperienced drivers into the trucking industry as a result of deregulation.

- *Medical condition*: Accident researchers and concerned organizations have identified medical conditions that impair a driver's ability to respond to a complex driving situation as a significant contributing factor in motor vehicle accidents. Waller estimated that 15 percent of all accidents could be attributed to medical conditions.[7] There is a lack of data relating truck crashes and relevant driver medical conditions.

- *Fatigue*: According to a study conducted by the American Automobile Association fatigue is the probable primary cause of 41 percent of large-truck crashes.[8] Smist and Ranney concluded that drivers of articulated vehicles were more often reported as fatigued or sleepy.[9]

- *Alcohol use*: The scope and nature of the drinking and driving problem among truck drivers are not well understood. Conclusions from studies thus far must also consider expected under-reporting of alcohol involvement. Among accidents in which the driver was fatally injured, alcohol involvement ranged from 36 percent[10] to 24 percent.[11] Also, drivers of straight trucks were slightly more likely to have been cited as drinking prior to an accident than drivers of articulated vehicles.[8]

- *Drug use*: There have been very few studies focused on the involvement of drug use in large-truck accidents. One study by Terhune and Fell indicated that about 1 percent of truck drivers are drug users.[12] Wyckoff stated that, based on his interview data, the use of marijuana appears to be at levels similar to those in the general population.[5]
- *Driver qualification*: The federal government, the states, and the motor carrier industry jointly administer the qualification of drivers to operate large trucks. From the point of view of accident causation, what is more relevant is the process of identification and disqualification of problem commercial drivers as a preventive measure. This is complicated by the fact that a significant number of problem drivers had multiple driver's licenses from different states.[13] This problem may be resolved to a large extent by the new licensing program implemented on January 1, 1989, under which every commercial vehicle driver will have only a single license.
- *Driver-safety motivation programs*: These programs aim at the prevention of large-truck crashes. There is a direct relationship between fuel-economical driving techniques and safe-driving techniques. Galligan described a program in which carriers gained an increase of 29 percent in fuel efficiency and a 50 percent reduction in accident rates.[14]

Vehicle-Related Factors

Vehicle design and maintenance are recognized as direct or indirect causes of accidents. The extent to which these factors interrelate with driver factors and highway or environmental factors to cause an accident is often difficult to establish.

The vehicle-related factors identified thus far in studies on the subject of large-truck crashes and other related topics are summarized in the following:

- *Vehicle design and weight*: By vehicle design characteristics, reference is made to truck length, width, number of towed units, cargo, body type, and gross vehicle weight. Many studies have investigated their influence on off-tracking, splash and spray, aerodynamics, backing, speed on grades, braking, and stability. One particular study by the Western Highway Institute claimed that braking and stability can deteriorate as truck length, weight, and the number of towed trailers increases.[15] Some studies have found that the accident involvement rates of double trailers are greater than those for single trailers.[3] Fatal accident rates have also been found to be greater for doubles.[16] There have not been many studies that have examined the relationship between vehicle weight and accident occurrence. Perhaps this is due to the particular difficulty in obtaining accurate weight data. A study by Winfrey et al. found that the heaviest weight group had the highest fatality rate but the lowest accident rate.[17]

- *Crashworthiness*: The crashworthiness of a large truck is defined here in relation to the types of protection provided for both the occupants of the truck and the occupants of other vehicles. The objective of studies done on this has mainly been to reduce the fatalities and injuries resulting from such crashes. Some of the results noted in the literature are summarized here:

  - *Truck occupants*: The most frequent type of accident leading to a truck occupant fatality is truck rollover. Rollover accounts for 50 percent of all single-unit truck fatalities as compared to 26 percent for passenger cars.[6] The relative levels of protection afforded by the different types of tractor cabs also have been studied. Truck driver fatalities for cab-over-engine tractors was found to be more than double that for cab-behind-engine trucks.[16]

  - *Occupants of other vehicles*: In all fatal accidents involving a truck and another vehicle, the probability of the fatality being an occupant of the other vehicle has been found to be 69 percent according to the Fatal Accident Reporting System data for 1979 through 1980.[18] Most (90 percent) of the fatal car-into-truck rear end collisions involved underride.[19]

- *Vehicular dynamics and crash avoidance*: Some accidents occur when a driver exceeds the safe dynamic performance bounds of his or her vehicle. As the task of driving the vehicle becomes more complex (as in the case of combination trucks), special skills are required to handle the vehicle to avoid a collision. Some of the relevant factors that have been studied in this area are summarized in the following:

  - *Brake system*: One of the common factors contributing to large-truck crashes in which passenger cars were involved was the disparity in the braking capabilities of the two types of vehicles.[20]

  - *Brake system maintenance*: The importance of brake system maintenance has been clearly emphasized by the results of many studies of truck accidents. The Bureau of Motor Carrier Safety (BMCS) found brake systems to be the vehicle defect cited most often. Brakes contribute to 31 percent of all accidents resulting from mechanical defects.[21]

  - *Handling and stability*: Dynamic instability in a vehicle can be caused either by simple braking or by steering maneuvers that cause unstable lateral motion or rollover. Ervin, analyzing 1976 through 1978 BMCS data, found a close relationship between the rollover threshold and the number of accidents involving rollover.[22]

  - *Aerodynamic disturbances and splash/spray effects*: Results of truck experiments by Weir et al.[23] indicated that a passenger car passing a truck was displaced laterally by the truck's wake from 0.5 to 3.3 ft depending upon lane widths, relative and absolute speeds, initial vehicle clearance, and crosswind conditions. Large trucks operating on most roads during wet weather create splash and spray. Spray-fouled rear view mirrors on trucks can increase the possibility of lane change accidents. There has been no study that investigated the contribution of this factor to truck accidents.

- *Truck-generated stress*: It has been suggested that the combined effect of long-term simultaneous exposure to heat, noise, and vibration leads to possible negative physiological or psychological effects that in turn lead to stress-induced fatigue. A study by Mackie et al. indicated that truck-cab heat decreased alertness and increased fatigue.[24]
- *Vehicle conspicuity*: Minahan and O'Day have cited this factor as the main cause of accidents involving an impact into the sides or rear of a large truck.[19] Green et al. reported the benefits of retroreflective treatments applied on trucks.[25] Lum found that flashers on trucks during both daylight and night hours are effective in reducing the risk of accidents.[26]

Highway, Traffic, and Environmental Factors

Accident experience in Virginia for the years 1980 through 1985 showed that tractor trailer accident involvement rates are lowest on interstates.[27] The same is true for all other vehicles. This clearly indicates the effect of superior highway and traffic conditions on reducing accidents, all else being equal.

This literature review indicated that there has been little research investigating the effect of highway and geometric factors on truck accidents. The following paragraphs summarize some of the relevant findings on the role of each factor.

- *Roadway type*: Classifying roadways into freeways or nonfreeways and urban or rural, an accident rate comparison by Vallette et al. found that the rates for large trucks were highest on urban nonfreeways and lowest on rural freeways.[3] A study by Cirillo et al. found that access control and other freeway design features had a positive impact on truck accident rates.[28]
- *Interchanges*: A study by Vallete et al. found that 16 percent of the truck accidents on freeways occurred in the vicinity of an interchange.[3] A similar finding has been reported by Cirillo et al., who also found that the accident rates at off-ramps in most cases were higher than the rate at on-ramps.[28]
- *Intersections*: The study by Vallette et al. found that of the large-truck accidents at intersections, 65 percent occurred on urban freeways and 23 percent on rural freeways. Other studies have also indicated that all types of trucks are more involved in accidents at junctions than other vehicles.[3]
- *Grades*: Large trucks encounter special risks on grades. On the upgrades, they are subject to being struck in the rear by faster vehicles, and on downgrades, they are susceptible to runaway accidents or striking slower vehicles. Scott and O'Day endorsed the former as the most likely cause of accidents on grades.[4]
- *Curves and superelevation*: Accidents involving large trucks on curves have been found to range from a low of 7 percent on urban freeways to a high of

34 percent on rural freeways.[3] An analysis of the fatal accident reporting system (FARS) data for combination trucks in which the driver was killed showed that 45 percent of single-vehicle accidents occurred on curved sections of roadway compared to 16 percent for multiple-vehicle accidents. Despite the critical role of superelevation in maintaining vehicle stability, few studies have addressed this issue. Using data from single-vehicle crash sites and comparison sites, an investigation by Zador et al. showed that inadequate banking on curves presents a significant risk to trucks.[29]

- *Stopping sight distance*: Stopping distance is the distance traveled by a vehicle from the instant its driver sights an object that necessitates a stop to the instant when the vehicle has been brought to a stop by the application of brakes. It has generally been assumed that the longer sight distance afforded by higher eye height compensated for the longer stopping distances required by trucks. An investigation of this assumption concluded that, although there is some compensating effect because of the higher eye height of the truck driver, the length of passing zones standardized for passenger cars is inadequate for trucks.[30]
- *Roadside hazards*: According to FARS data from 1980 through 1985, approximately one third of fatal accidents were reported as collisions with fixed objects. Considerable effort has gone into the development of breakaway roadside features and protection devices to reduce this toll, particularly for passenger cars since they represent the majority of vehicles. Many of these protection devices, such as impact attenuators, guardrails, bridge rails, and median barriers, which have been designed for automobiles, have been found to be inadequate to contain heavier vehicles.[31-33]
- *Speed differentials*: The greater the variation in speed of any vehicle from the average speed of all traffic, the greater its chances of being involved in an accident.[34] A beneficial effect of the national speed limit of 55 mph at the time it was imposed was a reduction in the speed differential that existed between cars and trucks.[35,36]
- *Lighting and weather*: Although data are available on accidents, there has been a lack of relevant exposure data needed for an investigation into the role played by lighting and weather. A study by Jovanis and Chang included the hours of snow exposure as an independent variable in an accident causation model.[37] A study by Garber and Joshua determined that about 2 percent of large-truck fatal accidents in Virginia can be attributed to environmental factors.[38]

Accident Theories

Theories that attempt to describe the accident phenomenon have primarily emerged as a result of accident investigations and the desire to establish a link between an accident and the associated causes.

As diverse interests and purposes are followed in accident investigations, the varied perceptions held of the accident phenomenon have resulted in a number of different views. Brenner[39] reported that these views combined with certain assumptions and rules of procedures lead to five distinct accident theories. They are

1. the single-event theory
2. the chain-of-events theory
3. the determinant-variable theory
4. the branched-events-chain theory
5. the multilinear-events-sequences theory.

The Single-Event Theory

The fundamental assumption of this theory is that an accident consists of a single event that can be attributed to an identifiable cause. According to this theory, the investigative task is uncomplicated. In order to prevent similar accidents, all one must do is to find the cause and correct it. This is a primitive view of the nature of accidents. This sort of view is exemplified in cases when the survivors of a harmful phenomenon attribute the phenomenon to a single cause as a scapegoat to satisfy the victims. This view of accidents leads to incomplete examination of the accident phenomenon.[39]

The Chain-of-Events Theory

This concept, also known as the domino theory, was first adapted by Heinrich.[40] This theory proposes that, if a set of unsafe conditions is set up as a row of dominoes, one unsafe act would start them toppling. The accident investigator gathers information in order to reconstruct the chain of events that resulted in the accident.

One inadequacy in this theory is that the terms *unsafe conditions* and *unsafe acts* lack proper definitions and criteria. Often they represent the investigator's conclusions rather than factual observations of the accident phenomenon. The lack of principles or criteria often yields findings that are not reproducible.

The Determinant-Variable Theory

A factorial view of the accident phenomenon was suggested by the work of Greenwood and Woods[41] and Newbold.[42] This theory suggests that "accident proneness" can be inferred statistically by the examination of accident-related data. This theory was further extended to static conditions by Thorndike.[43] He expressed the view that, if sufficient accident data are gathered, it is possible to obtain fair estimates of an accident. This theory suggests that there are common factors in all accidents and that they can be identified from accident data.

The Branched-Events-Chain Theory

This theory and the associated fault tree approach to accident analysis are the result of work related to the prevention of accidental missile launches in the missile program.[44] It is based on the perception that an accident would occur with some likelihood if a pathway to its occurrence was available. The fault tree approach to describing an accident phenomenon as a chain of events leading to the top event was a marked improvement over the other methods of accident prediction.

Although this theory is an adaptation of the chain-of-events theory, the information required for the analysis of the accident phenomenon according to this approach results in improved ability to predict accident probabilities. The fault tree method of accident investigation also facilitates the discovery of new knowledge during an investigation and organizes speculations if data are not available.

The Multilinear-Events-Sequence Theory

This theory has been advanced by Brenner,[39] who suggested a process view of the accident phenomenon in which accidents are a segment of a continuum of activities. According to this theory, an accident is defined as a transformation process that interrupts a homeostatic activity resulting in a harmful event. A homeostatic activity is defined as an activity that is in a relatively stable state of equilibrium or has a tendency toward such a state.

The analysis is based on changes of state and events that result in such changes. Events are defined as the product of interactions between actors and actions. This theory incorporates the benefits of branched-events-chain theory and also establishes a time relationship among the events.

METHODOLOGY AND RESEARCH APPROACH

The methodology for carrying out this study involved the following tasks:

- a compilation of historical accident data
- an analysis of the compiled accident data
- an identification of associated accident causal factors through fault tree analysis
- the development of models relating accident occurrence with significant causal factors.

Details of the methodology used for model development are given in Volume II.

Compilation of Historical Accident Data

The basic data on accidents in Virginia were obtained from the police accident report forms, which are completed by the police officer investigating every accident involving a fatality, an injury, or property damage of $500 or more. The recorded information for each year is coded and stored in a computer file; these are referred to as "crash files." The Virginia Department of Transportation also collects and records in a computer file travel characteristics of different categories of vehicles. Unfortunately, however, for the period 1980 through 1982, the vehicle type codes permitted only the extraction of tractor trailer data since twin trailers were then not permitted on Virginia highways. It was therefore not possible to obtain accident data for twin trailers as distinct from that for tractor trailers for these years. However, this was possible from 1983 onward. As a result, in some parts of the analysis, all tractor trailers were considered one vehicle category. Data on VMT were available for single-unit trucks and tractor trailers. Single-unit trucks were categorized as 2-axle 4 tires, 2-axle 6 tires, or 3-axle 6 to 10 tires.

All of the average daily traffic (ADT) reports and accident summary reports for 1980 through 1986 used in this analysis were extracted from the crash files.

The term *twin trailer* is used in this report to describe a combination of a tractor truck and two trailers or a tractor truck, semi-trailer, and a trailer coupled together.

Analysis of the Compiled Accident Data

The cross-correlation technique was used to develop matrices relating accident characteristics and associated factors, and the results obtained were used to prepare some of the tables presented herein. Student's *t* test and the binomial theory were also used when it was necessary to test for significant differences or overrepresentation. In order to facilitate comparison, some analysis was also carried out on crashes of passenger cars, vans, and pickups.

The analysis was carried out in two parts. In the first, the trends in large-truck travel and the accident rates of large trucks on all interstate and state primary routes were examined. This analysis yielded a macroview of the performance of the entire primary and interstate highway system in Virginia in terms of the impact of the increasing usage of this system by large trucks. Accident rates were determined for the interstate and primary routes together and separately. These rates are given in terms of accidents per 100 million VMT and are different from the accident involvement rates used later in the analysis.

Changes in traffic characteristics between the pre- and post-1982 periods were also evaluated. This evaluation focused on a microview of different highway and traffic environments represented by three different categories of highways. Data were compiled on selected interstate, designated primary, and undesignated primary routes.

The selected routes represented the bulk of the large-truck mileage within each highway category. For example, the selected interstate routes accounted for 90 percent of the total interstate mileage in Virginia and carried 96 percent of the total truck VMT on all interstate routes. The selected STAA primary routes accounted for 75 percent of the total STAA primary mileage in Virginia and carried 66 percent of total truck VMT on all STAA primary routes. The selected non-STAA primary routes accounted for 17 percent of total non-STAA primary mileages and carried 30 percent of the total truck VMT on non-STAA primary routes. The selected routes were

- interstates: I-64, I-66, I-77, I-81, I-85, I-95, and I-495
- designated primaries: 19, 23, 29, 58, 220, 360, and 460
- undesignated primaries: 1, 10, 11, 15, 17, 50, and 60

In this part of the analysis, accident involvement rates for tractor trailers and other vehicles were compared. Assuming equal responsibility for an accident in the case of two-vehicle accidents, both vehicles were counted in the process of obtaining the involvement rates for each vehicle type. These rates are given in terms of involvements per 100 million VMT. Only injury and fatal accidents were considered in obtaining these involvement rates. The reason for the exclusion of property damage accidents was to avoid the possible introduction of a bias into the reported accidents because of changing repair costs and the role of subjectivity in these estimated costs.

Fatal-accident involvement between the two vehicle categories was also compared in terms of involvement ratios. These involvement ratios are defined as the number of fatal involvements per 100 fatal and injury involvements. These ratios serve as an indicator of accident severity.

Analysis of variance was used to determine significant changes by investigating the following null hypotheses:

- There is no difference between injury and fatal-accident involvement rates for pre- and post-1982 periods.
- There is no difference between fatal-accident involvement rates for pre- and post-1982 periods.

A comparison was also carried out between the involvement rates of tractor trailers and other vehicles over the period under investigation. The relative involvement of tractor trailers compared to all other vehicles is defined in this study as the ratio of their respective involvement rates.

Fault Tree Analysis

Fault trees were used to analyze accidents to identify the chain of events that led to truck-involved accidents and their associated probabilities.

All single-vehicle accidents were first attributed to one of the main causative factors without which the accident would not have taken place. Under the heading of each of these factors, the analysis focused on the identification and description of fault and normal events relevant to accidents attributed to the major causal factor. These events together with appropriate logic gates were then used to describe all possible paths leading to an accident. At each level of the fault tree, the probabilities associated with each event were also determined from available accident information. These probabilities are indicated on the fault tree diagrams by (0.18) etc.

ANALYSIS AND RESULTS

The following sections summarize the results of the analysis conducted for this portion of the study.

Characteristics of Large-Truck Accidents

The results obtained from the different analyses carried out during this portion of the study are summarized in the following subsections. The details of the specific analytical methodology used are also described when this is necessary to clarify the computation carried out.

Effect of Day of the Week

The *t* test at a 5 percent significance level was performed on each set of data to determine whether accident frequency during weekdays (Monday through Friday) is significantly different than that for weekends (Saturday and Sunday). This was done by proposing the null hypothesis that the average percentage of crashes during the week equals the average percentage during the weekend. The analysis showed that, although it can be concluded that there is a significant difference between the frequency of large-truck crashes during weekdays and weekends, this conclusion cannot be made for other vehicle crashes (Appendix, Table A-2). In fact, it can be seen that although the highest percentage of crashes of both large trucks and other vehicles occurs on Friday, the number of large-truck crashes declines significantly during the weekend. The total percentage of large-truck crashes occurring during the weekend is less than that for any other day of the week. This may be due to the reduced truck VMT on these two days. These results suggest that countermeasures, such as increased police enforcement for reducing crashes resulting mainly from driver causes (e.g., speeding), may be effective during any day of the week for other vehicles but will be much more effective for large trucks if implemented during the week rather than on weekends.

Effect of Month

The percentage distribution of large-truck and other vehicle crashes was also obtained to determine whether the frequency of truck crashes varies seasonally (Appendix, Table A-3). There is little difference between the distributions for large trucks and that for other vehicles. The minimum frequency occurred in February both for large trucks and other vehicles. However, the maximum frequency for large trucks occurred in August, whereas that for other vehicles occurred in November and December.

Major Factors Associated with Large-Truck Crashes

The major factors associated with large-truck crashes can be categorized as follows:

- driver related
- vehicle related
- highway/environmental related.

Although age, experience, fatigue, alcohol, and drug use have in the past been treated as driver-related factors, in this study, the data available will allow a breakdown of driver-related factors into fatigue (handicapped driver), speeding, error, and alcohol and/or drugs. Examples of driver error are improper passing, driving left of the center line while not overtaking, failing to yield the right of way, improper turns, and following too closely.

Vehicle defects have traditionally included the brake system, tires, aerodynamic disturbances, and truck-generated stress—such as heat, noise, and vibration. The data available in Virginia, however, give nine subcategories, which include defects in lights, brakes, and steering; puncture or blow-out; worn or slick tires; and engine trouble. In this study, however, a detailed breakdown of vehicle defects was not carried out since the main objectives did not include the identification of countermeasures relating to vehicle defects.

Environmental causes usually include lighting, weather, and pavement condition (wet or dry). Highway causes usually relate to geometric characteristics, such as grades and curves. In this study, five subgroups were used for geometric characteristics: (1) straight and level, (2) curve and level, (3) grade and straight, (4) grade and curve, and (5) others (which include crest curve and sag curve).

The major factors are first presented for all large-truck crashes and then separately for straight trucks, tractor trailers, and double trailers in terms of the three major groups (driver, vehicle, and environment) and a fourth group that includes all other factors. Each year, driver-related factors accounted for 72 to about 76 percent of the crashes. Vehicle-related factors accounted for 6 to 9 percent of crashes, whereas other factors accounted for 14 to about 19 percent (Appendix, Table A-4). It should be noted again that it is likely that the percentage for vehicle-related factors may be higher than indicated in this table because of the way the accident reports are normally completed by the police. It is clear, however, that the percentage for vehicle-related factors is much lower than for driver-related factors. It is interesting to note, however, that although the percentage of crashes for which driver-related factors was identified is very high, it decreased between 1984 and 1985. Further analysis of the data also showed that the actual number of crashes for which a driver-related factor was identified increased by only 17 percent between 1984 and 1986, whereas the number of crashes for which factors other than driver, vehicle, and environment were identified increased by about 47 percent. This shows that the rate of increase in the number of driver-related crashes is significantly lower than that for all other crashes. The identification of countermeasures that will significantly reduce other crashes will therefore help in the reduction of total crashes.

The distribution of accidents by the major associated factors from 1984 through 1986 is similar for the different categories of trucks. Driver-related factors, for example, are the predominant associated factors in that they account for 75, 75, and 74 percent of crashes for straight trucks, tractor trailers, and twin trailers, respectively (Appendix, Table A-5).

Since it is essential to develop countermeasures that will not only reduce large-truck crashes but will also significantly reduce fatal large-truck crashes, an analysis of the fatal large-truck crashes was also carried out to determine the predominant associated factors. Driver-related factors have been the major cause of all large-truck fatal accidents from 1984 through 1986, accounting for 86 to 92 percent of such accidents (Appendix, Table A-6). Driver-related factors were also recorded as being associated with 84 percent of the fatal crashes for single-unit trucks, 92 percent for tractor trailers, and 100 percent for twin trailers (Appendix, Table A-7). It should be noted however that only one fatal accident was reported involving a twin trailer from 1984 through 1986. Of the specific driver factors involved, driver error has the highest frequency, followed by speeding, drinking, and driver handicap (which includes fatigue and sleeping) (Appendix, Tables A-8 and A-9). A countermeasure that will significantly reduce large-truck driver error will significantly reduce fatal crashes. It is, however, not easy to identify the specific errors made by drivers. However, since highway geometry was not considered as a factor in fatal crashes, it was necessary to investigate the correlation between driver error and road alignment. It is likely that driver error is related to the alignment characteristics of the road in that a driver is more likely to make a maneuvering error on a curvy section than on a straight and level section of road. The influence of road alignment on fatal crashes was therefore investigated. It should be noted, however, that for this part of the analysis, data on alignment characteristics were obtained from the police accident report forms. In the development of the models relating geometric and accident characteristics described in Volume II, actual field data were collected.

Thirty-two to 48 percent of all fatal truck accidents at different alignments occur on straight and level sections of road (Appendix, Table A-10). In 1984, for example, about 65 percent of all fatal truck accidents occurred on sections of roads on which there was either a horizontal curve or a vertical curve and/or a grade (Appendix, Table A-10). Although twin trailer data indicate that all fatal accidents occurred on straight and level road sections, this is based on a total of one accident and is therefore not an accurate representation of the effect of geometry. Both straight trucks and tractor trailers experienced 59 to 66 percent of all fatal accidents on road sections with horizontal and/or vertical curves (Appendix, Table A-11).

The alignment distribution for the locations of 1984 fatal large-truck crashes for which driver error was identified and for the different categories of trucks separately shows that nearly all of these crashes occurred at curves, which again suggests that highway alignment may be of importance (Appendix, Tables A-12 and A-13).

The results therefore indicate that alignment may influence fatal large-truck crashes and that an identification of the alignment characteristics that are predominant in fatal large-truck crashes would be useful in determining engineering countermeasures that would be effective in reducing these crashes.

Number of Vehicles Involved in Crashes

Table A-14 (Appendix) gives the distribution of total 1984 crashes on all highways by the number of vehicles involved in each crash for both large trucks and other vehicles. It is important to note that although about 35 percent of other vehicle crashes involved one vehicle, only about 22 percent of large-truck crashes involved one vehicle. The highest percentage (69) of large-truck crashes involved two vehicles, whereas about 59 percent of other vehicle crashes involved two vehicles. Also, 9 percent of large-truck crashes involved three or more vehicles, whereas about 6 percent of other vehicle crashes involved three or more vehicles. The results indicate that it is much more likely for a large-truck crash to involve more than other types of crashes.

Further analysis of the data for the interstate and primary highways (Appendix, Table A-15) indicates that, when a large truck is involved in a two-vehicle crash, there is a 94 percent chance that the other vehicle involved is not a truck. One may be tempted to conclude that this over-representation should be expected because of the large percentage of other vehicles in the vehicle fleet on the highways.

In order to determine whether this phenomenon is the result of the over-representation of other vehicles in the vehicle fleet, the binomial theorem was used to compare the actual and expected proportions of other vehicle/other vehicle, large-truck/other vehicle, and large-truck/large-truck crashes based on the exposure represented by VMT of each vehicle type. Only two-vehicle crashes were considered since they were the largest percentage of the multivehicle crashes.

Let the proportion of other vehicle exposure = p and the proportion of large-truck exposure = q. Then the expected proportions of crashes are:

- other vehicle/other vehicle crashes = p^2
- large-truck/large-truck crashes = q^2
- large-truck/other vehicle = $1 - (p^2 + q^2) = 2pq$ (since $p + q = 1$).

The 1984 annual VMT on Virginia interstate and primary highways was

- other vehicle = 21.73×10^9
- large trucks = 2.63×10^9.

Thus:

$$p = \frac{21.73}{24.36} = 0.89$$

$$q = \frac{2.63}{24.36} = 0.11.$$

The number of two-vehicle crashes in 1984 on the interstate and primary highways for which both vehicles were identified was:

- other vehicle/other vehicle = 19,951
- large-truck/large-truck = 333
- large-truck/other vehicle = 5,015.

The results show that although the proportion of other vehicle/other vehicle crashes is slightly lower than expected, the proportion for large-truck/large-truck and large-truck/other vehicle are slightly higher (Appendix, Table A-16).

Number of Vehicles Involved in Fatal Crashes

Although the highest percentage of other vehicle fatal crashes involved only one vehicle, the highest percentage (68.0) of large-truck fatal crashes involved two vehicles (Appendix, Table A-17). Also, about 15 percent of the fatal large-truck crashes involved three or more vehicles, whereas only about 3 percent of the other vehicle fatal crashes involved three or more vehicles (Appendix, Table A-17). The percentage of single-vehicle crashes that are fatal is 1.6 for large trucks and 1.3 for other vehicles, but the percentage of multivehicle fatal crashes involving large trucks is 13.3, whereas that for other vehicles is only 0.3 (Appendix, Table A-18). This clearly indicates that although the frequency of fatal crashes when a single vehicle is involved is about the same for large trucks and other vehicles, it is about 40 times more likely that a fatality will occur when a large truck is involved in a multivehicle crash than when only other vehicles are involved.

Under the assumption that all crashes are random events, the binomial theorem was used to compare actual and expected fatal crashes involving two vehicles on the interstate and primary systems. This analysis was based on VMT for large trucks and other vehicles. The number of two-vehicle fatal crashes in 1984 on the interstate and primary highways for which both vehicles were identified is:

- other vehicle/other vehicle = 196
- large-truck/large-truck = 2
- large-truck/other vehicle = 113.

Other vehicle/other vehicle and large-truck/large-truck fatal crashes are underrepresented, whereas large-truck/other vehicle fatal crashes are significantly overrepresented (by as much as 85 percent) (Appendix, Table 19). These results suggest that countermeasures that will reduce the number of multivehicle crashes involving large trucks will have a significant impact on fatal crashes involving large trucks. Since the data show that most multivehicle crashes involving large trucks also involve other vehicles, the separation of large trucks from other vehicles on the highway may be an effective way of reducing multivehicle crashes involving large trucks. It must be emphasized, however, that such a countermeasure should not be implemented until its full impact has been identified and a safe means of separating the large trucks from other vehicles has been determined.

Effect of the Type of Highway Facility on the Severity of Accidents Involving Large Trucks

For the purpose of this analysis, data for the years 1984 through 1986 were considered. Three types of highway categories were considered: two-way undivided facilities, divided facilities with partial or no control of access, and divided facilities with full control of access. The first and second categories consist entirely of the primary system, and the third category consists of the interstate system and some primary system mileage in Virginia. A comparison of the severity of all accidents involving large trucks on the different types of facilities and by the types of truck gave the following results. Injury accidents accounted for 36 to 38 percent and property damage accidents accounted for 59 to 63 percent of all accidents involving large trucks on all types of facilities (Appendix, Table A-20). However, statistics for fatal accidents indicate some difference between the types of facilities. For facilities with full control of access, fatal accidents account for 1.4 percent; for divided facilities with partial or no control of access, 2.0 percent; and for two-way undivided facilities, 3.0 percent. Further analysis on accident severity was carried out by considering all accidents involving large trucks as belonging to one of three categories: (1) large-truck/other vehicle accidents, (2) single vehicle/large-truck accidents, or (3) large-truck/large-truck accidents.

Large-Truck/Other Vehicle Accidents

A closer examination of the accidents on each type of facility and the accident type indicates that a majority of fatal and injury accidents involving large trucks consist of accidents involving large trucks and other vehicles on all of the facilities (Appendix, Tables A-21 through A-23). The risk of injury or property damage in any accident involving large trucks and other vehicles seems to be approximately the same for all truck types on any facility (Appendix, Tables A-24 through A-26). However, the risk of fatality seems to be worst on the two-way undivided facilities for tractor semi-trailers (Appendix, Table A-24). When the truck is a straight truck, this risk is almost equal for all divided facilities but is twice as much on undivided facilities. When the truck is a tractor semi-trailer, the risk is lowered by about 80 percent as we go from undivided two-way facilities to facilities with full control of access (Appendix, Tables A-24 through A-26). No such conclusions regarding the fatality risk can be arrived at for the twin trailers since there was only one fatal accident involving twin trailers during this period.

Single Vehicle/Large-Truck Accidents

A comparison of the percentages of fatal single vehicle/large-truck accidents on different types of highways indicate that tractor semi-trailers have the worst record on all facilities (Appendix, Tables A-27 through A-29). A somewhat surprising result is that the highest percentage of such involvements occurred on divided facilities with partial or no control of access (Appendix, Table A-28). This may be attributed to the fact that a significant amount of large-truck mileage in Virginia takes place on such facilities and at higher operating speeds than on the two-way undivided facilities. Also, these roads are not as safe as interstate facilities and are more susceptible to run-off-the-road accidents.

Large-Truck/Large-Truck Accidents

An examination of all large-truck/large-truck accidents indicate that accidents involving two tractor trailers tend to be more severe than accidents involving other combinations of large trucks on two-way undivided or divided highways with no or partial control facilities (Appendix, Tables A-30 through A-32). It should be noted, however, that only a small number of accidents involving a double trailer and a tractor trailer were recorded and no accident involving two double trailers was recorded.

Types of Collision in Accidents Involving Large Trucks

The distribution of various combinations of two-vehicle accidents involving large trucks by the type of collision shown in Table A-33 in the Appendix indicates that, in all accidents involving two large trucks, the leading type of collision is rear-end followed by same-direction-sideswipe. For accidents involving a large truck and any other vehicle, the leading type of collision is same-direction-sideswipe except in the case of straight trucks, for which it is rear-end collisions.

The high incidence of rear-end collisions between large trucks may be attributed to an inadequacy in the braking capacity of large trucks. However, when both vehicles involved are trucks, the braking distances could be expected to be similar, resulting in lower numbers of rear-end accidents between large trucks. The fact that crash data indicate otherwise may be because of large disparities in braking capacities or braking demand among trucks. Such disparities could arise because of differences in truck configuration and gross vehicle weight.

In collisions between large trucks and other vehicles, the high incidence of same-direction-sideswipe collisions indicate that a large percentage of such accidents take place in vehicle maneuvers that involve lane changing, passing, or lane straddling.

The Effect of Road Geometry on Accidents Involving Large Trucks

It is common knowledge that the demands on any vehicle or driver are greater on roadway sections that have curves or grades. This demand on the driving task is known to be greater in the case of large trucks because of their weight and size. In order to investigate the effect of road geometry on accidents, we compared the incidence of accidents on two types of roadway sections: (1) curves and grades and (2) all other geometries.

Single Vehicle/Large-Truck Accidents

Tractor trailers seem to have the highest probability of involvement in single vehicle/large-truck accidents (Appendix, Table A-34). Although twin trailers show a 1 percent involvement in such accidents, this is based on a small number of accidents involving twin trailers; hence, this may not indicate the true risk for twin trailers.

All types of trucks experience more single-vehicle accidents on curves and grades than at all other locations (Appendix, Table A-34). Twin trailers seem to experience the highest risk on such roadway sections followed by tractor trailers and straight trucks. However, the proportion of fatal accidents is lowest for twin trailers and highest for tractor trailers.

Large-Truck/Other Vehicle Accidents

The results for large-truck/other vehicle accidents indicate that straight trucks are involved in most of these accidents (53.2 percent) followed by tractor trailers (46.5 percent) and twin trailers (0.3 percent) (Appendix, Table A-35). Twin trailers seem to have the highest proportion (51.0 percent) of accidents with other vehicles on roadway sections with curves or grades. All of the fatal accidents involving twin trailers occurred on straight roadway sections. However, this is based on a single accident. Tractor trailer accidents have the next highest risk, with 42 percent of all such accidents occurring on curves and grades. The proportion of fatal accidents on curves is 1.5 times that on all other road alignments. Straight trucks are least involved on curve/grade road sections, with 36.0 percent of all accidents. However, their proportion of fatal accidents on such road sections is twice what it is on all other road alignments.

Pre- and Post-1982 Large-Truck Travel and Accidents

This section describes the results of an investigation carried out to assess changes in pre- and post-1982 large-truck travel and accident involvement in Virginia. These periods are 1980 through 1982 and 1983 through 1985. This division was selected because the larger and longer vehicles allowed by the STAA of 1982 first appeared on Virginia highways in 1983. First, a macroview of the performance of the interstate and primary highway system in Virginia was obtained by comparing travel miles and accident rates for the period 1980 through 1985. The performance of three different highway and traffic environments using the selected routes listed earlier was obtained through a comparison of their respective accident rates before and after 1982. The three highway environments—interstates, STAA-designated primaries, and undesignated primaries—were represented by the routes that carry the highest truck mileage within each category.

STAA of 1982

STAA of 1982 provided for the expansion of the federal role in the regulation of the size and weight of large trucks. STAA required states to raise any limits that were more restrictive than federal ones, and federal limits were extended to roads other than interstates.

Table A-1 (Appendix) shows the size and weight provisions of the STAA compared with those stipulated in the Federal-Aid Highway Act of 1956. The maximum allowable axle load is 20,000 lb for single axles and 34,000 lb for tandem axles. The overall gross weight of trucks with five or more axles is 80,000 lb. All states are prohibited from imposing lower weight limits than those shown in Table A-1. In addition to the increase in axle loads, no state can limit the length of the semi-trailer in a tractor trailer combination to below 48 ft or the length of each trailer in a twin trailer combination to less than 28 ft. The act also prohibits all states from limiting overall lengths of tractor semi-trailers or combinations with two trailers and requires all states to raise the limit on truck width to 102 in. These provisions apply to all interstate highways and other roads in the federal and primary systems that are so designated by the Secretary of Transportation. These roads are now commonly referred to as "designated and access highways."

Large-Truck VMT

An increase in the number of tractor trailers and twin trailers has been observed on the nation's highways since 1983. A similar increase has also been observed on Virginia highways, where the annual daily VMT for tractor trailers on interstate, arterial, and primary routes increased by about 27 percent between 1983 and 1986, whereas the increase for passenger cars during the same period was only about 23 percent. During the same period, the annual VMT for all large trucks increased by about 26 percent on similar roads (Appendix, Table A-36). One reason commonly given for the support of some aspects of the STAA is that the increased use of twin trailer trucks will not have a significant impact on overall highway safety since their increased capacity may cause the overall truck travel to decline. Analysis of the data in Virginia showed, however, that annual miles of total truck travel has continued to increase at a very high rate despite increasing twin trailer travel. Tractor-trailer VMT significantly increased in 1983 and continued to increase through 1986 (Appendix, Table A-36). Overall, large-truck travel also significantly increased in 1983 and has continued to increase since. Two- and three-axle trucks also showed similar results. These results do not indicate that large-truck travel decreased as anticipated. In fact, the results indicate that not only is the travel of tractor trailers increasing in the state, the travel of other large trucks is also increasing significantly. It should be noted, however, that other factors, such as the growth in the nation's economy and deregulation of the trucking industry, might have contributed to the significant increase in large-truck VMT.

Large-Truck Accident Rates

An analysis of the accident rates for different types of vehicles will indicate the extent to which STAA vehicles are involved in accidents and thereby the effect of the STAA on highway safety in Virginia. However, because of the way accident data have been recorded in Virginia, data on lengths and widths of large trucks involved in accidents are unavailable for the period before 1987. Also, it is not possible to determine the VMT of twin trailers as distinct from that for tractor semi-trailers since up to recently the data for both types of vehicles were recorded as "tractor trailers." Some sections of the analysis presented here, therefore, cover both types of vehicle under the category tractor trailer. Also, because of the lack of adequate data, the direct effect of STAA vehicles on overall large-truck accident rates cannot be evaluated at this time.

- *Total accident rates on interstate and primary routes*: A comparison of the accident rates on interstate and state primary highways for different categories of vehicles was carried out to determine whether a significant increase in these rates occurred for tractor trailers after 1982. These accident rates are based on the total number of accidents per 100 million VMT. A comparison between the average accident rates for the pre- and post-1982 periods indicate that the tractor trailer total accident rates have decreased by 0.17 percent, whereas those for all vehicles have decreased by 2.80 percent (Appendix, Table A-37).
- *Fatal accidents*: The average fatal accident rates for the pre- and post-1982 periods indicate that there has been a decrease of 10.75 percent for other vehicles, whereas for tractor trailers there has been an increase of 26.75 percent (Appendix, Table A-38). On the interstates, tractor trailer fatal accident rates increased by almost 34 percent, whereas the rate for other vehicles increased by only 5.06 percent (Appendix, Table A-39). In the case of state primary highways, tractor trailer fatal accident rates have increased by 27.3 percent, whereas those for all vehicles have decreased by 13.33 percent (Appendix, Table A-40).
- *Comparison of pre- and post-1982 accident involvement rates*: In the following analysis, the hypothesis that the accident involvement rates for the pre- and post-1982 periods are the same was tested. These accident involvement rates are based only on injury and fatal accidents. The reason for omitting property damage accidents is the possible bias introduced into the data when such accidents are included without making adjustments for the effect of increasing property damage estimates and changes in property damage reporting thresholds.

  The involvement rates used in this analysis are the annual (injury + fatal) involvement total per 100 million VMT. Therefore, for the pre- and post-1982 periods, equal samples of 21 observations from the selected seven routes were obtained. Each observation consisted of an accident involvement rate for tractor trailers and one for all other vehicles. These involvement rates are shown in Tables A-41, A-42, and A-43 in the Appendix.

The results of ANOVA for the pre- and post-1982 periods carried out for three categories of highways and two categories of accidents are shown in Table A-44 in the Appendix. In the usual testing procedure, the null hypothesis is tested at a suitable level of significance in order to reject or accept it. Following this procedure, for the 5 percent significance level, the null hypothesis cannot be rejected for all the highway and vehicle combinations since the *F* values are all less than the critical value of 4.08. However, in order to investigate the dissimilarity between involvement rates, Type I error probabilities for rejecting the null hypothesis were obtained from the corresponding *F* values and are shown in Table A-45 in the Appendix. For example, if a Type I error probability for rejecting the null hypothesis is very high, there is hardly any difference between the pre- and post-1982 involvement rates. However, if this probability is low, it indicates some difference between the pre- and post-1982 involvement rates, although this difference may not be large enough to be significant at the 5 percent confidence level. Therefore, these error probabilities serve as an indicator of the dissimilarity between the pre- and post-1982 involvement rates compared in the hypothesis. Although these probability values are indicative of the significance of the dissimilarity between the pre- and post-1982 accident involvement rates, they do not directly indicate whether the difference is an increase or a decrease (Appendix, Table A-45). These indications are, however, given in Table A-46.

In the case of tractor trailers, the involvement rates increased the most on undesignated primaries followed by designated primaries and interstates (Appendix, Table A-46). The probability value of 0.256 for non-STAA primaries in Table A-45 indicates the lowest probability of error for rejecting the null hypothesis that pre- and post-1982 truck involvement rates are the same. Similarly, the highest probability of 0.824 is indicated for interstates, implying the least change in involvement rates. In the case of accident involvement rates of other vehicles, interstates have experienced a decrease, whereas the STAA primary routes and non-STAA routes have experienced a slight increase. The involvement rates of other vehicles for non-STAA primary routes show the least change, which is reflected by a probability value of 0.843.

- *Fatal involvement ratio*: In order to determine whether there had been any significant change in accident severity, the fatal involvement ratio of tractor trailers and all other vehicles was analyzed. The fatal involvement ratio is defined as the percentage of fatal involvements in all injury and fatal involvements.

Tables A-47, A-48, and A-49 in the Appendix show the fatal involvement ratios for the selected routes. The fatal involvement ratio is considered to be a measure of the involvement in severe crashes. The analysis was carried out by comparing the pre- and post-1982 ratios for tractor trailers and other vehicles. The results of ANOVA on these ratios are presented in

Table A-50 in the Appendix, with the corresponding probability values in Table A-51. The mean involvement ratios are given in Table A-52.

These results indicate that the interstate routes have experienced the least change in fatality involvement ratios, which is also a decrease for tractor trailers and a slight increase for other vehicles. On both STAA and non-STAA primary routes, there has been a significant drop in fatal involvement ratios for other vehicles, which is indicated by the low probability values supporting the null hypothesis. However, on these same routes, tractor trailers have experienced an increase in fatal involvement ratios with the highest such rates occurring on non-STAA routes.

Comparison of Tractor Trailer and Other Vehicle Involvement Rates for Injury and Fatal Accidents

Trends in the involvement rates (number of involvements per 100 million VMT) for the two categories of vehicles considered were examined. Since these rates are based on the annual VMT, which is a measure of exposure, a comparison of rates between the vehicle categories will yield an indication of the relative accident risk.

The selected routes for each category of highway type represent the bulk of the highway miles bearing large-truck traffic. Therefore, by this comparison, an effort is made to identify any significant differences between tractor trailers and other vehicles particular to a highway environment with a relatively high presence of truck traffic.

The involvement rates for tractor trailers on interstates were relatively unchanged from 1981 through 1983, with an increase in 1984 (Appendix, Table A-53). Rates for tractor trailers on all highway categories indicate a decrease in 1985. The involvement rates for tractor trailers on primary routes indicate a decreasing trend from 1980 through 1982, which is a low year for each of the highway systems analyzed (Appendix, Table A-53). The involvement rates for other vehicles also indicate a similar decrease from 1980 through 1982 and an increase from 1983 through 1985 (Appendix, Table A-53). In light of this, it is difficult to attribute the increase in tractor trailer involvement rates since 1982 to STAA per se.

The relative accident involvement of tractor trailers in comparison to other vehicles was estimated by the ratio of tractor trailer involvement rates to other vehicle involvement rates. Considering the change in relative involvement between pre- and post-1982 periods, an increase across all categories of highways was observed (Appendix, Table A-54). STAA primary routes have experienced the lowest increase (4.38 percent), non-STAA primary routes have experienced the highest (11.43 percent), and interstate routes have experienced an increase of 10.24 percent (Appendix, Table 54).

From these results, it seems that the relative accident involvement risk for tractor trailers has increased the least on STAA-primary routes and the most on non-STAA primary routes.

Fault Tree Analysis of Accidents

The basic hypothesis postulated in this analysis is that by describing the overall large-vehicle accident phenomenon within the framework of the branched events chain theory, valuable insights could be gained.

A fault tree analysis based on this theory is therefore used to determine the likelihood of failures and also to determine preventive measures.

The fault tree analysis provides a method of examination of an event that is an undesired outcome of some process. This event is referred to as the top event, as it is located at the top of the fault tree. All the paths of the fault tree describe the sequences and relationships between basic events and the top event. These paths are defined such that all possible events or actions leading to the occurrence of the top event are sufficiently described through them. This definition increases the level of understanding of the system being analyzed. In the particular context of an accident involving a large vehicle, this understanding includes

- how accidents occur
- the functional relationships between failures
- the degree of protection the vehicle design provides
- an insight into the basic design concepts or design requirements from a system safety perspective.

The increased understanding about the system allows

- the identification of potential failures
- the quantificaton of such failures
- identification of cause and effect relationships
- informed judgment about how, why, and with what frequency systems fail.

Fault Tree Construction of an Accident

The objective of fault tree construction is to develop a model that portrays the circumstances under which an accident takes place. Therefore, before this can proceed, a thorough understanding of the system in which an accident is an undesired event is essential. A system description together with the assumptions made during construction of the fault tree is provided to make the analysis understandable.

Event Descriptions

A fault tree is a model that graphically and logically represents the various combinations of possible events, both fault and normal, occurring in a system that lead to the top event. The term *event* denotes a dynamic change of state that occurs to any of the elements of the system. For this study, these system elements consist of the driver, the vehicle, and environmental factors.

Event Symbols

The symbols used in fault tree analysis are depicted in Figure 1. They represent events and logic gates that describe the possible outcomes of events related to the system. A fault event is an abnormal system state, and a normal event is an event that is expected to occur. The circle defines a basic inherent failure of a system element when operated within its design specifications or under normally expected conditions of operations. It is therefore referred to as a primary failure. The rectangle defines an event that is the output of a logic gate and is dependent on the type of logic gate and the inputs to the logic gate. The diamond represents a failure other than a primary failure that is purposely not developed further.

Logic Gates

There are two kinds of logic gates for fault tree construction: the AND and the OR gates (shown in Figure 1). The AND gate describes the logical operation that requires the coexistence of all input events to produce the output event. The OR gate describes a situation in which the output event will exist if one or more of the input events exist.

Construction Process

A fault tree is so structured that the sequence of events that lead to the accident or the undesired event is shown below the top event and is logically related to the undesired event by AND or OR gates. The input events to each logic gate that are also outputs of other logic gates at a lower level are shown as rectangles. These events are developed further until the sequence of events leads to basic events that in reality are basic causes of interest. In this analysis, the top event is any single vehicle/truck-involved accident.

All single-vehicle truck accidents are attributed to one of the three main system failures mentioned previously. The occurrence of such an accident is attributed primarily to the main failure, with secondary failures arising out of interactions with the other factors.

Figure 2 shows a schematic of the partial fault tree of a single-vehicle truck accident. The top event, or the accident, could occur as a result of any one of the three causal factors linked through an OR gate to the top event. The fault tree analysis is performed on each partial tree. The resulting minimum cut and minimum path sets for the partial trees are also valid for the complete fault tree.

Adaptation of the Problem for Application of Fault Tree Analysis

Before fault tree analysis could be applied to large-vehicle accidents, it was necessary to define the problem in a manner suitable for this type of analysis. The purpose of this effort was to describe the problem in a way that could be effectively handled through fault tree analysis and that at the same time yielded effective results.

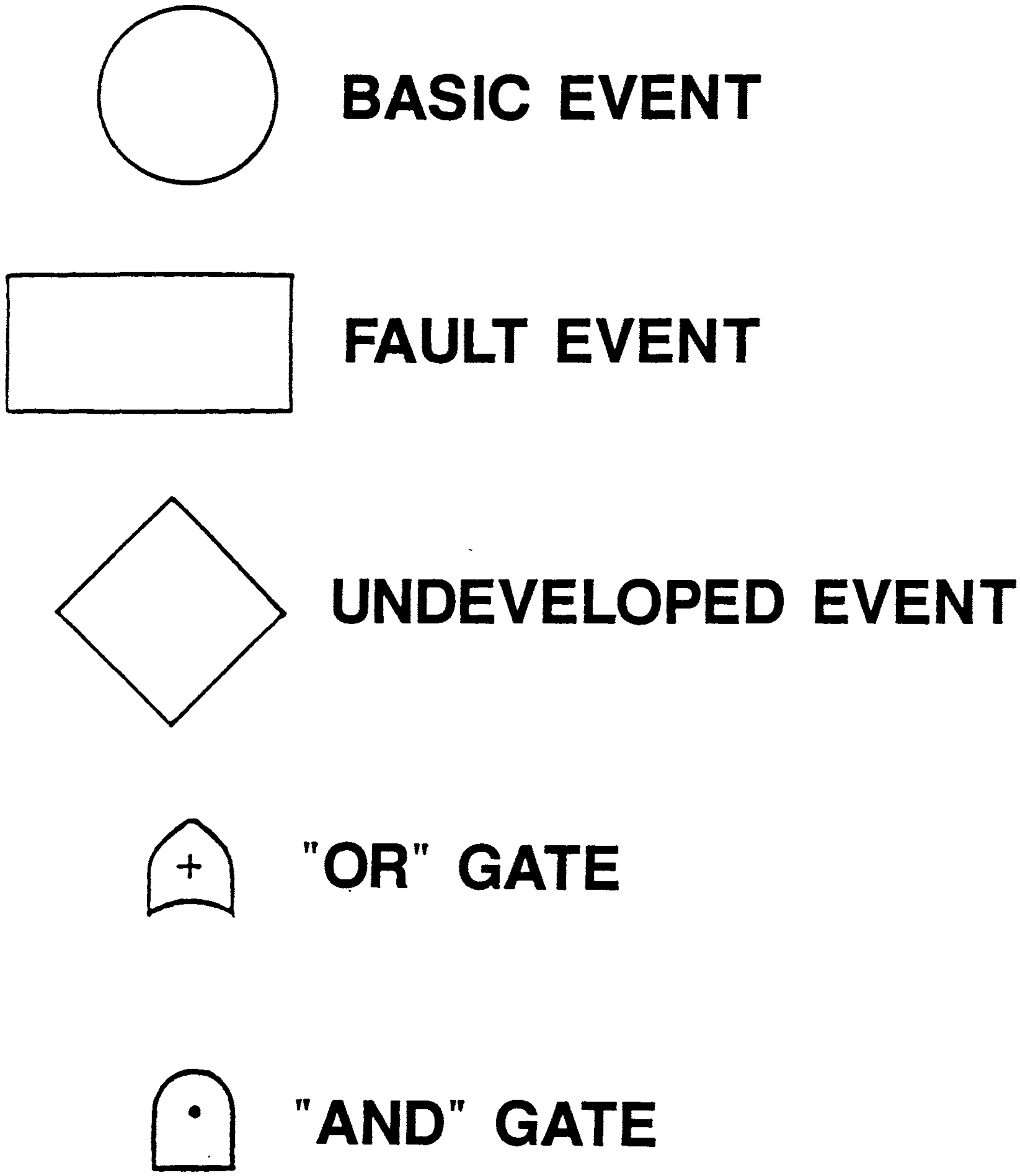

Figure 1. Symbols used in fault tree analysis.

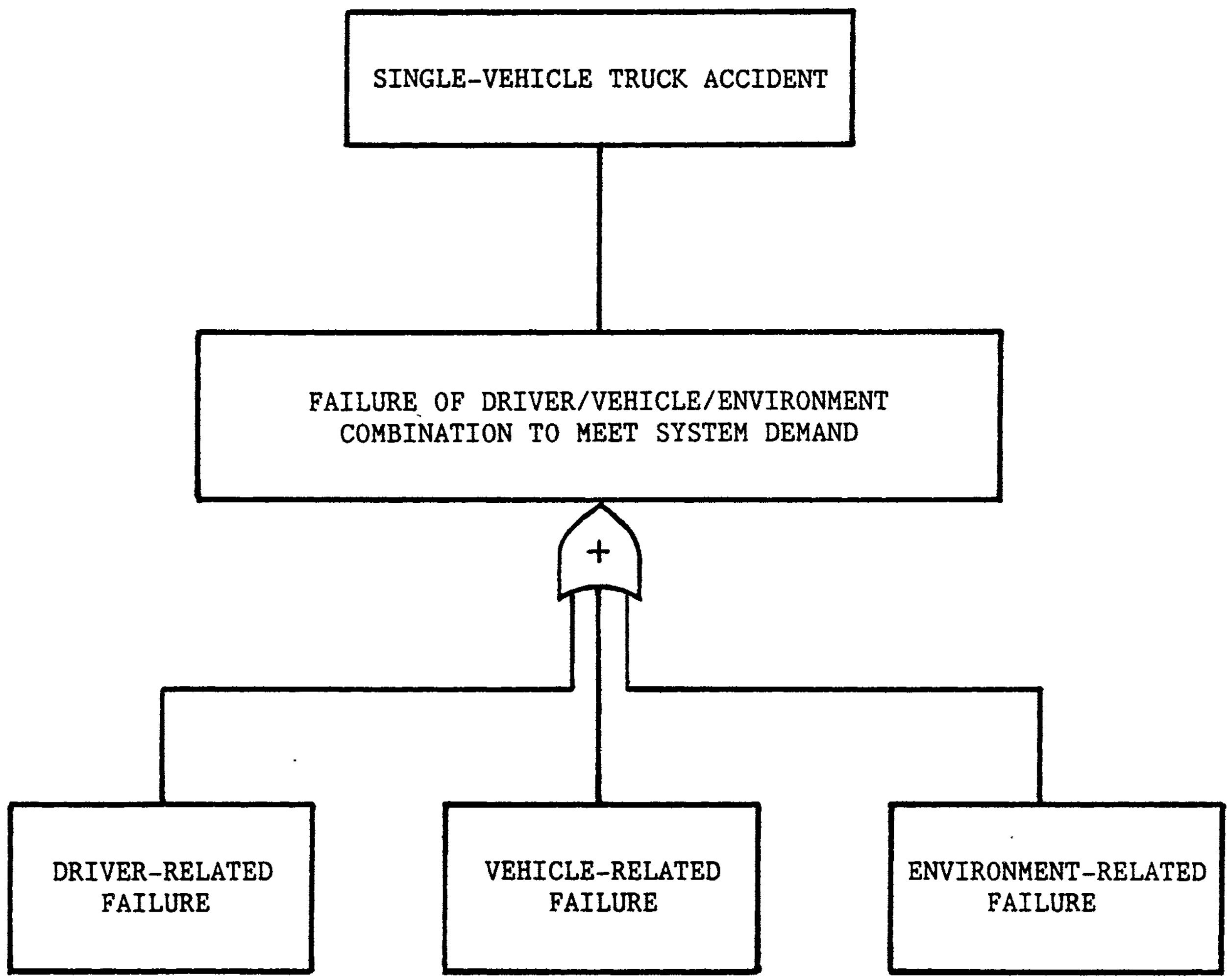

Figure 2. The partial fault tree of a single-vehicle accident.

All large-vehicle accidents can be categorized into three types depending on the types of vehicle involved: large truck/large truck, large truck/other vehicle, and single vehicle/large truck.

In an analysis where a detailed examination of the causal mechanism of large-truck accidents is carried out, the significance of information obtainable from multi-vehicle accidents is limited for many reasons. Chief among these is that culpability or causality in such accidents cannot be determined with any significant degree of reliability from available data. Even if such data were available, the contribution of information gained from such data would only tend to obscure the more reliable information available from single-vehicle accidents.

The adaptation of the large-vehicle accident problem for fault tree analysis in this study is based on the concept of induced exposure. This concept was introduced by Thorpe[45] and has been developed further by Haight[46] and Koornstra.[47] The basic idea of induced exposure as formulated by Thorpe is that the proportion of a vehicle category, which in this case is large trucks, responsible in two-vehicle collisions is directly related to the proportion of that category involved in single-vehicle accidents. The validity of this concept has been proven in studies such as that by Joksch[48] in which close agreement was observed between single car accidents involving female drivers and the percentage of female drivers observed on a segment of roadway. Based on this relationship between the single-vehicle accident occurrence and multi-vehicle accident occurrence, it is likely that most of the accident-related information obtainable from single-vehicle accidents is also relevant to multivehicle accidents. The fault tree analysis builds upon this premise and describes two-vehicle accidents as consisting basically of mechanisms that adequately describe single-vehicle accidents.

The main factors contributing to accident causation have been identified as driver-, vehicle-, and environment-related. Based on observations by the recording officers at the accident site, each accident is attributed to one of these major factors. However, in almost all accidents there are secondary effects resulting from interactions between the major factors. In the following fault tree analysis, each of these factors is investigated together with the interaction effects.

Estimation of the Probabilities Associated with Events

The probabilities associated with the events in this analysis were obtained from 2,760 single-vehicle/large-truck accidents contained in the accident data base. The following key fields were used to estimate the number of occurrences of each event through a sequential screening process.

- major factor
- driver condition
- driver drunk factor
- driver vision factor
- vehicle defect

- vehicle skid
- weather
- surface condition
- roadway defects
- alignment.

For example, the major factor code identifies into which of the partial fault trees a particular accident belongs. Let us suppose that an accident was attributed to a driver-related failure. A further examination of the driver condition, driver drunk factor, and driver vision factor revealed whether the driver was physically impaired at the time of the accident. If data suggested that the driver was impaired, vehicle and environment-related fields were examined for interaction effects, such as poor visibility and vision impairment. When all the accidents had been sufficiently identified with respect to their fault events, the probabilities were calculated for the branch events at each OR gate. No probabilities were estimated for events at AND gates since both events must occur with certainty for a fault to proceed to the top event through such a gate.

Assumptions and Limitations

In carrying out the fault tree analysis, the following assumptions were made:

- All basic events were assumed to be statistically independent.
- The expected driver performance refers to the expected minimums in driver characteristics (both from the legal and the system design point of view) for the normal driving task. Some examples of these characteristics are driving skill level, reaction time, and driver vision.

Evaluation of the Fault Trees

The evaluation of a fault tree can be qualitative and/or quantitative. The objective of the qualitative evaluation is to determine the shortest failure paths or the minimum cut sets. The quantitative evaluation is the probability evaluation for various outcomes. In this analysis, both quantitative and qualitative evaluations of the fault tree were carried out.

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 determined when a cut set cannot be reduced further and the occurrence of the top event is still ensured. The minimum cut set algorithm described by Fussel and Vesely[49] determines the weakest links in the system. The algorithm is based on the fact that an AND gate always increases the size of a cut set and an OR gate always increases the number of cut sets. Minimum cut sets can also be described as the shortest paths along the fault tree that lead to the top event.

Dual Fault Trees

Similar to the way information is obtainable from minimum cut sets with regard to safety and the occurrence of the top event, it is also possible to gain information on reliability or the nonoccurrence of the top event through dual fault trees. In a dual fault tree, all fault events in the fault tree are replaced by their dual events or events with an opposite outcome. For example, the dual of a driver-related failure is the nonoccurrence of such a failure. Also, the AND gates are replaced by OR gates and the OR gates by AND gates. The top event is also changed to its dual, which is equivalent to the nonoccurrence of the original fault event. The minimum cut sets, which are determined by using the minimum cut algorithm on the resulting dual fault tree, are the minimum path sets for the original fault tree. These minimum path sets identify events whose nonoccurrence will ensure the nonoccurrence of the top event. Therefore, these paths identify the most effective preventive measures.

Probability Evaluation

Calculation of the probability of the top event is a major goal of the fault tree analysis. Utilizing the Boolean representation used for coherent structure by Birnbaum, Esary, and Saunders,[50] the probabilities are calculated as follows:

Ψ = 1 if basic event i occurs

0 otherwise

Let $\underline{Y} = (Y_1, Y, \ldots, Y_n)$ 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:

$$\coprod_{i=1}^{m} = 1 - \prod_{i=1}^{m}(1 - Y_i). \qquad (1)$$

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

$$\Psi(\overline{Y}) = \prod_{s=1}^{k} \prod_{i \in K_s} Y_i \qquad (2)$$

is the minimum cut representation for Ψ.

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

$$P\ [Top\ event] \ = \ \prod_{1 \leq s \leq k} \ \prod_{i \epsilon K_s} q_i \tag{3}$$

The minimum path representation for Ψ is

$$\Psi(\overline{Y}) \ = \ \prod_{r=1}^{p} \prod Y_i. \tag{4}$$

To calculate the probability of the top event, let

$$P[Y_i \ = \ 1] \ = \ E(Y_i) \ = \ q_i \tag{5}$$

then

$$P[Top\ event] \ = \ E\Psi(\underline{Y}). \tag{6}$$

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

For Min. Cut Sets

$$P[Top\ event] \ = \ \bigsqcup_{1 \leq s \leq k} \ \prod_{i \epsilon K_s} q_i \tag{7}$$

For Min. Path sets

$$P[Top\ event] \ = \ \prod_{1 \leq r \leq p} \ \bigsqcup_{i \epsilon P_r} q_i. \tag{8}$$

Fault Trees for Driver-Related Failure

Figure 3 shows the fault tree for driver-related failures and the corresponding probabilities at each level of the tree. A driver-related failure could occur when the driver condition, that is, his or her ability to perform the normal driving task, is either normal or impaired. This is the first OR gate of the tree. At the next level of the tree, the condition of the driver is examined. A normal driver could cause an accident if he or she makes an error in judgment and the resulting path of the vehicle, with or

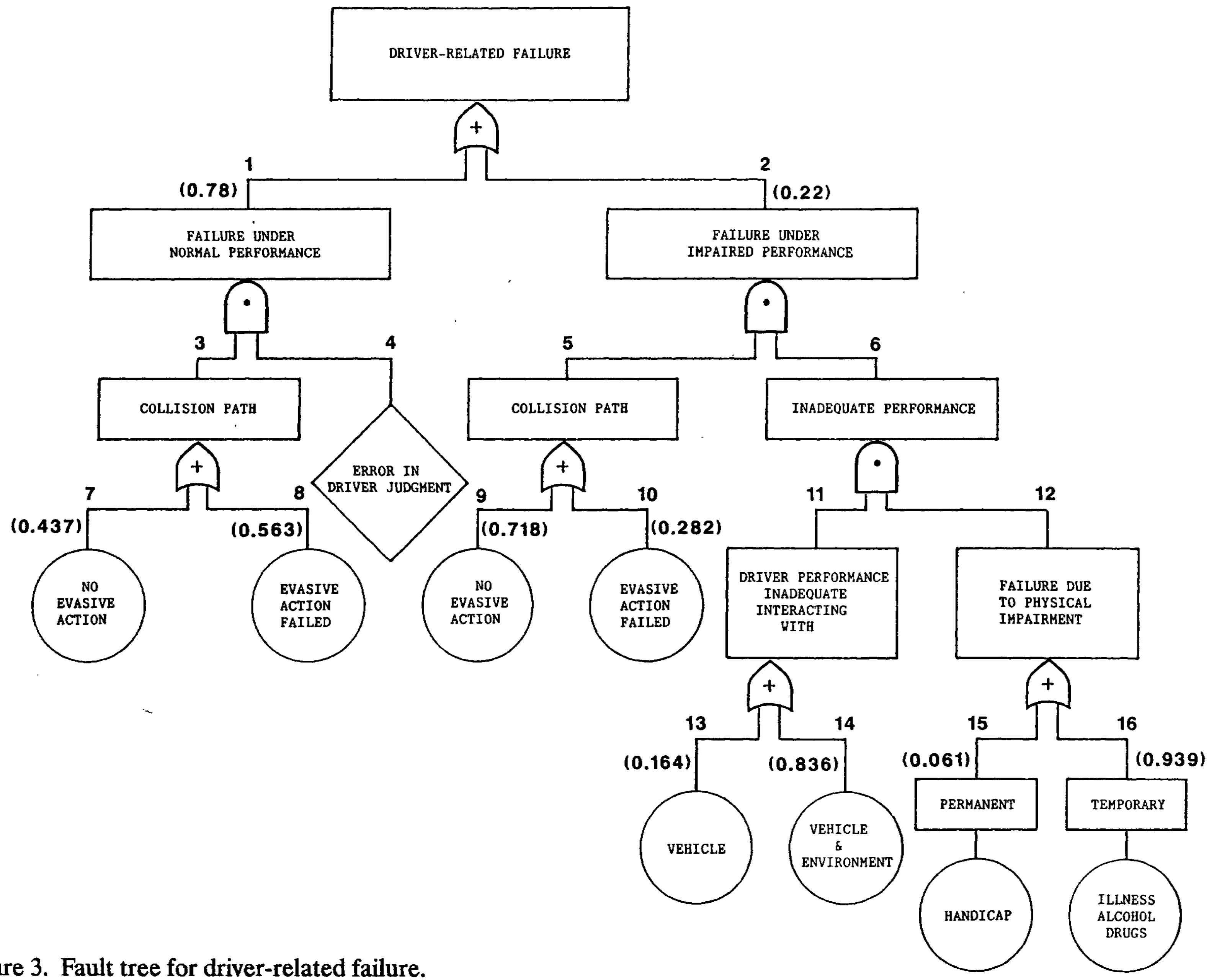

Figure 3. Fault tree for driver-related failure.

without evasive maneuvers, leads to a crash. On the other hand, the driver's performance could be impaired physically either temporarily or permanently, leading to an inadequacy in his or her interaction with the vehicle, the environment, or both. When such an inadequacy in the driver's performance arises during the driving task, it leads the vehicle into erratic maneuvers leading to a crash.

The presence or absence of an evasive maneuver was based on the presence or absence of skidding prior to the crash. The interaction with the vehicle and/or the environment by the impaired driver was determined by the weather, roadway surface, and vehicle condition at the time of the accident. The extent of physical impairment was determined from the driver's condition at the time of the accident. This impairment was further categorized as permanent or temporary. A permanent impairment is a physical handicap, whereas temporary impairment included fatigue, illness, and alcohol- or drug-related conditions.

The minimum cut sets determined are shown in Figure 4. The resulting minimum cut sets consist of ten combinations of events that can result in a driver-related accident. The minimum cut set with the highest probability (0.4400) defines a failure event when a normal driver makes an error in judgment and is unsuccessful in his or her evasive action. The next highest minimum cut set (probability 0.3400) also relates to driver error in judgment but with no evasive action. Of all the minimum cut sets involving an impaired driver, the set with the highest probability (0.1240) defines a fault event when a temporarily impaired driver cannot meet the system demand while interacting with vehicle and environment.

Figure 5 shows the dual fault tree for the driver-related failure. Unfortunately, the information required to determine the probabilities is not available. The reason for this is the complexity of obtaining such information in the field. A qualitative analysis is therefore carried out to determine preventive measures (shown in Table 1) based on the minimum path sets and the associated preventive measures.

Table 1

MINIMUM PATH SETS AND ASSOCIATED PREVENTIVE MEASURES
FOR DRIVER-RELATED FAILURES

Minimum Path Set*	Preventive Measure
7, 8, 9, 10 4, 9, 10	Training, driving skills, defensive driving, etc.
7, 8, 13, 14 4, 13, 14	Improved vehicle and roadway compatibility with driver through human factor design etc.
7, 8, 15, 16 4, 15, 16	Driver education and increased law enforcement

*Refers to event numbers in Figure 5.

Event Number*		Probability
	7, 4	0.3400
1 → 3, 4 →		
	8, 4	0.4400
2 → 5, 6 →	5, 11, 12	
↙	9, 13, 15	0.0015
	10, 13, 15	0.0007
5, 13, 15	9, 13, 16	0.0640
5, 13, 16	10, 13, 16	0.0095
5, 14, 15 →	9, 14, 15	0.0081
5, 14, 16	10, 14, 15	0.0031
	9, 14, 16	0.1240
	10, 14, 16	0.0486

*Refers to event number in Figure 3.

Figure 4. Minimum cut sets for driver-related failures.

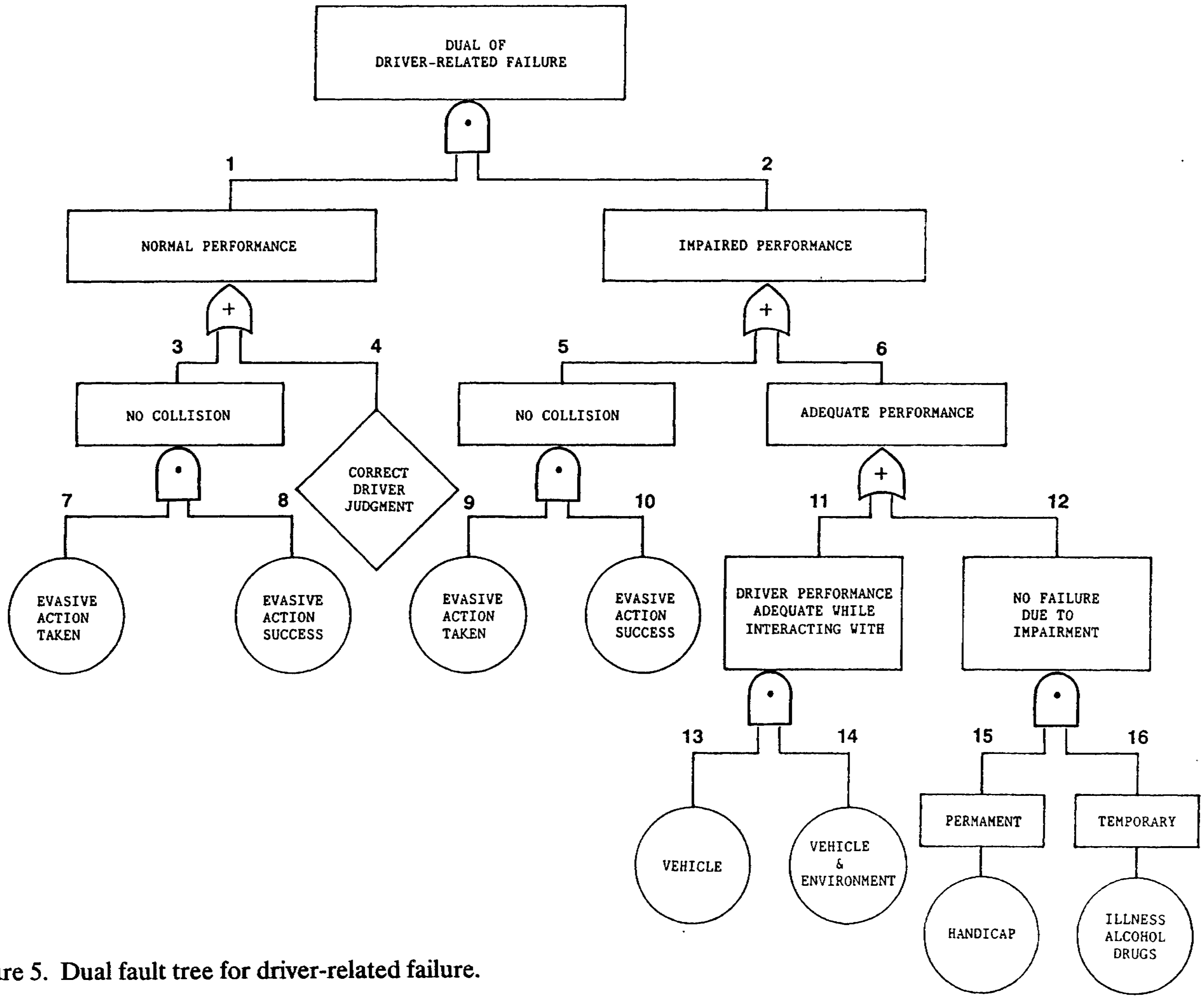

Figure 5. Dual fault tree for driver-related failure.

Vehicle-Related Failure

Figures 6, 7, and 8 show the fault tree, the minimum cut set, and the dual fault tree respectively for vehicle-related failure. The resulting minimum cut sets consist of ten combinations of events that can result in a vehicle-related accident. The minimum cut sets describing the failure events resulting from the failure of vehicle equipment accounts for nearly 73 percent of all vehicle-related failures. The next highest minimum cut set with a probability of 9.85 percent defines a fault event when the driver/vehicle interaction is inadequate to meet the system demand. The rest of the minimum cut sets have low associated probabilities.

The minimum path sets and associated preventive measures are shown in Table 2.

Table 2

MINIMUM PATH SETS AND ASSOCIATED PREVENTIVE MEASURES FOR VEHICLE-RELATED FAILURES

Minimum Path Set*	Preventive Measure
7, 8, 11, 12	Training, driving skills, defensive driving, etc.
7, 8, 13, 14, 15	Training, driving skills, and improved overall design of the vehicle for driver/environment interaction
9, 10, 11, 12	Improved reliability of the vehicle through better design, vehicle inspection programs, and driver education
9, 10, 13, 14, 15	Improved reliability of vehicle equipment together with overall design improvements

*Refers to event numbers in Figure 8.

Environment-Related Failure

A failure due to an environment-related factor would occur in one of three ways:

1. inadequate highway design leading to incompatibilities with vehicle, driver, or both
2. inadequate maintenance of the traveled way or the presence of foreign objects in the vehicle path
3. adverse weather conditions that increase the demand on driver/vehicle performance requirements.

At the next level of the fault tree, the basic events that initiate any of the three fault events reside. In the case of fault event 1 and 3, a basic event occurs when the system demand exceeds driver performance, vehicle performance, or both. This

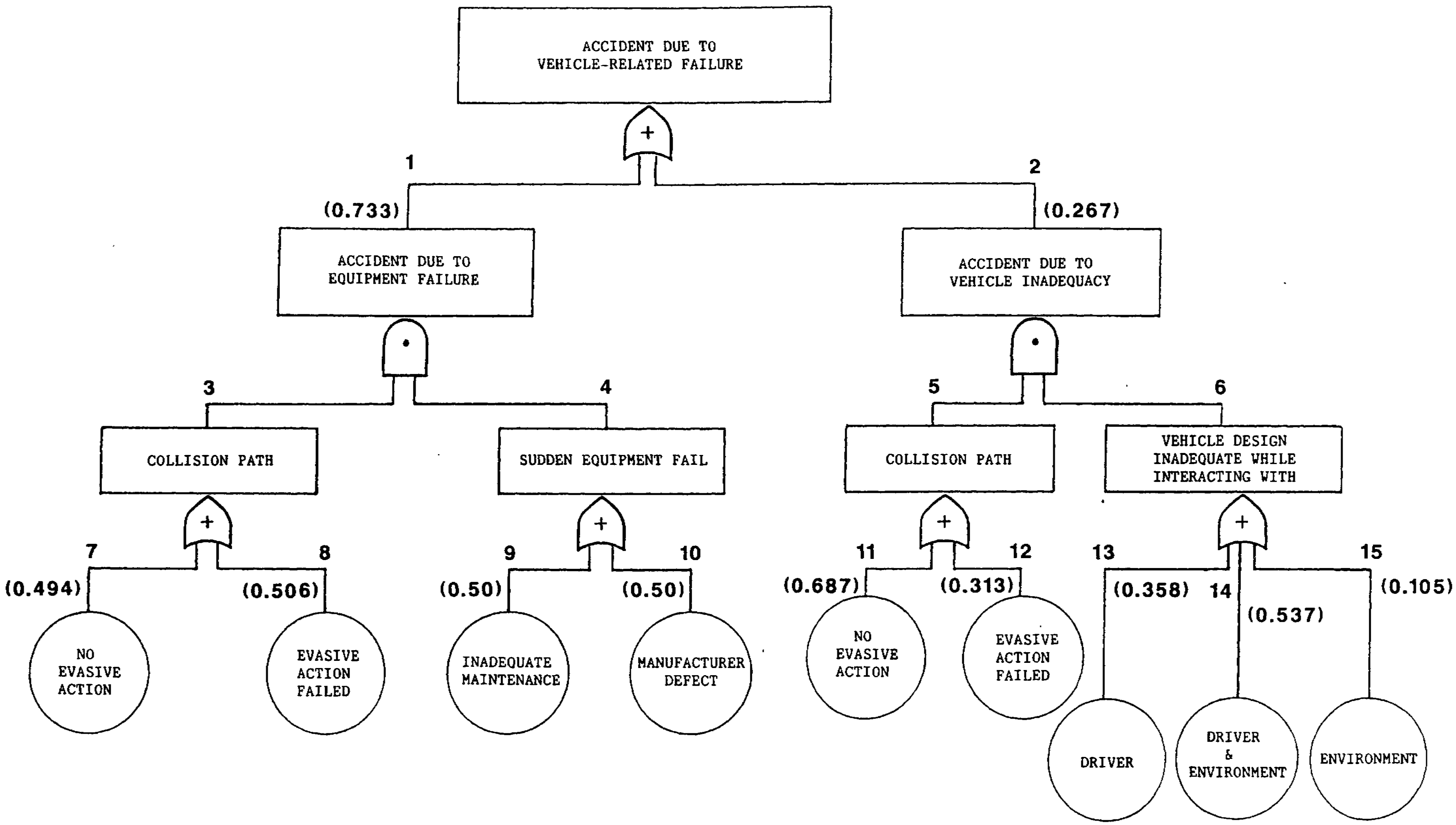

Figure 6. Fault tree for vehicle-related failure.

Event Number*		Probability
	7, 9	0.181
	7, 10	0.181
1 → 3, 4 →		
	8, 9	0.1855
	8, 10	0.1855
	11, 13	0.0657
	11, 14	0.0985
	11, 15	0.019
2 → 5, 6 →		
	12, 13	0.0299
	12, 14	0.0488
	12, 15	0.0088

*Refers to event number in Figure 6.

Figure 7. Minimum cut sets for vehicle-related failures.

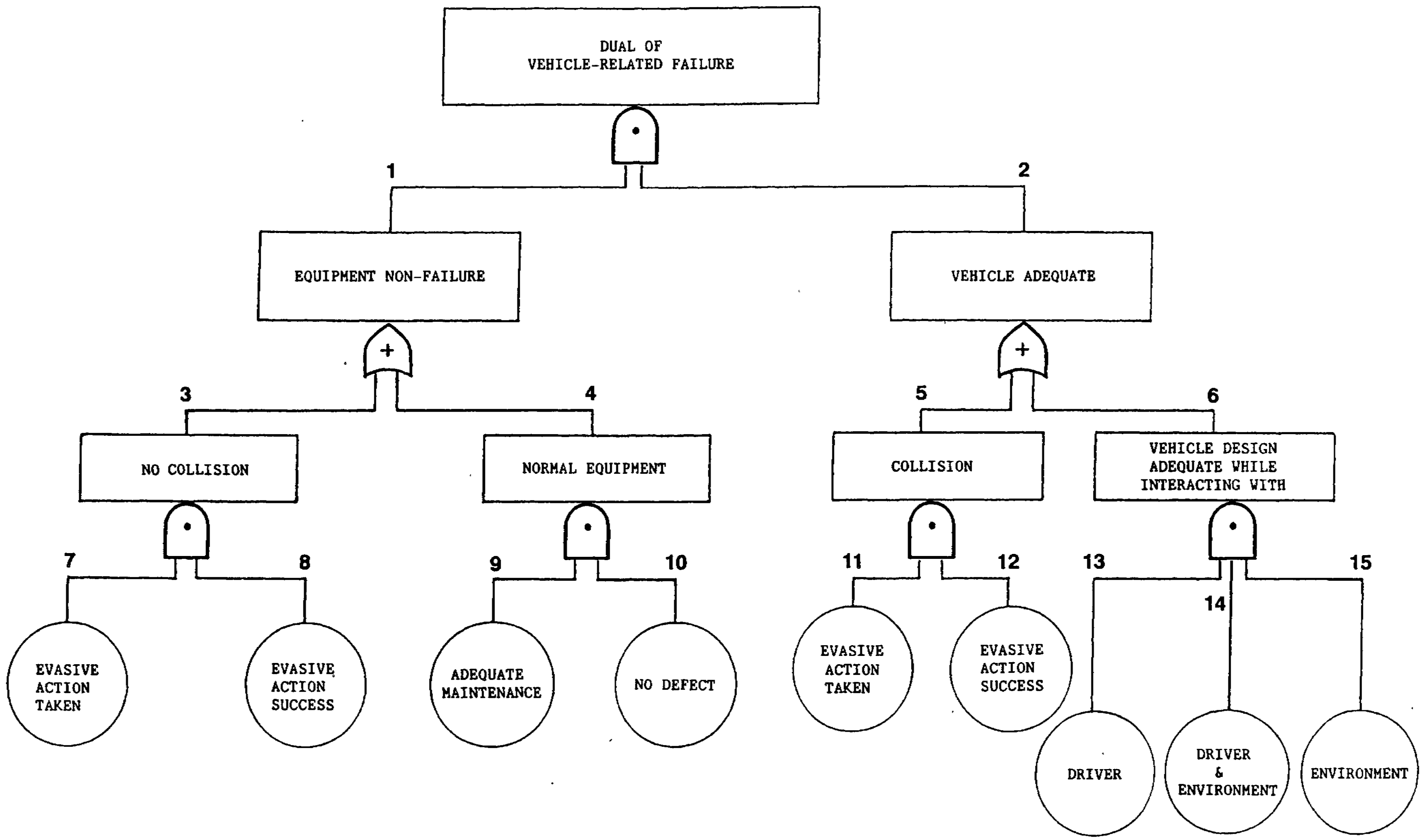

Figure 8. Dual fault tree for vehicle-related failure.

occurs, for example, when an unexpected highway feature or weather condition overwhelms the driver/vehicle performance. Fault event 2 occurs when a component of the highway system fails, such as when a surface defect causes a vehicle to veer off the desired path. This event is not developed further since it is not possible to attribute causality beyond this with any reliability.

Figure 9 shows the fault tree and the associated probabilities for environment-related failures. The minimum cut sets are shown in Figure 10 and consist of 14 combinations of events that can result in an environment-related accident. The failure events that are related to the inability of the driver/vehicle interaction to meet the system demand account for nearly 0.90 of the total probability. The dual fault tree is shown in Figure 11, and the minimum path sets and associated preventive measures are shown in Table 3.

Table 3

MINIMUM PATH SETS AND ASSOCIATED PREVENTIVE MEASURES FOR ENVIRONMENT-RELATED FAILURES

Minimum Path Set*	Preventive Measure
10, 11, 15, 16, 17, 18	Training, driving skills, defensive driving, etc.
12, 13, 14, 15, 16, 17, 18	Improved traffic and roadway factors
10, 11, 15, 16, 19, 20, 21	Improved facility design for adverse weather conditions
12, 13, 14, 15, 16, 19, 20, 21	Improved traffic and roadway factors
10, 11, 7, 17, 18	Improved facility maintenance
12, 13, 14, 7, 17, 18	Improved facility maintenance and improved traffic and roadway conditions
10, 11, 7, 19, 20, 21	Improved facility design for adverse weather conditions
12, 13, 14, 7, 19, 20, 21	Improved traffic and roadway conditions under adverse weather conditions

*Refers to event numbers in Figure 11.

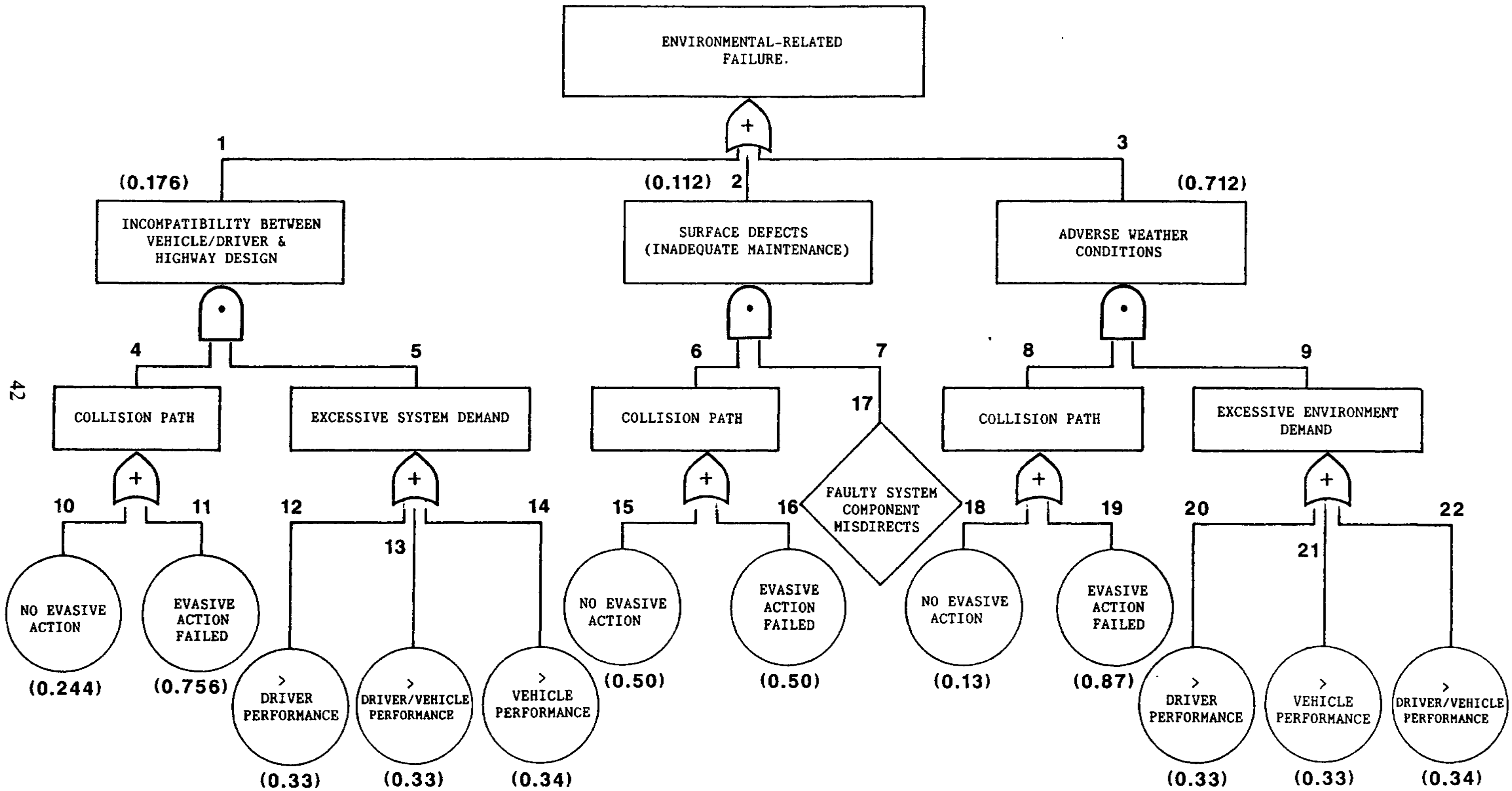

Figure 9. Fault tree for environment-related failure.

Event Number*		Probability
	10, 12	0.014
	10, 13	0.014
	10, 14	0.014
1 → 4, 5 →		
	11, 12	0.044
	11, 13	0.044
	11, 14	0.045
	15, 17	0.056
2 → 6, 7 →		
	16, 17	0.056
	18, 20	0.031
	18, 21	0.031
	18, 22	0.031
3 → 8, 9 →		
	19, 20	0.204
	19, 21	0.204
	19, 22	0.204

*Refers to event number in Figure 9.

Figure 10. Minimum cut sets for environment-related failures.

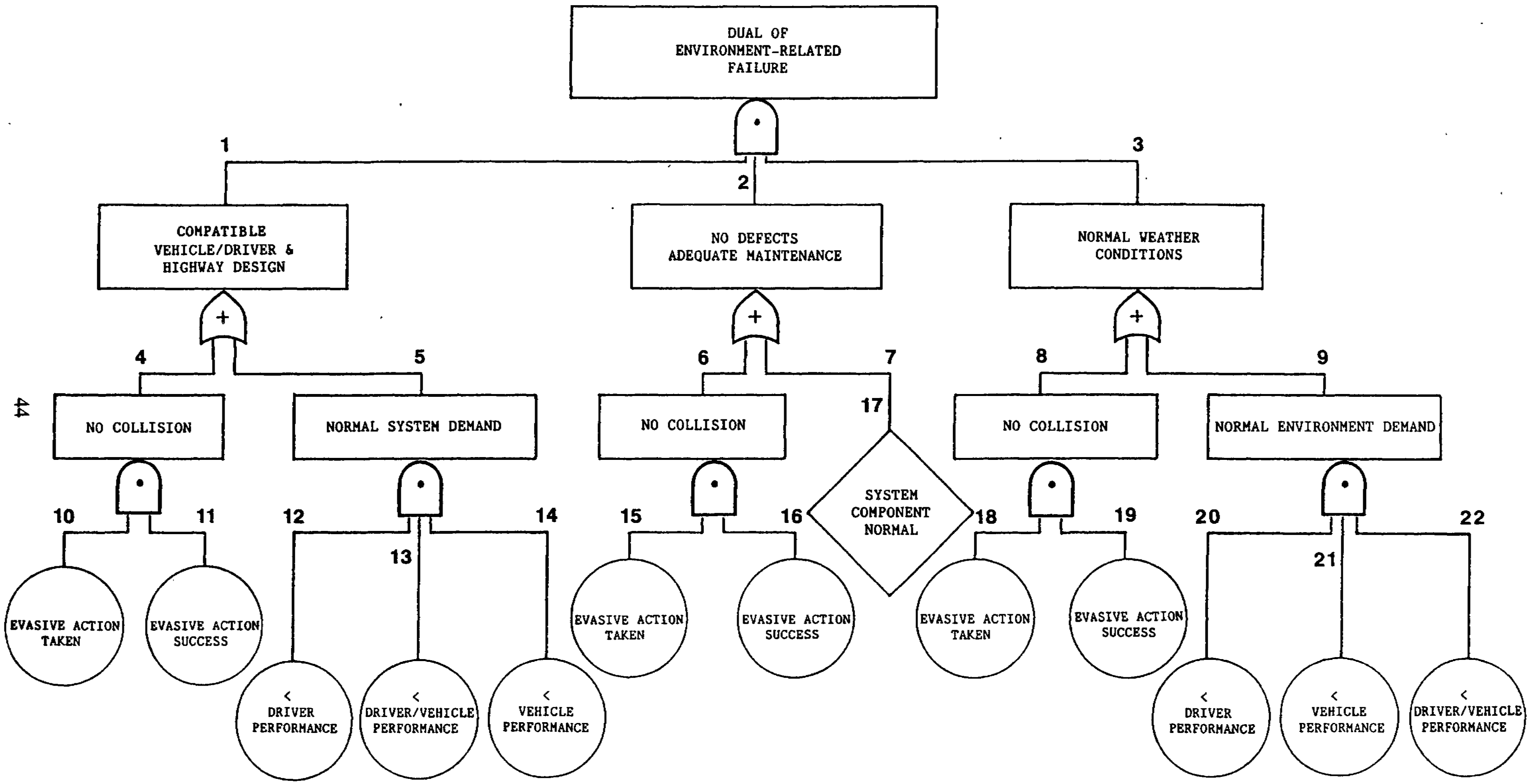

Figure 11. Dual fault tree for environment-related failure.

SUMMARY OF FINDINGS

Factors Associated with Large-Truck Accidents

Since 1983, annual VMT for large trucks in Virginia has been increasing at a rate higher than that for all other vehicles. Fatal crashes for all large trucks increased from 3.81 to 5.88 per 100 million VMT and for tractor trailers from 2.81 to 5.36 per 100 million VMT between 1982 and 1984, whereas that for other vehicles remained practically constant below 0.30 per 100 million VMT.

Although the frequency of crashes of vehicles other than large trucks is not significantly different on any day of the week, the frequency of large-truck crashes is affected by the lower truck VMT on weekends. Countermeasures that are designed to reduce large-truck crashes primarily resulting from driver-related causes (e.g., police enforcement to reduce speeding) will therefore be more effective when implemented during the week than on weekends.

No significant difference was observed in the monthly percentage distribution of large-truck crashes. Large-truck crashes tend to involve more than a single vehicle, and when a large truck is involved in a two-vehicle crash, there is a 94 percent chance that the second vehicle is not a large truck.

Based on the VMT of each type of vehicle, large truck/other vehicle crashes are overrepresented when compared with the expected frequency for two-vehicle crashes. Large-truck/other vehicle fatal crashes are also overrepresented by as much as 85 percent when compared with the expected frequency for two-vehicle fatal crashes.

Driver-related factors seem to be the primary associated factors for truck crashes: they are associated with an average of about 90 percent of all fatal crashes involving large trucks. Driver error is associated with 50 percent of fatal accidents involving large trucks, speeding is associated with 21 percent; and alcohol with 15 percent. Also, crashes involving large trucks, particularly fatal crashes for which driver error is listed as a factor, occur predominantly on stretches of highways with vertical or horizontal curves and/or grades. This strongly suggests that drivers are more likely to make maneuvering errors on a curvy section than on a straight, level section of the road.

The risk of either injury or property damage in any large-truck/other vehicle accident is approximately the same for all types of trucks on any single type of highway facility.

The risk of a fatality in any large-truck/other vehicle accident is highest for such accidents involving a tractor trailer. This risk is highest when the type of facility on which the accident occurs is a two-way undivided highway, and the risk is reduced by 50 percent on divided highways with partial or no control of access. It is further reduced to 25 percent of the maximum (that on undivided facilities) if the facility is divided with full control of access.

In single large-truck accidents, tractor trailers have the highest proportion of fatal accidents on all types of highway facilities. The highest percentage of single-vehicle fatal accidents involving tractor trailers occurs on two-way divided facilities with partial or no control of access.

Most truck/other vehicle accidents are same-direction-sideswipe collisions except when a straight truck is involved, whereas most large-truck/large-truck accidents and straight truck/other vehicle accidents are rear-end collisions.

Most single-vehicle/large-truck accidents take place on roadway sections with curves and/or grades. The worst record is for twin trailers; however, the proportion of fatal accidents is highest for tractor trailers.

Twin trailers have the highest percentage of accidents with other vehicles on roadway sections with curves and/or grades followed by tractor trailers and straight trucks. However, the proportion of fatal accidents is again highest for tractor trailers.

Pre- and Post-1982 Changes

Although tractor trailer travel has increased significantly since the enactment of STAA (reflected in the annual VMT), the total truck VMT has also continued to increase, contrary to projections made during hearings in Congress before the enactment. This however may be the result of significant growth in the nation's economy and/or deregulation of the trucking industry.

From 1980 through 1985, tractor trailer accident rates on all interstate and primary routes increased by about 1 percent in comparison to 0.03 percent for other vehicles. Although there is no clear evidence of any impact on accident rates by the passage of STAA, the rates of fatal accidents involving tractor trailers increased immediately after the enactment of STAA. The injury/fatal-accident mean involvement rates for tractor trailers and other vehicles prior to and after 1982 indicate that:

- Tractor trailer involvement in accidents has increased across all types of highways since 1982, with the highest increase on non-STAA primary routes. The next highest increase was on STAA primary routes, and the smallest increase was on interstate routes.
- For all vehicles other than tractor trailers, the mean involvement rate has decreased on the interstates and increased on the STAA primary routes and on non-STAA primary routes.
- On the interstate routes, tractor trailers have experienced higher accident involvements than all other vehicles since 1982. On all primary routes, on the other hand, all other vehicles exhibit higher involvement rates than tractor trailers.

The mean fatal accident ratios for tractor trailers and other vehicles prior to and after 1982 indicate

- a decrease in the proportion of fatal accidents since 1982 for vehicles other than tractor trailers on all primary routes
- an increase in the proportion of fatal accidents for tractor trailers on STAA and non-STAA primary routes, with the non-STAA primary routes showing the largest increase.

Between the pre- and post-1982 periods, the relative accident involvement of tractor trailers (when compared with all other vehicles) has increased across all highway categories. The highest such increase has taken place on non-STAA primary routes (11.43 percent) followed by interstate routes (10.24 percent) and STAA primary routes (4.38 percent). These trends in relative involvement indicate significant increases on interstate and undesignated primary routes.

Associated Causes of Driver-Related Failures

For driver-related failures leading to an accident, 10 minimum cut sets or possible ways of accident occurrence were identified. Among these, the most prevalent form of accident occurrence is that in which a normal driver makes an error in judgment and is unsuccessful in his or her evasive action. This indicates that, although evasive action is taken by a driver in most driver-related accidents, this action is not sufficient to avoid a crash.

When an accident is caused as a result of driver performance reduced through some physical impairment, it is most likely that this impairment is a temporary rather than a permanent condition. In other words, most such accidents are caused by drivers whose performance has been impaired by alcohol, drugs, or an illness.

Associated Causes of Vehicle-Related Failures

For this type of accident, 10 minimum cut sets were identified. Among these, the minimum cut set describing an equipment failure accounts for about three fourths of all vehicle-related accidents.

The next most probable way for a vehicle-related accident to occur is when the driver/vehicle interaction cannot meet the demands of the system. Such a condition arises when the driver/vehicle interaction is hampered by deficiencies in vehicle design.

Associated Causes of Environment-Related Failures

Of the 14 minimum cut sets and their corresponding probabilities identified, approximately 85 percent of the total is accounted for by excessive demand on driver and vehicle performance created by environmental or roadway effects.

Preventive Measures for Driver-Related Failures

Improving vehicle and roadway compatibility with the characteristics of the driver population through means such as human factor considerations can bring about significant reductions in truck involvement in accidents.

Driver education programs and increased law enforcement programs for trucks are also identified as possible actions that can reduce truck accidents.

Preventive Measures for Vehicle-Related Failures

Improved reliability of vehicles through better vehicle design and vehicle inspection programs would contribute significantly to truck accident reduction.

Improved vehicle design through ergonomic considerations leading to better environment for vehicle-driver interaction could reduce truck accidents.

Better driver education that identified the bounds of vehicle capabilities would also prevent disparities arising between vehicles' capabilities and demands on their performance.

Preventive Measures for Environment-Related Failures

All of the following would contribute to the prevention of environment-related failures:

- improved training and skills for vehicle operation under adverse weather conditions, perhaps under simulated adverse weather conditions as a prerequisite for licensing
- improved traffic and highway design through considerations of other factors, such as driver expectancy and human factors
- improved traffic and highway design for safe operations under adverse weather conditions
- better maintenance to ensure a more reliable system
- better guidelines for the evaluation of highways for possible truck operation.

CONCLUSIONS

1. The increase in tractor trailer involvement in accidents may be the result of a multitude of factors, including deregulation of the trucking industry and the pas-

sage of the STAA. However, the role of STAA in increased tractor trailer involvement rates is likely to be secondary to other factors, such as the type of highway environment and its conduciveness to accommodating large trucks.

2. Non-STAA routes experienced the highest increase in accident rates after the passage of the STAA. The fact that these routes were not affected by this legislation indicates this increase may be the result of causes other than the STAA.

3. The significant increases in tractor trailer accident involvement rates and relative involvement on non-STAA primary routes may be the result of an incompatibility between the geometric characteristics of these highways and the dynamic characteristics of tractor trailers coupled with the general increase of truck travel across all types of highways.

4. Safety on Virginia highways may be significantly improved if large-truck traffic is separated from all other truck traffic. This may however create other traffic problems if implemented on existing facilities. A detailed study should be carried out to determine the feasibility of implementing such a plan.

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APPENDIX

Table A-1

MAXIMUM SIZE AND AXLE WEIGHTS OF LARGE TRUCKS

Static Characteristics	Federal-Aid Highway Act 1956	Surface Transportation Assistance Act of 1982
Loaded Weight (lb)		
Single axle	18,000	20,000
Tandem axle	32,000	34,000
Loaded	76,280	80,000
Width (in)	96	102
Length* (ft)		
Semi-trailers and trailers	—	48
Each twin trailer	—	28
Overall length	55	*

*No state is allowed to establish limits on overall truck lengths.

Table A-2

PERCENTAGE DISTRIBUTION OF CRASHES BY DAY OF WEEK (1984)

Day of Week	Percentage: Large-Truck*	Percentage: Other Vehicle** (Passenger Cars, Vans, Pickups)
Monday	17.3	13.8
Tuesday	16.6	12.5
Wednesday	16.9	13.3
Thursday	17.4	13.4
Friday	19.1	17.7
Saturday	8.2	16.8
Sunday	4.5	12.5
Weekday mean	17.5	14.1
Weekend mean	6.4	14.7

* Based on 11,399 truck crashes.
** Based on 123,355 other vehicle crashes.

Table A-3

PERCENTAGE DISTRIBUTION OF CRASHES BY MONTH (1984)

Month	Percentage	
	Large-Truck*	Other Vehicle** (Passenger Cars, Vans, Pickups)
January	7.9	8.0
February	6.6	6.9
March	7.8	7.1
April	7.2	7.6
May	9.0	8.9
June	8.6	8.4
July	8.4	8.8
August	9.5	8.8
September	8.6	8.6
October	8.8	8.7
November	9.2	9.1
December	8.4	9.1

* Based on 11,399 crashes.
** Based on 123,355 crashes.

Table A-4

ACCIDENTS INVOLVING LARGE TRUCKS BY PERCENTAGE OF ASSOCIATED FACTORS (1984–1986)

Year	Number	Percentage			
		Driver	Environmental	Vehicle	Others
1984	5431	75.6	0.7	8.8	14.9
1985	5587	72.8	2.3	6.2	18.7
1986	6347	75.8	1.1	5.7	17.4

Table A-5

ACCIDENTS INVOLVING LARGE TRUCKS BY PERCENTAGE OF ASSOCIATED FACTORS FOR DIFFERENT TRUCK TYPES (1984-1986)

Truck Type	Number	Percentage			
		Driver	Environmental	Vehicle	Others
Straight truck	8459	74.9	4.3	8.0	12.8
Tractor trailer	8685	74.5	5.2	5.8	14.5
Twin trailer	72	73.9	15.1	4.1	6.9

Table A-6

FATAL LARGE-TRUCK ACCIDENTS
BY PERCENTAGE OF ASSOCIATED FACTORS (1984–1986)

Year	Number	Percentage			
		Driver	Environmental	Vehicle	Others
1984	115	92.3	0.0	6.0	1.7
1985	96	91.5	2.1	2.1	4.3
1986	110	86.0	0.9	5.6	7.5

Table A-7

FATAL ACCIDENTS INVOLVING LARGE TRUCKS BY TYPE OF
TRUCK AND PERCENTAGE OF ASSOCIATED FACTORS (1984-1986)

Truck Type	Number	Percentage			
		Driver	Environmental	Vehicle	Others
Straight truck	81	83.7	2.4	7.6	6.3
Tractor trailer	224	91.8	1.8	1.7	4.7
Twin trailer	1	100.0	0.0	0.0	0.0

Table A-8

LARGE-TRUCK FATAL CRASHES BY PERCENTAGE OF
MAJOR DRIVER FACTORS ASSOCIATED WITH DRIVERS (1984-1986)

Year	Number	Percentage			
		Error	Alcohol	Speeding	Handicap
1984	106	49.1	15.1	29.2	6.6
1985	88	65.9	10.5	11.8	11.8
1986	95	71.8	5.4	8.7	14.1

Table A-9

LARGE-TRUCK FATAL CRASHES BY PERCENTAGE OF
MAJOR DRIVER FACTORS FOR DIFFERENT TRUCK TYPES (1984-1986)

Truck Type	Number	Percentage			
		Error	Alcohol	Speeding	Handicap
Straight truck	68	59.8	19.4	11.9	8.9
Tractor trailer	206	61.8	7.9	19.2	11.1
Twin trailer	1	100.0	0.0	0.0	0.0

Table A-10

LARGE-TRUCK FATAL CRASHES BY PERCENTAGE OF LOCATION ALIGNMENT (1984-1986)

Year	Number	Percentage				
		Straight/Level	Curve/Level	Grade/Straight	Grade/Curve	Others
1984	115	39.1	7.8	28.7	19.1	5.3
1985	96	48.4	10.8	17.2	19.4	4.2
1986	110	31.8	10.3	39.3	14.0	4.6

Table A-11

LARGE-TRUCK FATAL CRASHES BY PERCENTAGE OF LOCATION ALIGNMENT FOR DIFFERENT TRUCK TYPES (1984-1986)

Truck Type	Number	Percentage					
		Straight/ Level	Curve/ Level	Grade/ Straight	Grade/ Curve	Hillcrest Str/Curve	Dip/Str/ Curve
Straight truck	86	33.7	16.2	25.0	16.3	6.3	2.5
Tractor trailer	234	41.0	7.3	30.3	17.9	2.2	1.3
Twin trailert	1	100.0	0.0	0.0	0.0	0.0	0.0

Table A-12

DISTRIBUTION OF LARGE-TRUCK FATAL CRASHES ASSOCIATED WITH DRIVER ERROR BY THE LOCATION ALIGNMENT (1984)

Location Alignment	Number	Percentage
Hillcrest/curve	96	90.4
Dip/curve	8	7.7
Not stated	2	1.9

Table A-13

LARGE-TRUCK FATAL CRASHES ASSOCIATED WITH DRIVER ERROR BY PERCENTAGE OF ALIGNMENT AND TYPE OF TRUCK (1984-1986)

Truck Type	Number	Percentage					
		Straight/ Level	Curve/ Level	Grade/ Straight	Grade/ Curve	Hillcrest Str/Curve	Dip/Str/ Curve
Straight truck	24	27.5	12.5	30.0	22.5	7.5	0.0
Tractor trailer	80	42.1	8.3	34.6	12.0	2.3	0.7
Twin trailer	—	0.0	0.0	0.0	0.0	0.0	0.0

Table A-14

DISTRIBUTION OF CRASHES BY NUMBER OF VEHICLES INVOLVED (1984)*

Number of Vehicles Involved in Crash	Large Truck		Other Vehicles	
	Number	Percent	Number	Percent
1	2,529	22.1	39,661	35.4
2	7.855	68.9	65,731	58.7
3	830	7.3	5,591	5.0
4	157	1.4	784	0.7
5	18	0.2	140	0.1
6 or more	10	0.1	49	0.1
TOTAL	11,399	100.0	111,956	100.0

*Crashes on all highways for which all vehicles involved are identified.

Table A-15

PERCENTAGE DISTRIBUTION OF VEHICLE MIX IN TWO-VEHICLE CRASHES INVOLVING LARGE TRUCKS (1984)

Vehicle Mix	Number of Crashes*	Percentage
Large-truck/large-truck	333	6.2
Large-truck/other vehicle	5,105	93.8

*These are for two-vehicle crashes involving large trucks on the interstate and primary highways where the other vehicle was identified.

Table A-16

COMPARISON OF ACTUAL TO EXPECTED PROPORTIONS OF VEHICLE MIX IN TWO-VEHICLE CRASHES (1984)

Collision Type (1)	Actual Proportion (2)	Expected Proportion (3)	Actual/Expected (4)
Other vehicle/ other vehicle	0.7886	0.7921	0.9956
Large-truck/ large-truck	0.0132	0.0121	1.0909
Large-truck/ other vehicle	0.1982	0.1958	1.0122

Table A-17

DISTRIBUTION OF FATAL CRASHES
BY NUMBER OF VEHICLES INVOLVED (1984)*

Number of Vehicles Involved in Crash	Large Trucks		Other Vehicles (Passenger Cars, Vans, Pickups)	
	Number	Percent	Number	Percent
1	40	25.3	520	68.0
2	95	60.1	219	28.6
3	18	11.4	21	2.8
4	4	2.6	4	0.5
5	1	0.6	0	0.0
6 or more	0	0.0	1	0.1
TOTAL	158	100.0	765	100.0

*Fatal crashes on all highways for which all vehicles involved were identified.

Table A-18

SINGLE AND MULTIVEHICLE FATAL CRASHES (1984)

	Large Trucks			Other Vehicles		
Type of Crash	Total No. of Crashes	Fatal Crashes	Percentage of Fatal Crashes	Total No. of Crashes	Fatal Crashes	Percentage of Fatal Crashes
Single vehicle	2,529	40	1.6	39,661	520	1.3
Multivehicle	8,870	118	13.3	72,295	245	0.3

Table A-19

COMPARISON OF ACTUAL TO EXPECTED PROPORTIONS
OF VEHICLE MIX IN TWO-VEHICLE FATAL CRASHES

Collision Type (1)	Actual Proportion (2)	Expected Proportion (3)	Actual/Expected (4)
Large-truck/ other vehicle	0.6302	0.7921	0.7956
Large-truck/ large-truck	0.0064	0.0121	0.5289
Large-truck/ other vehicle	0.3633	0.1958	1.8554

Table A-20

THE EFFECT OF TYPE OF FACILITY ON SEVERITY OF ALL ACCIDENTS INVOLVING LARGE TRUCKS (1984-1986)

Type of Facility	Fatal	Injury	Property Damage
Two-way undivided	146 3.0%	1835 37.9%	2864 59.1%
Divided no/partial access control	84 2.0%	1547 37.0%	2550 61.0%
Divided full access control	83 1.4%	2111 35.5%	3753 63.1%

Table A-21

THE EFFECT OF VEHICLE TYPE ON SEVERITY OF ALL ACCIDENTS INVOLVING LARGE TRUCKS ON TWO-WAY UNDIVIDED FACILITIES (1984-1986)

		Percentage	
Severity	Number	Truck/Other Vehicle	All Others
Fatal	146	82.2%	17.8%
Injury	1835	70.7%	29.3%
Prop. dmg.	2864	68.2%	31.8%
All	4865	69.7%	30.3%

Table A-22

THE EFFECT OF VEHICLE TYPE ON SEVERITY OF ALL ACCIDENTS INVOLVING LARGE TRUCKS ON DIVIDED FACILITIES WITH NO OR PARTIAL CONTROL OF ACCESS (1984-1986)

		Percentage	
Severity	Number	Truck/Other Vehicle	All Others
Fatal	84	70.2%	29.8%
Injury	1547	77.3%	22.7%
Prop. dmg.	2550	76.8%	23.2%
All	4181	77.0%	23.0%

Table A-23

THE EFFECT OF VEHICLE TYPE ON SEVERITY OF ALL ACCIDENTS INVOLVING LARGE TRUCKS ON DIVIDED FACILITIES WITH FULL CONTROL OF ACCESS (1984–1986)

Severity	Number	Percentage	
		Truck/Other Vehicle	All Others
Fatal	84	63.9	36.1
Injury	2111	66.2	33.8
Prop. dmg.	3753	70.9	29.1
All	5947	69.1	30.9

Table A-24

THE EFFECT OF VEHICLE TYPE ON SEVERITY OF ALL LARGE-TRUCK/OTHER VEHICLE ACCIDENTS ON TWO-WAY UNDIVIDED FACILITIES (1984–1986)

Vehicle Type†	Number	Percentage		
		Fatal	Injury	Property Damage
ST/other vehicle	2214	1.7	38.7	59.6
TT/other vehicle	1156	7.2	38.0	54.8
TW/other vehicle	7	0	28.6	71.4

†ST = straight truck; TT = tractor trailer; TW = twin trailer.

Table A-25

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL LARGE-TRUCK/OTHER VEHICLE ACCIDENTS ON DIVIDED FACILITIES WITH NO OR PARTIAL CONTROL OF ACCESS (1984–1986)

Vehicle Type†	Number	Percentage		
		Fatal	Injury	Property Damage
ST/other vehicle	1982	0.9	35.9	63.2
TT/other vehicle	1231	3.3	39.3	57.4
TW/other vehicle	8	0	37.5	62.5

†ST = straight truck; TT = tractor trailer; TW = twin trailer.

Table A-26

THE EFFECT OF VEHICLE TYPE ON SEVERITY OF ALL LARGE-TRUCK/OTHER VEHICLE ACCIDENTS ON DIVIDED FACILITIES WITH FULL CONTROL OF ACCESS (1984–1986)

		Percentage		
Vehicle Type†	Number	Fatal	Injury	Property Damage
ST/other vehicle	1295	0.8	34.1	65.1
TT/other vehicle	2794	1.5	33.9	64.6
TW/other vehicle	20	0	45.0	55.0

†ST = straight truck; TT = tractor trailer; TW = twin trailer.

Table A-27

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL SINGLE VEHICLE/ LARGE-TRUCK ACCIDENTS ON TWO-WAY UNDIVIDED FACILITIES (1984–1986)

		Percentage		
Truck Type†	Number	Fatal	Injury	Property Damage
ST	567	0.9	38.1	61.0
TT	553	1.6	34.2	64.2
TW	1	0	0	100.0

†ST = straight truck; TT = tractor trailer; TW = twin trailer.

Table A-28

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL SINGLE VEHICLE/LARGE-TRUCK ACCIDENTS ON DIVIDED FACILITIES WITH NO OR PARTIAL CONTROL OF ACCESS (1984–1986)

		Percentage		
Truck Type†	Number	Fatal	Injury	Property Damage
ST	280	0	39.6	60.4
TT	424	4.5	36.4	59.1
TW	7	0	14.3	85.7

†ST = straight truck; TT = tractor trailer; TW = twin trailer.

Table A-29

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL SINGLE VEHICLE/LARGE-TRUCK ACCIDENTS ON DIVIDED FACILITIES WITH FULL CONTROL OF ACCESS (1984–1986)

Truck Type†	Number	Percentage		
		Fatal	Injury	Property Damage
ST	437	0.9	39.6	59.5
TT	937	1.6	38.3	60.1
TW	15	0	20.0	80.0

†ST = straight truck; TT = tractor trailer; TW = twin trailer.

Table A-30

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL LARGE-TRUCK/LARGE-TRUCK ACCIDENTS ON TWO-WAY UNDIVIDED FACILITIES (1984–1986)

Vehicle Combination†	Number	Percentage		
		Fatal	Injury	Property Damage
SU/SU	136	0	27.7	72.3
SU/TT	92	2.2	34.8	63.0
SU/TW	—	0	0	0
TT/TT	68	2.9	41.2	55.9
TT/TW	1	0	0	100.0
TWTW	—	0	0	0

†SU = single unit truck; TT = tractor trailer; TW = twin trailer.

Table A-31

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL LARGE-TRUCK/LARGE-TRUCK ACCIDENTS ON DIVIDED FACILITIES WITH NO OR PARTIAL CONTROL OF ACCESS (1984–1986)

Vehicle Combination†	Number	Percentage		
		Fatal	Injury	Property Damage
SU/SU	88	0	33.0	67.0
SU/TT	69	1.4	31.9	66.7
SU/TW	0	0	0	0
TT/TT	61	1.6	34.5	63.9
TT/TW	—	0	0	0
TW/TW	—	0	0	0

†SU = single unit truck; TT = tractor trailer; TW = twin trailer.

Table A-32

THE EFFECT OF TRUCK TYPE ON SEVERITY OF ALL LARGE-TRUCK/LARGE-TRUCK ACCIDENTS ON DIVIDED FACILITIES WITH FULL CONTROL OF ACCESS (1984–1986)

Vehicle Combination†	Number	Percentage Fatal	Injury	Property Damage
SU/SU	69	0	46.4	53.6
SU/TT	91	3.3	36.3	60.4
SU/TW	3	0	66.7	33.3
TT/TT	227	1.8	37.4	60.8
TTTW	3	0	33.3	66.7
TW/TW	—	0	0	0

†SU = single unit truck; TT = tractor trailer; DT = twin trailer.

Table A-33

TYPES OF COLLISION FOR TWO-VEHICLE ACCIDENTS INVOLVING LARGE TRUCKS (1984–1986)

Vehicle Type	Number	Percentage Rear	Angle	Head	Side Swipe*	Side Swipe**	Others
Straight truck/ other vehicle	6042	43.8	25.0	1.9	23.3	3.5	2.5
Tractor trailer/ other vehicle	5591	28.7	14.5	1.4	47.0	3.2	5.2
Twin trailer/ other vehicle	38	35.2	13.5	0.0	43.2	2.7	5.4
Straight truck/ straight truck	331	58.4	16.1	2.0	13.8	6.2	3.5
Straight truck/ tractor trailer	280	50.2	15.8	1.5	20.4	7.9	4.2
Straight truck/ twin trailer	3	66.7	0.0	0.0	33.3	0.0	0.0
Tractor trailer/ tractor trailer	390	56.1	8.7	0.6	20.1	4.5	10.0

*Same direction.
**Opposite direction.

Table A-34

EFFECT OF ROAD GEOMETRY ON
SINGLE VEHICLE/LARGE-TRUCK ACCIDENTS (1984–1986)

Type of Truck	Number	% All Single Truck Accidents	Severity	% Occurrences Curves & Grades	% Occurrences All Other Locations
Straight truck	1803	42.0	All	55.0	45.0
			Fatal	1.0	0.5
			Injury	45.0	32.2
			Prop. dmg.	54.0	67.3
Tractor trailer	2420	57.0	All	61.0	39.0
			Fatal	2.5	1.5
			Injury	40.5	30.6
			Prop. dmg.	57.0	67.9
Twin trailer	27	1.0	All	65.0	35.0
			Fatal	0.0	0.0
			Injury	18.0	33.3
			Prop. dmg.	82.0	66.7

Table A-35

EFFECT OF ROAD GEOMETRY ON
LARGE-TRUCK/OTHER VEHICLE ACCIDENTS (1984–1986)

Type of Truck	Number	% All Truck & Other Vehicle Accidents	Severity	% Occurrences Curves & Grades	% Occurrences All Other Locations
Straight truck	6039	53.2	All	36.0	64.0
			Fatal	1.6	0.8
			Injury	41.3	33.8
			Prop. dmg.	57.1	65.4
Tractor trailer	5590	46.5	All	42.0	58.0
			Fatal	3.8	2,5
			Injury	36.9	35.9
			Prop. dmg.	59.3	61.6
Twin trailer	37	0.3	All	51.0	49.0
			Fatal	0.0	4.2
			Injury	56.0	16.7
			Prop. dmg.	44.0	79.1

Table A-36

AVERAGE DAILY (24 HR) VEHICLE MILES OF TRAVEL (VMT) ON INTERSTATE, ARTERIAL, AND PRIMARY ROUTES

Year	2-Axle Six-Tire and 3-Axle Six-Tire Trucks		Tractor Trailers		All Large Trucks	
	VMT (10^6)	% Increase	VMT (10^6)	% Increase	VMT (10^6)	% Increase
1980	2.26	—	3.99	—	6.25	—
1981	2.20	-2.65	4.06	1.75	6.26	0.16
1982	2.16	-1.82	4.03	-0.74	6.19	-1.12
1983	2.24	3.70	4.35	7.94	6.59	6.46
1984	2.45	9.37	4.76	9.42	7.21	9.41
1985	2.58	5.31	5.08	6.72	7.66	6.24
1986	2.77	7.36	5.51	8.46	8.28	8.09

Table A-37

TOTAL ACCIDENTS PER 100 MILLION VEHICLE MILES OF TRAVEL ON INTERSTATE AND PRIMARY HIGHWAYS

Year	Tractor Trailers			Other Vehicles		
	Rate	B/A†	Percent Change	Rate	B/A	Percent Change
1980	143.10			168.07		
1981	140.22	140.69*		169.04	165.46*	
1982	138.75			159.28		
			-0.17			-2.80
1983	144.55			154.68		
1984	132.09	140.45**		159.66	160.82**	
1985	144.70			168.13		

†B/A = before/after STAA.
*Average for before period.
**Average for after period.

Table A-38

FATAL ACCIDENTS PER 100 MILLION VEHICLE MILES OF TRAVEL ON INTERSTATE AND PRIMARY HIGHWAYS

Year	Tractor Trailers			Other Vehicles		
	Rate	B/A†	Percent Change	Rate	B/A†	Percent Change
1980	4.05			2.43		
1981	3.17	3.29*		2.19	2.14*	
1982	2.65			1.75		
			+26.75			−10.75
1983	3.90			1.83		
1984	5.01	4.17**		2.06	1.91**	
1985	3.61			1.85		

†B/A = before/after STAA. *Average for before period. **Average for after period.

Table A-39

FATAL ACCIDENT RATES* ON INTERSTATE HIGHWAYS

Year	Tractor Trailers			Other Vehicles		
	Rate	B/A†	Percent Change	Rate	B/A†	Percent Change
1980	1.21			0.84		
1981	1.38	1.53		0.79	0.79	
1982	2.00			0.74		
			+33.99			+5.06
1983	2.16			0.82		
1984	2.25	2.05		0.93	0.83	
1985	1.74			0.74		

*Fatal accident rate = number of fatal accidents per 100 million VMT.
†B/A = before/after 1982.

Table A-40

FATAL ACCIDENT RATES* ON PRIMARY HIGHWAYS

Year	Tractor Trailers			Other Vehicles		
	Rate	B/A†	Percent Change	Rate	B/A†	Percent Change
1980	8.81			3.26		
1981	6.27	6.30		2.95	2.85	
1982	3.82			2.34		
			+27.30			−13.33
1983	7.03			2.33		
1984	9.92	8.02		2.66	2.47	
1985	7.10			2.43		

*Fatal accident rate = number of fatal accidents per 100 million VMT.
†B/A = before/after 1982.

Table A-41

INJURY AND FATAL ACCIDENT INVOLVEMENT RATES ON INTERSTATE ROUTES*

	1980		1981		1982		1983		1984		1985	
RT†	TT†	Others†	TT	Others	TT	Others	TT	Others	TT	Others	TT	Others
64	40.6	41.5	50.3	44.9	35.2	46.3	45.0	49.0	45.2	49.7	53.1	55.6
66	17.7	27.2	32.6	32.1	21.7	34.4	34.2	40.6	32.2	33.8	42.8	40.6
77	78.6	51.5	42.6	42.3	44.9	20.3	43.4	22.4	40.9	21.5	36.2	30.5
81	17.8	35.0	22.8	37.8	20.4	25.7	20.1	24.7	23.4	27.5	23.7	29.2
85	48.6	49.4	29.1	48.1	18.9	39.5	19.0	36.2	26.4	35.0	26.9	41.8
95	52.7	76.3	48.0	75.9	51.2	59.7	52.2	66.8	64.5	67.6	61.7	68.4
495	79.7	49.5	57.6	41.9	120.8	45.1	62.1	46.2	138.3	41.1	79.4	41.7

*Injury and fatal accident involvement = number of injury and fatal involvements per 100 million VMT.

†RT = route; TT = tractor trailers; Others = all vehicles other than tractor trailers.

Table A-42

INJURY AND FATAL ACCIDENT INVOLVEMENT RATES ON PRIMARY STAA ROUTES*

	1980		1981		1982		1983		1984		1985	
RT†	TT†	Others†	TT	Others	TT	Others	TT	Others	TT	Others	TT	Others
19	119.4	81.6	50.6	83.6	14.4	74.9	92.1	87.0	134.8	71.2	46.5	85.0
23	133.3	118.2	113.6	102.6	73.1	88.0	127.6	104.4	115.3	105.1	161.2	104.9
29	72.1	152.6	89.3	172.1	74.9	134.9	81.1	137.8	55.9	159.8	65.5	166.8
58	96.2	130.3	104.4	133.0	97.6	122.7	86.4	121.0	109.0	145.4	91.4	138.8
220	128.2	114.5	121.9	146.7	102.6	105.8	95.8	117.7	119.5	125.4	65.5	132.2
360	40.6	99.8	42.3	117.4	44.5	95.4	79.9	122.7	51.6	116.2	55.1	134.4
460	64.2	108.6	74.5	127.8	67.0	126.0	84.9	125.8	93.7	118.2	61.9	126.9

*Injury and fatal accident involvement = number of injury and fatal involvements per 100 million VMT.

†RT = route; TT = tractor trailers; Others = all vehicles other than tractor trailers.

Table A-43

INJURY AND FATAL ACCIDENT INVOLVEMENT RATES ON PRIMARY NON-STAA* ROUTES

RT†	1980		1981		1982		1983		1984		1985	
	TT†	Others†	TT	Others	TT	Others	TT	Others	TT	Others	TT	Others
1	125.0	258.9	198.4	265.2	188.0	250.2	180.4	279.5	186.2	290.7	163.7	278.7
10	92.5	149.2	152.5	165.9	86.9	124.3	213.3	161.5	105.2	158.6	95.2	162.3
11	97.1	133.5	85.2	129.5	75.1	117.6	89.8	117.5	121.3	129.0	106.2	133.0
15	72.0	100.6	63.2	99.4	59.5	83.1	83.3	94.7	100.3	92.6	60.1	100.4
17	73.9	141.6	102.7	137.9	75.8	107.1	143.8	109.8	85.1	113.0	101.8	133.2
50	81.3	196.9	119.0	220.7	73.6	201.3	85.1	204.2	153.0	180.9	91.9	174.1
60	160.9	156.3	123.5	141.6	97.8	130.2	107.8	152.4	125.0	146.7	103.7	169.7

*Injury and fatal accident involvement = number of injury and fatal involvements per 100 million VMT.

†RT = route; TT = tractor trailers; Others = all vehicles other than tractor trailers.

Table A-44

ANOVA RESULTS FOR HYPOTHESIS I*

Highway Type/ Accident Type	$F(n, d)$*		
	Interstate	STAA Primary	Non-STAA Primary
Tractor trailer	$F(1, 40) = 0.05$	$F(1, 40) = 0.52$	$F(1, 40) = 1.33$
Non-tractor trailer	$F(1, 40) = 0.35$	$F(1, 40) = 0.50$	$F(1, 40) = 0.04$

*$F(n, d) = F$ value with numerator = n, denominator = d.

Table A-45

PROBABILITY VALUES FOR HYPOTHESIS I*

Highway Type/ Accident Type	Type I Error Probability*		
	Interstate	STAA Primary	Non-STAA Primary
Tractor trailer	0.824	0.475	0.256
Other vehicle	0.557	0.484	0.843

*Probability = the probability of error in rejecting the null hypothesis.

Table A-46

MEAN INVOLVEMENT RATES (INJURY & FATAL)*

		Interstate	STAA Primary	Non-STAA Primary
Tractor trailer	B†	44.42	82.17	105.00
	A†	46.28	89.17	119.19
Other vehicle	B	44.08	116.08	157.72
	A	41.47	121.33	161.12

*Number of involvements per 100 million VMT.
†B = before STAA (1980–1982); A = after STAA (1983–1985).

Table A-47

FATAL INVOLVEMENT RATIO ON INTERSTATE ROUTES*

RT†	1980		1981		1982		1983		1984		1985	
	TT†	Others†	TT	Others	TT	Others	TT	Others	TT	Others	TT	Others
64	11.6	4.1	1.8	2.6	7.6	2.0	3.7	1.7	3.5	3.0	4.1	1.1
66	25.0	4.4	0.0	4.1	16.6	0.6	0.0	0.3	16.6	2.7	0.0	1.6
77	4.0	8.2	21.4	11.1	6.6	3.1	0.0	10.8	5.8	5.0	5.5	6.3
81	2.7	2.8	5.2	4.3	3.5	3.1	9.6	6.2	5.8	4.4	5.3	3.3
85	0.0	1.2	0.0	3.7	0.0	2.8	10.0	8.0	28.5	7.8	0.0	2.5
95	1.5	2.0	3.8	2.5	5.7	2.0	3.5	2.0	2.0	1.2	3.0	1.3
495	0.0	1.4	0.0	3.7	5.5	0.7	0.0	0.3	0.0	1.5	0.0	1.4

*The ratios are fatal involvements per 100 involvements in all fatal and injury accidents.
†RT = route; TT = tractor trailers; Others = all vehicles other than tractor trailers.

Table A-48

FATAL INVOLVEMENT RATIOS ON PRIMARY STAA ROUTES*

RT†	1980		1981		1982		1983		1984		1985	
	TT†	Others†	TT	Others	TT	Others	TT	Others	TT	Others	TT	Others
19	12.5	7.4	0.0	3.8	0.0	0.0	14.2	5.0	8.3	2.3	0.0	2.3
23	0.0	2.4	0.0	1.3	0.0	2.2	0.0	1.8	16.6	4.1	0.0	2.9
29	2.9	2.2	6.9	2.6	2.6	1.3	6.5	1.7	5.7	0.9	4.5	1.9
58	13.7	5.6	11.1	4.3	4.0	2.5	6.2	3.5	7.2	2.4	8.0	3.5
220	7.6	5.6	7.5	6.3	2.8	2.5	2.7	1.6	12.2	1.9	3.7	3.0
360	13.3	4.0	0.0	2.3	0.0	1.4	0.0	2.2	0.0	0.6	4.3	2.7
460	20.0	6.5	6.5	3.8	7.5	2.0	11.1	2.7	9.2	2.0	15.2	2.8

*The ratios are fatal involvements per 100 involvements in all fatal and injury accidents.
†RT = route; TT = tractor trailers; Others = all vehicles other than tractor trailers.

Table A-49

INJURY AND FATAL ACCIDENT INVOLVEMENT RATES ON PRIMARY NON-STAA* ROUTES

RT†	1980		1981		1982		1983		1984		1985	
	TT†	Others†	TT	Others	TT	Others	TT	Others	TT	Others	TT	Others
1	13.3	1.9	0.0	2.0	0.0	0.7	16.6	1.3	7.4	1.3	7.1	1.1
10	20.0	3.7	33.3	5.9	0.0	1.6	6.2	1.5	25.0	2.4	12.5	2.7
11	5.8	2.1	13.3	4.8	0.0	2.5	0.0	1.7	4.0	3.1	5.8	2.2
15	5.8	6.7	0.0	3.4	7.1	4.7	21.7	3.3	25.0	6.7	5.2	2.2
17	15.7	4.0	3.8	3.7	4.7	4.4	7.1	2.3	11.1	3.2	3.5	1.8
50	14.2	1.8	0.0	2.2	0.0	1.2	12.5	1.4	6.6	2.3	37.5	1.2
60	7.1	4.6	0.0	3.0	0.0	1.8	9.0	1.7	15.3	1.5	9.0	0.8

*The ratios are fatal involvements per 100 involvements in all fatal and injury accidents.

†RT = route; TT = tractor trailers; Others = all vehicles other than tractor trailers.

Table A-50

ANOVA RESULTS FOR HYPOTHESIS II*

Highway Type/	*F*(*n*, *d*)*		
Era	Interstate	STAA Primary	Non-STAA Primary
Pre-STAA	$F(1, 40) = 0.12$	$F(1, 40) = 0.22$	$F(1, 40) = 3.27$
Post-STAA	$F(1, 40) = 0.01$	$F(1, 40) = 3.26$	$F(1, 40) = 5.23$

*$F(n, d)$ = F value with numerator = n, denominator = d.

Table A-51

PROBABILITY VALUES FOR HYPOTHESIS II*

Highway Type/	Type I Error Probability*		
Era	Interstate	STAA Primary	Non-STAA Primary
Pre-STAA	0.731	0.642	0.079
Post-STAA	0.921	0.079	0.028

*Probability = the probability of error in rejecting the null hypothesis.

Table A-52

MEAN INVOLVEMENT RATIOS*

		Interstate	STAA Primary	Non-STAA Primary
Tractor trailer	B†	5.859	5.684	6.892
	A†	5.119	6.485	11.853
Other vehicle	B	3.396	3.393	3.234
	A	3.483	2.514	2.221

*Involvement ratio in fatal accidents = (100 x Total involvement in fatal crashes)/Total involvement in fatal and injury accidents.

†B = (1980–1982); A = (1983–1985).

Table A-53

ANNUAL FATAL INJURY ACCIDENT INVOLVEMENT RATES

Year	Interstate		STAA Primary		Non-STAA Primary	
	Tractor Trailer	Other Vehicles	Tractor Trailer	Other Vehicles	Tractor Trailer	Other Vehicles
1980	48.00	47.25	93.47	115.13	100.43	162.48
1981	40.49	46.22	85.28	126.26	120.70	165.80
1982	44.77	38.76	67.77	106.85	93.86	144.80
1983	39.48	40.88	92.15	116.70	129.11	160.00
1984	53.05	39.51	97.16	120.24	125.20	158.83
1985	46.31	44.02	78.20	127.04	103.27	164.52

*Number of fatal injury involvements per 100 million VMT.

Table A-54

RELATIVE INVOLVEMENT OF TRACTOR TRAILERS IN FATAL INJURY ACCIDENTS BEFORE AND AFTER STAA*

Year	Interstate			STAA Primary			Non-STAA Primary		
	Ratio	B/A	% Increased	Ratio	B/A†	% Increased	Ratio	B/A†	% Increased
1980	1.016			0.812			0.618		
1981	0.876	1.016		0.675	0.707		0.728	0.665	
1982	1.155			0.634			0.648		
			+10.24			+4.38			+11.43
1983	0.966			0.790			0.807		
1984	1.343	1.120		0.808	0.738		0.788	0.741	
1985	1.052			0.618			0.628		

*Relative involvement = ratio of tractor trailer involvement rate and other vehicle involvement rate.
†B/A = before and after STAA.

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