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Operational Impacts of Wider Trucks on Narrow Roadways

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FOREWORD

This report, FHWA-RD-90-103, contains information on the performance of 102-inch trucks and 96-inch trucks, of various lengths, and the impact these trucks have on other traffic. The information in the report will be useful to engineers involved in the design and operation of highways with a significant amount of truck traffic.

The type of highways where data were collected and analyzed were two-lane and multi-lane undivided rural roadways. The predominant truck types studied were tractor semitrailers with trailer lengths between 40 and 53 feet and widths of 96- or 102-inches. Therefore, the results of this study should not be extrapolated to other types of roadways or other types of trucks, especially wider or longer trucks.

This study was conducted as part of a Highway Planning and Research Pooled-Fund study. A technical panel including representatives from the various States monitored the study. We would like to express our appreciation to the State representatives for their suggestions and comments during the course of the study.

Sufficient copies of this report are being distributed to provide a minimum of one copy to each Region and Division Office and State highway agency. Direct distribution is being made to the Division Offices. Additional copies for the public are available from the National Technical Information Service (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. A small charge will be imposed by NTIS.

R J Betsold
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Operations Research and Development

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16. Abstract

This study was conducted to determine the differences in performance between 102-in (259-cm) wide and 96-in (244-cm) wide trucks and the impact that these trucks have on other traffic. Trucks which were studied primarily included random trucks in the traffic stream, although a limited amount of control truck data were also collected to account for driver differences. Truck data were collected on rural two-lane and multilane roads which included curve and tangent sections and a variety of roadway widths and traffic conditions. The data collection effort resulted in approximately 100 hours of videotape and 9,000 slides from which various measures of effectiveness (MOE's) were extracted.

A number of MOE's were used to test for the operational effects of differential truck widths, lengths, and configurations. Such measures included: (1) lateral placement of the truck and the opposing or passing vehicle, (2) lane encroachments by the truck or opposing vehicle, and (3) edgeline encroachments by the truck or opposing vehicle. Analysis of variance (ANOVA) and regression modeling techniques were used to determine the significance of and the relationship among the variables used.

This final report summarizes the differential effects of the operation of 96-in (244-cm) versus 102-in (259-cm) wide trucks as a function of roadway width, curvature, and other site parameters which should impact their safe operation and that of other traffic. The results of this study are presented to help organizations develop guidelines which specify the geometric and operational parameters under which wider trucks may safely operate.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.093	metres squared	m²
yd²	square yards	0.836	metres squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometres squared	km²

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
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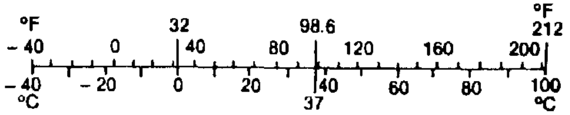

* SI is the symbol for the International System of Measurement

(Revised April 1989)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Officials
ANOVA	analysis of variance
BMCS	Bureau of Motor Carrier Safety
CB	citizens-band
CCTV	closed circuit television
CFR	Code of Federal Regulations
cm	centimeter(s)
df	degrees of freedom
DMI	distance-measuring instrument
FAP	Federal-aid Primary
FHWA	Federal Highway Administration
ft	(1) foot, (2) feet
in	inch(es)
kg	kilogram(s)
km	kilometer(s)
KRA	kingpin-to-rear axle
lb	pound(s)
m	meter(s)
mi	mile(s)
MOE	measure of effectiveness
MVM	million-vehicle miles
PSU	Primary Sampling Unit
R^2	coefficient of regression
STAA	Surface Transportation Assistance Act
TRB	Transportation Research Board
UMTRI	University of Michigan Transportation Research Institute
VHS	video home system
vs.	versus

CHAPTER 1 - INTRODUCTION

BACKGROUND

The Surface Transportation Assistance Act (STAA) of 1982 (P.L. 97-424) was enacted on January 6, 1983. This piece of legislation contained provisions that have had a major impact on the Nation's trucking industry. Among the changes included in the STAA of 1982 were requirements for States to allow the following:

- Trailers with lengths up to 48 ft (14.6 m), previously 45 ft (13.7 m), and widths up to 102 in (259 cm), previously 96 in (244 cm), on the Interstate System and designated Federal-aid Primary (FAP) highways.

- Vehicles weighing up to the maximum permissive weight limit of 80,000 lb (36,320 kg) on the Interstate System.

- Twin trailers (two 28-ft (8.5-m) trailers) on the Interstate System and designated FAP highways.

With these changes came an increase in the use of longer and wider trucks. In fact, 70 percent of the van trailers purchased in 1984 were 102 in (259 cm) wide instead of the older 96 in (244 cm).(1) This increase in the use of wider trucks has stimulated concern as to whether the operation of wider trucks in the traffic stream impacts the safety of other vehicles on the roadway.

While the STAA of 1982 was intended to allow these wider trucks to operate only on routes with lane widths of 12 ft (3.7 m) or greater, the wording of the act and recent amendments have changed the outcome. The STAA allows the operation of 102-in (259-cm) wide trucks on highways *designed* with lane widths of 12 ft (3.7 m) or greater. However, many of these highway segments have been reconfigured to increase the number of lanes, thus decreasing the lane widths to 10 or 11 ft (3.0 or 3.4 m). Even though these highways are inadequate in terms of lane width under the new configuration, their original *design* width of 12 ft (3.7 m) still allows for the operation of the wider trucks.

On the other hand, amendments to the STAA, as stated in the Tandem Truck Safety Act (1984), have allowed some States to exempt segments of the Interstate System from allowing the operation of 102-in (259-cm) wide trucks even though these segments may be adequate in terms of lane width and other geometrics. A State's governor may file a request with the Secretary of Transportation listing the safety problems perceived to be the result of wider truck operations on a specific Interstate segment. A decision is then made as to whether the segment will be included on the National Network for trucks.

The lack of information concerning the safety of wider trucks makes the decisions about which routes are adequate for such operation difficult to justify. This leads to considerable controversy over the decisions made with respect to route designation. For example, the Motor Carrier's Road Atlas clearly shows that some States such as Arkansas, Ohio, and Indiana have extensive truck networks, whereas few routes in New York and Arizona allow large trucks.(2) This study was designed to examine the safety effects of wider trucks on narrow roadways to enable future decisions concerning operational impacts to be based on sound transportation engineering research.

STUDY OBJECTIVE AND GENERAL RESEARCH APPROACH

The purpose of this study was to determine the effects of truck width (102 in (259 cm) versus 96 in (244 cm)) on traffic operations and safety under various roadway and traffic conditions. Several different truck lengths and configurations, and their relative performance, were also investigated as part of this study. The study primarily focused on random trucks in the traffic stream, although a limited amount of control truck data were also collected to account for driver differences.

Numerous measures were used to test for the operational effects of differential truck widths, lengths, and configurations. Such measures included: (1) lateral placement of the truck and the opposing or passing vehicle, (2) centerline encroachments by the truck or opposing vehicle, and (3) edgeline encroachments by the truck or opposing vehicle. Truck data were collected on two-lane and multilane rural roads which included curve and tangent sections, a range of roadway widths, and a variety of traffic conditions.

In another phase of the study, existing truck fleet data bases were examined to assess the feasibility of quantifying the safety impacts of wider trucks. The results of this investigation led to recommendations on the most feasible manner to conduct an accident analysis of various truck sizes. A discussion of the work conducted in this phase of the study is contained in appendix B of this report. Since budget restrictions prevented actual conduct of the recommended analysis, the remaining study efforts focused on operational measures as the research criteria.

ANALYSIS ISSUES OF CONCERN

As noted above, the primary focus of this study was to compare the safety and operational effects of 102-in (259-cm) wide trucks versus 96-in (244-cm) wide trucks. However, there are many other truck characteristics which also influence truck operation which must be accounted for, to the extent possible, in a carefully-controlled study. Some of these other characteristics include truck configuration (i.e., semitrailers vs. doubles vs. triples), trailer length (e.g., 40 ft (12.2 m), 45 ft (13.7 m), 48 ft (14.6 m), and 53 ft (16.2 m)), kingpin-to-rear axle distance, and other truck features.

Differences in driver experience and skill can also greatly influence truck safety as measured by accidents and those operational characteristics related to safety like lane encroachments. In addition, roadway features such as lane and shoulder width, horizontal curvature, roadway grades, sight distance, and traffic control devices can greatly affect truck operations. Thus, it would not be possible to determine the effect of truck width on traffic operations by comparing operations of a 96-in (244-cm) wide, 45-ft (13.7-m) semi travelling on an urban multilane road with driver A, who is inexperienced and drowsy, with a 102-in (259-cm) wide, 48-ft (14.6-m) semi travelling on a rural two-lane road driven by driver B, who is experienced and alert. Obviously, the many vehicle, driver, and roadway features all interact to affect the safety and operations of the vehicle. Thus, it is desirable when collecting data to properly account for the numerous vehicle, roadway, and driver variables to the extent possible.

In order to fully address the truck width issue in its entirety, it was important to consider the other "truck system" variables (e.g., length, trailer configuration) which also affect operational measures related to safety on a given set of geometrics. As a result of this need to examine these other truck characteristics, it was considered practical to examine, to some degree, additional questions related to operational measures. Thus, the primary issue was:

- What are the operational effects of 102-in (259-cm) wide trucks compared to 96-in (244-cm) wide trucks while accounting for other truck and driver characteristics?

The data analysis plan was structured to address this issue along with a number of secondary issues which included:

- *Subissue 1* - How do the various truck configurations (e.g., semitrailers vs. doubles) compare with each other with respect to operational practices?

- *Subissue 2* - What are the effects of truck trailer length (e.g., 45 ft (13.7 m) vs. 48 ft (14.6 m)) and kingpin-to-rear axle distance on operational practices with respect to trailer width (96 in (244 cm) vs. 102 in (259 cm))?

- *Subissue 3* - How do the operational characteristics of various truck types and sizes compare with cars? In other words, to what degree are the large trucks, relative to cars, causing operational problems?

- *Subissue 4* - For a given truck type and size (e.g., 102-in (259-cm) wide, 48-ft (14.6-m) semi), how much variation in operational measures occurs due to driver differences? In other words, do all drivers handle a given truck type in relatively the same manner or in largely different manners?

- *Subissue 5* - For a given truck type and size, how much operational variation occurs for various roadway geometrics?

ORGANIZATION OF THE REPORT

This report summarizes the differential effects of the operation of 96-in (244-cm) wide trucks versus 102-in (259-cm) wide trucks as a function of other truck characteristics such as length and configuration, geometrics such as roadway width and curvature, and other site parameters which may impact the safe operation of other traffic. These results will be of great value in developing guidelines to specify the geometric and operational parameters under which wider trucks may safely operate.

A review of the literature on the operational effects of truck size is provided in chapter 2. The detailed research methodology is presented in chapter 3 while the details of the data collection and data reduction are given in chapter 4. Chapters 5 and 6 contain the details of the data analyses and results from observations of traffic stream trucks and control trucks, respectively. The summary and conclusions are provided in chapter 7, and other issues relevant to the study are discussed in chapter 8.

CHAPTER 2 - LITERATURE REVIEW

While many studies have been conducted in recent years related to large truck safety and operations, only a few of them have specifically investigated the effects of truck width. Presented here is a summary of the literature reviewed for this study. The entire literature review is contained in appendix A.

In 1982, Seguin et al. studied the effects of truck size on vehicles performing same-direction passing maneuvers around trucks on two-lane roads, as well as the impact of truck size at freeway entrances and on narrow bridges. Using an expandable control truck with widths of 96 to 114 in (244 to 290 cm), in 6-in (15-cm) increments, on a two-lane tangent section, data were collected on same-direction passing maneuvers. A statistical analysis of passing time, distance, and speed for 434 trials revealed no major differences caused by truck width. However, the speed of 1,292 opposing vehicles was slightly higher for the 108-in (274-cm) truck compared to the 96-in (244 cm) truck. Also, as might be expected, lateral separation between the control truck and passing or opposing vehicles decreased as the width of the truck increased. However, the frequency of shoulder encroachments was not affected by truck width. The authors concluded that drivers were sensitive to truck width, but that the added width did not create a safety hazard.(3)

A 1986 study by Zegeer, Hummer, and Hanscom studied the effects of various truck configurations (semis and doubles), lengths (40 ft (12.2 m), 45 ft (13.7 m), and 48 ft (14.6 m)), and widths (96 in (244 cm) and 102 in (259 cm)) at intersections and on two-lane roads with respect to traffic operations and safety. Computer simulations of truck offtracking revealed that 102-in (259-cm) wide trucks generally have maximum offtracking distances which are 0.5 ft (0.15 m) to 1.5 ft (0.45 m) greater than 96-in (244-cm) wide trucks, depending on the road geometry and truck configuration. The kingpin-to-rear axle distance was found to have a much greater effect on truck offtracking than the added 6 in (15 cm) of truck width. Field studies were also conducted using various sizes of control trucks on two-lane roads, and both traffic stream and control trucks at intersections in two States (New Jersey and California). The longer and wider trucks (102-in (259-cm) wide, 28-ft (8.5-m) doubles and 102-in (259-cm) wide, 48-ft (14.6-m) semis) were found to have greater operational problems (e.g., increased turning times) and to produce a greater change in lateral placement by opposing vehicles for some restrictive geometrics when compared to shorter, narrower trucks.(4)

A 1977 study by Parker in Virginia used traffic conflicts and evasive maneuvers as measures to assess the safety problems associated with 12-ft (3.7-m) to 14-ft (4.3-m) wide housing units. Data were collected with cameras mounted on research vehicles, and 832 conflicts were observed for the 14-ft (4.3-m) wide units compared to 737 conflicts for the 12-ft (3.7-m) wide units. The author concluded that narrow pavements on mainly two-lane roads should be avoided when transporting these oversized loads.(5)

In 1973, Kakaley et al. compared the offtracking effects of 102-in (259-cm) (MC-6) and 96-in (244-cm) (MC-7) wide buses. The wider bus was found to offtrack beyond 12-ft (3.7-m) lanes on curves of 27 degrees, while curves of 31 degrees or more were encountered before the narrow bus exceeded the 12-ft (3.7-m) lane width. Results from field observations made during the same study showed no significant differences between the two width buses with respect to lateral placement of passing or opposing vehicles.(6) A similar 1972 study by Weir and Sihilling studied effects of vehicles passing buses of 96-in (244-cm) and 102-in (259-cm) widths on two-lane and multilane roads in rural flat terrain. The data revealed no differences in the lane placement of passing vehicles between the two types of buses.(7)

Gericke and Walton examined effects of increased legal truck size limits on highway geometric design elements based on an investigation of the American Association of State Highway and Transportation Officials' (AASHTO) standards and formulas. Truck configuration and length were identified as the primary factors in AASHTO's pavement width formula. The authors recommended lane widening to at least 12 ft (3.7 m) to ensure safe operation of 102-in (259-cm) wide trucks. Strict adherence to AASHTO shoulder width standards was also recommended to handle the larger trucks.(8)

In summary, truck length and configuration have been found to have more impact on operations which may be related to safety than truck width. However, there appears to be increased offtracking, up to about 1.5 ft (0.45 m), for the 102-in (259-cm) wide truck when compared to the 96-in (244-cm) wide truck. While limited research is available on other isolated effects of truck width, there is some evidence that it can adversely affect traffic operations, particularly under restrictive geometrics.

CHAPTER 3 - RESEARCH METHODOLOGY

Considering the analysis issues discussed in chapter 1, the collection and analysis of truck operational data first required addressing the following items:

- Data collection and analysis limitations.
- Roadway situations of interest.
- Operational measures.
- Analysis framework.

DATA COLLECTION AND ANALYSIS LIMITATIONS

Several real-world limitations were identified which had to be faced regarding data collection and analysis:

- *Limitation 1* - Not all truck lengths are commonly found in 96-in (244-cm) and 102-in (259-cm) widths. For example, most 45-ft (13.7-m) semis are 96 in (244 cm) wide and most doubles and 48-ft (14.6-m) semis are 102 in (259 cm) wide. This may cause difficulties in comparing various truck widths for certain truck configurations and lengths.

- *Limitation 2* - The most critical truck sizes (e.g., 48-ft (14.6-m) or 53-ft (16.2-m) semis which are 102 in (259 cm) wide) are, for obvious reasons, not typically allowed on roadways with highly restrictive geometrics (e.g., two-lane roads with severe curvature, narrow shoulders, and lane widths of 10 ft (3.0 m) or less). Thus, it will be difficult to determine the operational practices of such large trucks on roadways with highly restrictive geometrics.

- *Limitation 3* - Measuring the width and length of traffic stream trucks accurately will require either: (1) developing a procedure for measuring moving trucks, or (2) finding locations where trucks are stopped (e.g., truck stops, portable or permanent weigh stations, and rest areas). Finding such locations might not allow for selecting roads with all of the desired geometric features of interest.

- *Limitation 4* - The driving population of one size of trucks (e.g., 102-in (259-cm) wide trucks) might be more experienced than drivers of another size of trucks (e.g., 96-in (244-cm) wide trucks) which would cause problems in directly comparing traffic stream trucks of those two sizes.

- *Limitation 5* - There is no universally accepted definition of "acceptable" versus "unacceptable" tolerances when operational measures are being studied. Thus, this study had to include decisions concerning, for example, how much edgeline encroachment is "unacceptable" and how much lateral clearance between the truck and the opposing vehicle is "acceptable."

The data collection and analysis procedures were structured to deal with these and other limitations to the extent possible.

ROADWAY SITUATIONS OF INTEREST

There are many types of roadway situations where the additional truck width may present a potential safety problem for the truck itself and/or other vehicles with which the truck interacts in the traffic stream. Examples of such roadway situations include:

- Narrow two-lane roads, particularly on horizontal curves, where wider trucks may encroach over the edgeline or centerline causing it or other vehicles to run off the road.

- Multilane roads with narrow lanes where wider trucks may encroach into adjacent lanes causing same direction passing traffic to change speed or lateral placement. Arterial routes in New Jersey are known to have this problem.

- Narrow bridges, particularly long bridges with little or no shoulders, where wider trucks may be forced to travel dangerously close to the bridge rail to remain in the proper lane and/or may encroach over the centerline causing severe problems for opposing traffic.

- Steep grades, particularly in conjunction with horizontal curves and narrow lanes, where large trucks typically are forced to reduce speeds on upgrades and often travel at relatively high speeds on downgrades. The added truck width may create additional safety problems for opposing traffic on two-lane roads and for same-direction passing traffic on both two-lane and multilane roads.

- Urban freeways having poor alignment, lanes less than 12 ft (3.7 m) wide, and high truck volumes, where the extra truck width could create problems when wide trucks pass other wide trucks.

- Intersection turns involving sharp turning radii and/or narrow street widths, where wider trucks result in greater offtracking. This can adversely affect other traffic either stopped on other approaches which lie within the truck offtracking region, or vehicles passing through the intersection in the same or opposing direction.

- Other critical locations such as freeway on-ramps, off-ramps, median turnarounds, narrow driveway entrances, sites with limited sight distance, etc.

As can be seen from the above list, there are a number of critical situations where increased truck width may impact the operations and safety of other traffic. However, time and budget constraints required the selection and examination of those situations believed to be the most prevalent. The situations selected for the study were those which most closely met the following criteria:

- Situations in which traffic was expected to be most adversely affected by the additional 6 in (15 cm) of truck width.

- Situations where meaningful safety-related data, which are related to truck width, could be collected and truck dimensions accurately measured.

- Situations which are frequently found in the "real-world."

After careful consideration of the various roadway situations for possible data collection, the two types of roadway situations selected for field testing included two-lane roads and multilane roads, both with narrow and wide lanes (including curves and tangents).

It is clear that two-lane roads can present a problem for wide and long trucks, particularly where horizontal curves and/or narrow lanes exist. The types of problems which may exist on two-lane roads, as a result of wider trucks, include run-off-road type accidents often resulting in rollover due to the truck dropping a tire off the pavement, or head-on collisions resulting when a wider truck crosses into the adjacent lane when an opposing vehicle is present. Also, because a great majority of roadways in the U.S. are two-lane, and since they will naturally include a variety of geometrics (curves, tangents, narrow lanes, wide lanes, etc.), such roads were an excellent choice for data collection.

Wider trucks can also cause problems on multilane roads with narrow lanes, particularly on curves, since same-direction passing maneuvers between two vehicles, especially two wide trucks, present the potential for sideswipe accidents. When such roadways are undivided, the potential for head-on or opposite-direction sideswipe accidents is created for a truck in the left lane and any opposing vehicle (particularly if either vehicle is encroaching over the centerline). Many miles of undivided multilane road are currently on the National Network for trucks (*see chapter 1*), and more needs to be known about the safety and operations of wide trucks on such routes. Thus, multilane roads were also selected as candidates for data collection.

The types of roadway situations not selected for field testing of truck width effects included:

- Steep grades - These conditions primarily result in problems with truck braking on downgrades and acceleration on upgrades. Some variation in grade naturally occurred within the two-lane and multilane sections which were selected. In addition, the effects of grades on trucks have been rather extensively researched for the FHWA in the recent past.

- Intersection turns - Intersection turns are often a problem for large trucks. For example, some delay and operational problems occur when long trucks (e.g., 48-ft (14.6-m) semis) turn right at intersections with tight turning radii and/or narrow lanes. However, truck turn accidents are not considered as serious a problem as other types of truck accidents, due to their lower impact speeds and relatively low frequency of occurrence. Also, this issue was recently studied for the FHWA by Zegeer, Hummer, and Hanscom.(4)

- Narrow bridges - Narrow bridges can also pose problems for wider trucks, particularly when a wide truck meets a wide truck on a narrow, two-lane bridge. However, most bridges are relatively short and the chance of two trucks meeting on a bridge is relatively remote, unless the bridge is several miles long. This would make data collection difficult and impractical. In any case, data collection on narrow two-lane roads allows for detecting any problems of wide trucks on narrow pavements.

- Urban Freeways - The majority of urban freeways are designed with lane widths and shoulder widths which are adequate for wide trucks. For those cases where there are sections with narrow lanes or narrow shoulders, it is expected that operations will be similar to those found on the multilane roads chosen for this study. In addition, high traffic volume and high speeds would make the data collection increasingly difficult.

- Other situations - Freeway on-ramps, off-ramps, median turnarounds, narrow driveway entrances, etc. may also pose problems for wide trucks. However, they are not considered as much a safety or operational problem as the roadway situations selected, and operational data at such sites would be more difficult to collect.

OPERATIONAL MEASURES

Operational measures to be used for evaluating truck differences on the selected roadway situations should:

- Be most likely to be affected by the additional truck width.

- Be practical to obtain in the field or reduce from collected data.

- Have a logical relationship to safety, i.e., be related to the types of potential accidents discussed above (head-on, sideswipe, run-off-road).

The types of measures which are appropriate and which can practically be collected depends on whether unbiased traffic stream truck data are collected (i.e., without the truck driver being aware that data are being collected) or whether a control truck is being used (i.e., a driver is hired to drive two or more truck sizes down preselected routes and thus is aware that data are being collected). For example, when employing control trucks, a trailing data collection vehicle may use a moving radar unit to record speeds of opposing vehicles when they are beside the truck. Such radar units cannot be used when following traffic stream trucks since many truck drivers use radar detectors and would likely alter their driving behavior (e.g., slow down) when they discovered the use of radar.

Many types of appropriate measures for testing the effects of differential truck widths can be found in past studies. For example, several speed and lateral placement measures were used for comparing the effects of long and wide trucks on two-lane rural roads in the study conducted by Zegeer, Hummer, and Hanscom.(4) Using a control truck of known size, as well as lead and trail vehicles, the following data were collected relative to opposing vehicles:

- Speed change (speed of opposing vehicles in advance of the lead car minus the speed when next to the truck).

- Lateral placement change (lateral placement when beside the lead car minus lateral placement when beside the truck).

- Percent of opposing vehicles slowing down (from the lead car to the truck) by more than 5 mi/h (8 km/h).

- Centerline and edgeline encroachments when beside the lead car and the truck.

The research team also collected numerous types of operational data at urban intersections, including truck and vehicle conflicts; centerline, adjacent lane, and curb encroachments; and truck turn time. These measures were collected for both control and traffic stream trucks.(4)

Hanscom, in his 1981 study on the effect of truck size and weight on operations, collected numerous data regarding basic flow descriptors, flow perturbations, rear-end accident potential, flow delay, and passing interactions. These measures were used for a variety of location types, including urban intersections, interchanges, two-lane passing situations, grade and curve combinations, curves, and rural two-lane roadways.⁽⁹⁾

Thus, there are data which have been successfully collected and used for comparison purposes in past projects. Knowledge of these measures was combined with the criteria listed above to help define the data which were used for this study.

In general, there were two basic types of operational measures collected in the current study. The first type involved *truck data* -- speed, lateral placement, and encroachments of the truck as it traversed the selected routes. The second type involved *interaction data* -- lateral placements and speeds of vehicles which passed the subject truck in the opposing direction or same direction.

For the current study, the data were collected by following trucks along preselected routes using two data collection instruments -- a 35-mm camera and a video camera. Using the 35-mm camera, slides were taken of opposing vehicles when they were directly beside the rear of the truck. These slides were used to scale off the lane placement of the truck being followed and the lane placement of the opposing vehicle when the vehicles were side-by-side. Edgeline and centerline encroachments by either the truck or the oncoming vehicle were also indicated. For reference purposes, this slide data base was termed the *lane placement data file*. Included in the file were the following specific two-lane road operational measures:

- Measures thought to be related to run-off-road accidents, including:
  - Edgeline encroachments.
  - Distance from the edge of pavement.
  - Proportion of vehicles within 1 ft (.31 m) of the edge of pavement.
- Measures thought to be related to head-on or opposite direction sideswipe accidents, including:
  - Distance from the centerline.
  - Proportion of vehicles within 1.75 ft (.53 m) of the centerline.
  - Clearance distance between the truck being followed and the opposing vehicle.

The selection of the lateral placement measures listed above required defining a consistent point of reference for comparison purposes. Since the roadway edgeline could easily be seen in the slides, the use of *edgeline encroachments* was an obvious choice as an operational measure. However, since relatively few trucks encroached the edgeline in the slides taken, other points of reference were needed to define lateral placement of trucks within the traffic lane.

Distance from the edge of pavement was defined as the distance from the outside tire edge of the vehicle to the edge of the paved surface. Where no paved shoulder existed, this was the distance from the tire to the outside edge of the paved lane. Where a paved shoulder existed, it was the distance from the tire to the outside edge of the shoulder. Distance from the edge of pavement was considered to be perhaps a better measure of potential run-off-road crashes than edgeline encroachments. This is due to the fact that trucks and other vehicles often encroach onto a paved shoulder intentionally to increase the clearance distance to opposing vehicles, while still being positioned several feet from the outside edge of the paved shoulder. Although an edgeline encroachment occurred, the vehicle was probably in no real danger of a run-off-road type accident.

A distribution of truck lane placement data revealed that a point within 1 ft (.31 m) of the edge of pavement was associated with an adequate number of occurrences for comparison purposes, was easy to measure, and was thought to be related to run-off-road type accidents. Thus, the proportion of vehicles within 1 ft (.31 m) of the edge of pavement (termed *CLOSE*) was also used as an operational measure.

Similar criteria were used for selecting operational measures thought to be related to head-on or opposite direction sideswipe accidents. *Distance from the centerline* was a logical choice and was easily measured since the centerline was an obvious, visible point of reference on the slides. The *clearance distance between the truck being followed and the opposing vehicle* represented the closeness of the vehicles when they were side-by-side, and should be related to the likelihood of a collision.

The *proportion of vehicles within 1.75 ft (.53 m) of the centerline* was also selected for several reasons. First of all, since very few trucks encroached the centerline in the slides taken, the measure of centerline encroachments was of limited usefulness. Therefore, some specified point of reference was needed. The 1.75 ft (.53 m) distance was derived from the simple fact that a 102-in (259-cm) wide truck which is centered in a 12-ft (3.7-m) wide lane would leave 1.75 ft (.53 m) between either side of the truck and the centerline or edgeline. Also, a review of the lateral placement distribution of trucks revealed that a value of approximately 1.75 ft (0.53 m) from the centerline resulted in an adequate sample of trucks for statistical comparisons of the various truck sizes.

The second data base, termed the *encroachment data file*, was simultaneously developed from the videotape which provided a real-time record of the path of the truck (or car) being followed in terms of its number of centerline and edgeline encroachments along the preselected routes. The video data measures collected on two-lane roads were:

- Number of edgeline/centerline encroachments per mile.
- Number of edgeline/centerline encroachments per mile which exceeded 1 tire width.
- Number of edgeline/centerline encroachments per mile which exceeded 2 tire widths.
- Number of edgeline/centerline encroachments per mile which exceeded 3 tire widths.

For multilane roads, the edgeline measures were the same as those listed above for two-lane roads. Laneline encroachments (i.e., encroachments into the adjacent, same-direction lane) were also recorded for the truck (or car) being followed. However, data related to clearance distances and centerline distances were only appropriate for undivided multilane situations where the truck was in the left lane (i.e., the passing lane).

ANALYSIS FRAMEWORK

The framework for the collection and analysis of operational data required determination of the following:

- Roadway geometrics of concern.
- Sizes and configurations of trucks for data collection and analysis.
- Source of truck sample (i.e., use of traffic stream and/or control trucks).

Roadway Geometrics of Concern

In the recent study of the effect of truck size on opposing vehicle operations on two-lane roads, a variety of roadway variables were collected for each vehicle passing a control truck. Using the analysis of variance, the roadway geometrics found to affect the operational measures, relative to opposing vehicles passing large trucks on two-lane roads, were lane and shoulder width, and the presence and degree of curve.(4)

The data collection plan for the current study was structured to include these and other geometric and roadway variables considered to be important in affecting truck operations and included the following:

- Number of lanes (two-lane or multilane roadway).
- Presence of median (multilane roads only).
- Lane width.
- Width of paved shoulders.
- Degree and length of curves.
- Traffic volume.
- Percent trucks.
- Presence of bridges.
- Speed limit.

As discussed later in chapter 4, sites were selected to cover a range of lane and shoulder widths, traffic volume, curvature, and other roadway features. This allowed for comparing the operational effects of different truck sizes on wide versus narrow lanes, tangents versus curves, etc.

Truck Sizes and Configurations

The primary objective of this study was to compare the operations of truck widths (96 in (244 cm) versus 102 in (259 cm)) for various trailer lengths, including tractors with 45-ft (13.7-m) and 48-ft (14.6-m) trailers. Also, if possible, some comparison of doubles to semis was desired.

One potential problem which was addressed during the development of the analysis plan was the possibility of not finding comparable truck lengths of differing widths. For example, it was thought that a great majority of 48-ft (14.6-m) semis and 28-ft (8.5-m) doubles would be 102 in (259 cm) wide and nearly all 45-ft (13.7-m) semis would be 96 in (244 cm) wide. If this were indeed true, there would be a problem in comparing 96-in (244-cm) wide semis to 102-in (259-cm) wide semis for the same trailer length and type.

To determine whether adequate samples of both width trailers existed for truck types of interest, a total of 693 trucks were randomly selected at truck stops and weigh stations in North Carolina in a preliminary survey study. Each sampled truck was measured to determine its trailer(s) length, overall truck length, and width.

A summary of this information is provided in figures 1 and 2. The number of trucks with various dimensions is shown separately in figure 1 for trucks measured at Interstate truck stops, two-lane truck stops, and weigh stations (located off I-85 near Hillsborough and I-40 near Statesville in North Carolina). As indicated in figure 2, 81.8 percent of all 48-ft (14.6-m) semis were 102 in (259 cm) wide while only 7.6 percent of the 45-ft (13.7-m) semis were this wide. Conversely, only 18.2 percent of the longer semis were 96 in (244 cm) wide while 92.4 percent of the shorter semis were this wide. Of the 58 doubles measured, 17 percent, 38 percent, and 45 percent had 26-ft (7.9-m), 27-ft (8.2-m), and 28-ft (8.5-m) trailers, respectively. Of all doubles, 36.2 percent were 96 in (244 cm) wide and 63.8 percent were 102 in (259 cm) wide. Of the 26 "28-ft (8.5-m) doubles," 23.1 percent were 96 in (244 cm) wide and the remaining 76.9 percent were 102 in (259 cm) wide.

These results suggest that the longer trucks (e.g., 48-ft (14.6-m) semis and 28-ft (8.5-m) doubles) are typically 102 in (259 cm) wide and the shorter trucks (e.g., 45-ft (13.7-m) semis) are more often 96 in (244 cm) wide. However, there did seem to be enough of both width trailers in the traffic stream for the three truck types of interest (28-ft (8.5-m) doubles and 45-ft (13.7-m) and 48-ft (14.6-m) semis) to allow for collecting an adequate sample of each.

Source of Truck Sample

For the types of trucks and roadway situations selected for field testing, the two most likely sources of truck data included: (1) observation of traffic stream trucks, and (2) observation of control trucks with a hired driver who repeatedly drove various trucks of known dimensions along a preselected route.

Each of these data sources offered certain advantages and limitations. Since this study involved an attempt to quantify the operational effects of truck widths for various truck types, traffic stream truck data would be useful to show what is happening in the "real-world" with the existing population of truck drivers. It should be remembered, however, that Zegeer, Hummer, and Hanscom found:

> "Overall, driving behavior at urban and rural sites and site differences had more of an effect on operations than the different truck types tested."(4)

In other words, the effect of a given truck on traffic operations may be influenced more by the characteristics of the driver (experience, skill, use of drugs or alcohol, fatigue level, state-of-mind, etc.) than of the truck. Thus, the influence of the truck driver had to be recognized in the data collection and analysis plan.

If one could assume the population of truck drivers were exactly similar in all respects for drivers of 102-in (259-cm) wide and 96-in (244-cm) wide trucks, then the traffic stream data alone could be used with little need for control truck data. However, since this assumption may well not be true, control truck data were also needed.

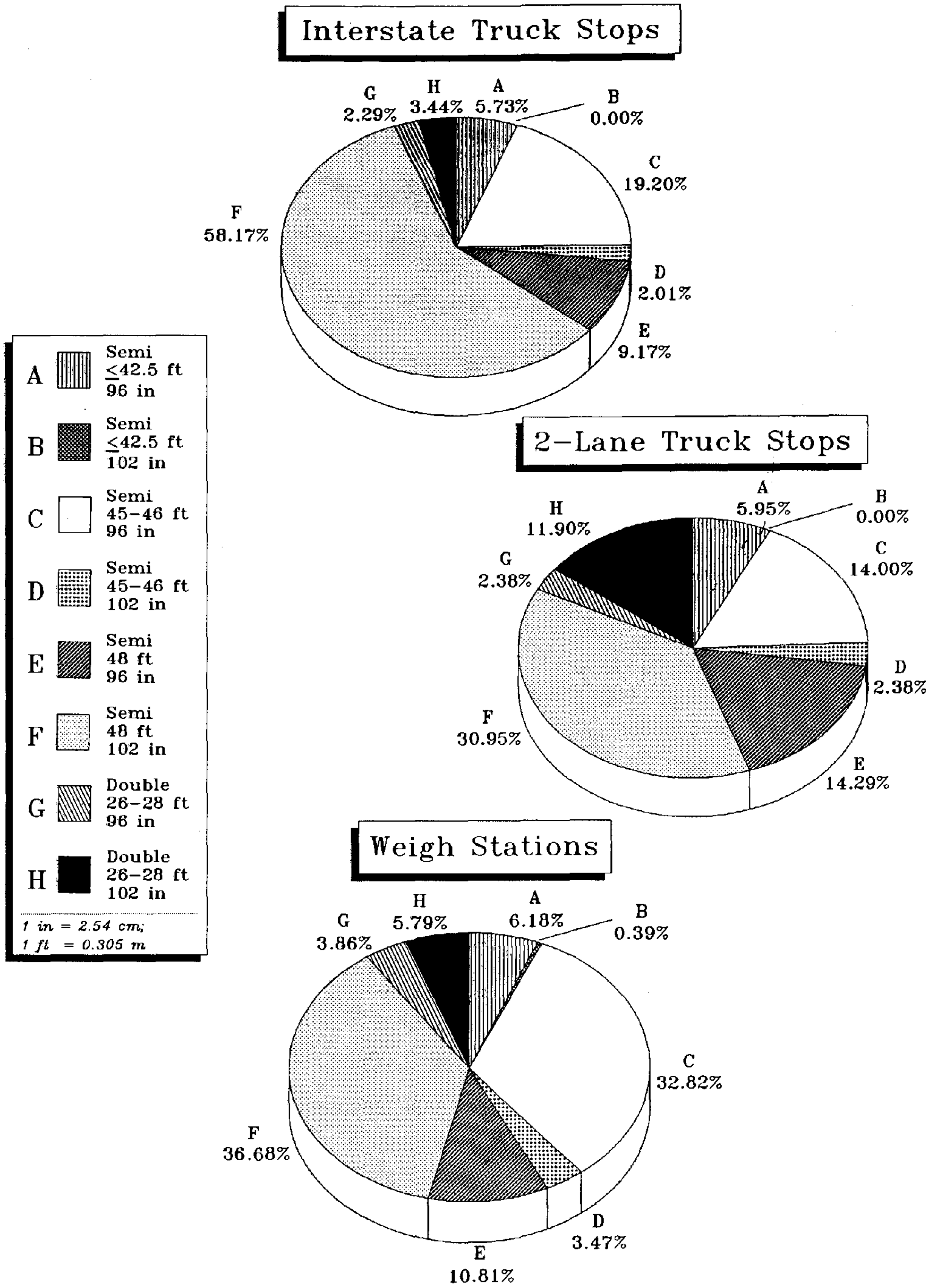


Figure 1. Results of truck length and width survey.

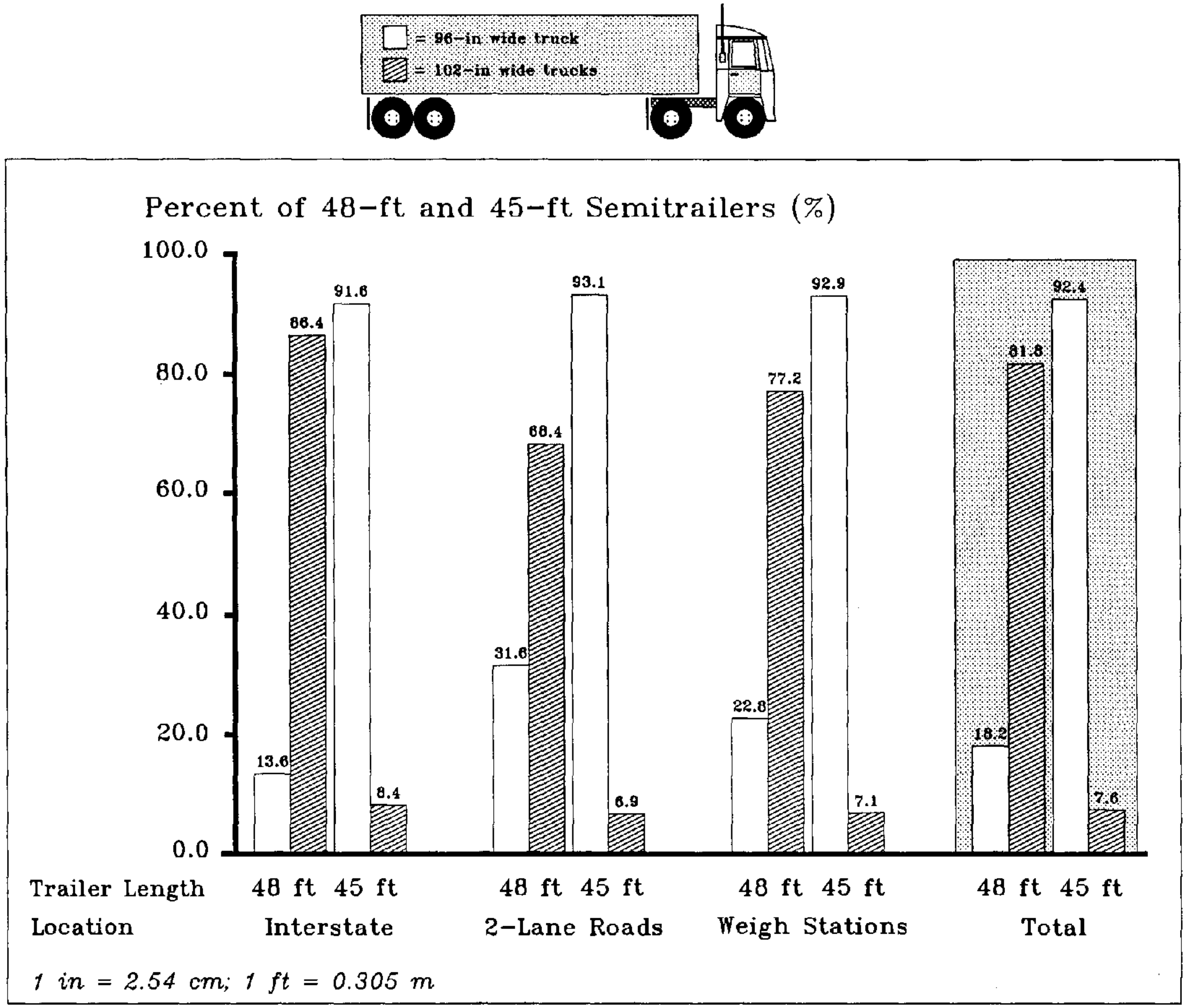


Figure 2. Distribution of 48-ft (14.6-m) and 45-ft (13.7-m) semitrailers by width and location.

Control truck data would help answer the question:

What is the effect of particular truck characteristics (e.g., 102-in (259-cm) wide vs. 96-in (244-cm) wide trailers) for a given driver on test sites having a variety of conditions?

Control truck data would also essentially help to control for the varying driver effects so more focus could be placed on truck size effects. The collection of both control truck data and traffic stream data provided more useful results in order to address the fundamental question:

If an operational problem is found to exist on certain roadway geometrics, is it due primarily to the added truck width alone, or to the poor driving performance of the traffic stream drivers?

Thus, if the added truck width is found to be a problem on certain roadway geometrics, possible solutions may be to prohibit 102-in (259-cm) wide trucks on those types of roadways. On the other hand, if problems are prevalent from traffic stream trucks but not for (experienced) drivers of similar-sized control trucks, then this may point to the need for increased truck driver training, stiffer licensing requirements for driving some trucks, etc.

Data were therefore collected and analyzed initially on traffic stream trucks at four selected sites. Then, at the site with the most restrictive geometrics, a highly-experienced driver was used with each of the four control trucks of interest:

- 96-in (244-cm) wide, 45-ft (13.7-m) semi.

- 102-in (259-cm) wide, 48-ft (14.6-m) semi.

- 96-in (244-cm) wide, 48-ft (14.6-m) semi.

- 102-in (259-cm) wide, 28-ft (8.5-m) double.

Comparing the results between the traffic stream trucks and control trucks provided insights into the influence of truck size and driver behavior on vehicle operations.

CHAPTER 4 - DATA COLLECTION AND REDUCTION

SITE SELECTION

The criteria for the sites selected for data collection were:

- The roadway segments selected had to consist of a number of different geometric characteristics (narrow and wide lane widths, varying degrees of curvature, paved and unpaved shoulders, etc.) in order to properly address the issues established in the research methodology and discussed in chapter 1.

- The truck volume, specifically the number of van trailers, had to be adequate to ensure efficient data collection. In other words, there had to be enough van trailers of the various dimensions needed to avoid having the data collection team waiting between runs for extended periods of time.

- The overall traffic volume had to be adequate to ensure that enough opposing vehicle interactions could be recorded on both curve and tangent sections of the routes.

Discussions with officials in several States revealed a number of potential sites with one or more of the characteristics described above. After obtaining maps, traffic volumes, and geometric data on specific routes from nine different States, a decision was made to focus efforts in three States (Arkansas, North Carolina, and Virginia) where a number of routes existed with all of the desired characteristics.

Within each of the three States, field visits were made to potential routes, where information such as route mileage, curve severity, traffic volume, and counts of van-type semis and doubles were obtained. These field observations were used to develop a final list of potential sites along with the advantages and disadvantages of each.

From that list, four sites were selected as shown in table 1. The roadway types listed in the table are illustrated in figure 3. Each of these routes are major highways between urbanized areas which are not connected by an Interstate highway. Thus, the traffic volumes for these routes ranged from 8,000 to 20,000 vehicles per day with 10 to 30 percent truck traffic. As indicated in the table, the majority of the mileage was on two-lane segments as opposed to multilane segments. The two routes in Arkansas (US 71A and US 71B) also consisted of a number of miles of roadway with climbing lanes for trucks since this area is primarily mountainous. These two sites were also the most severe in terms of geometrics as indicated by the number of curves greater that 3 degrees. The other sites, US 1 in North Carolina and US 220 in North Carolina and Virginia, consisted of mild horizontal curvature and rolling terrain.

DATA COLLECTION

As previously discussed in chapter 3, the sources of truck data for this study were: (1) observation of traffic stream trucks, and (2) observation of control trucks, driven by a single driver. In both cases, two basic types of operational measures were of concern:

Table 1. Geometric characteristics of selected routes.

Route	Roadway[1] Type	Length (mi)	Number of Curves		Range in Lane Width (ft)	Range in Paved Shoulder Width (ft)
			≤ 3°	> 3°		
US 220	2-lane	8.496	13	0	9.75 - 12.50	0.00 - 6.50
	Divided Multilane	16.336	21	10	9.50 - 12.50	0.00 - 6.50
US 1	2-lane	14.865	20	0	10.50 - 12.75	0.00 - 7.25
US 71A	2-lane	13.315	22	13	11.00 - 12.25	2.50 - 11.25
	2-lane (climb)	1.523	4	7	11.75 - 12.75	4.00 - 8.00
	Undivided Multilane	4.222	4	2	9.50 - 12.75	0.00 - 5.00
US 71B	2-lane	10.004	4	29	11.50 - 12.75	5.00 - 12.00
	2-lane (climb)	8.261	12	30	11.25 - 12.75	1.50 - 25.00

1 - See figure 3 for illustration of roadway type.

1 ft = 0.305 m; 1 mi = 1.61 km

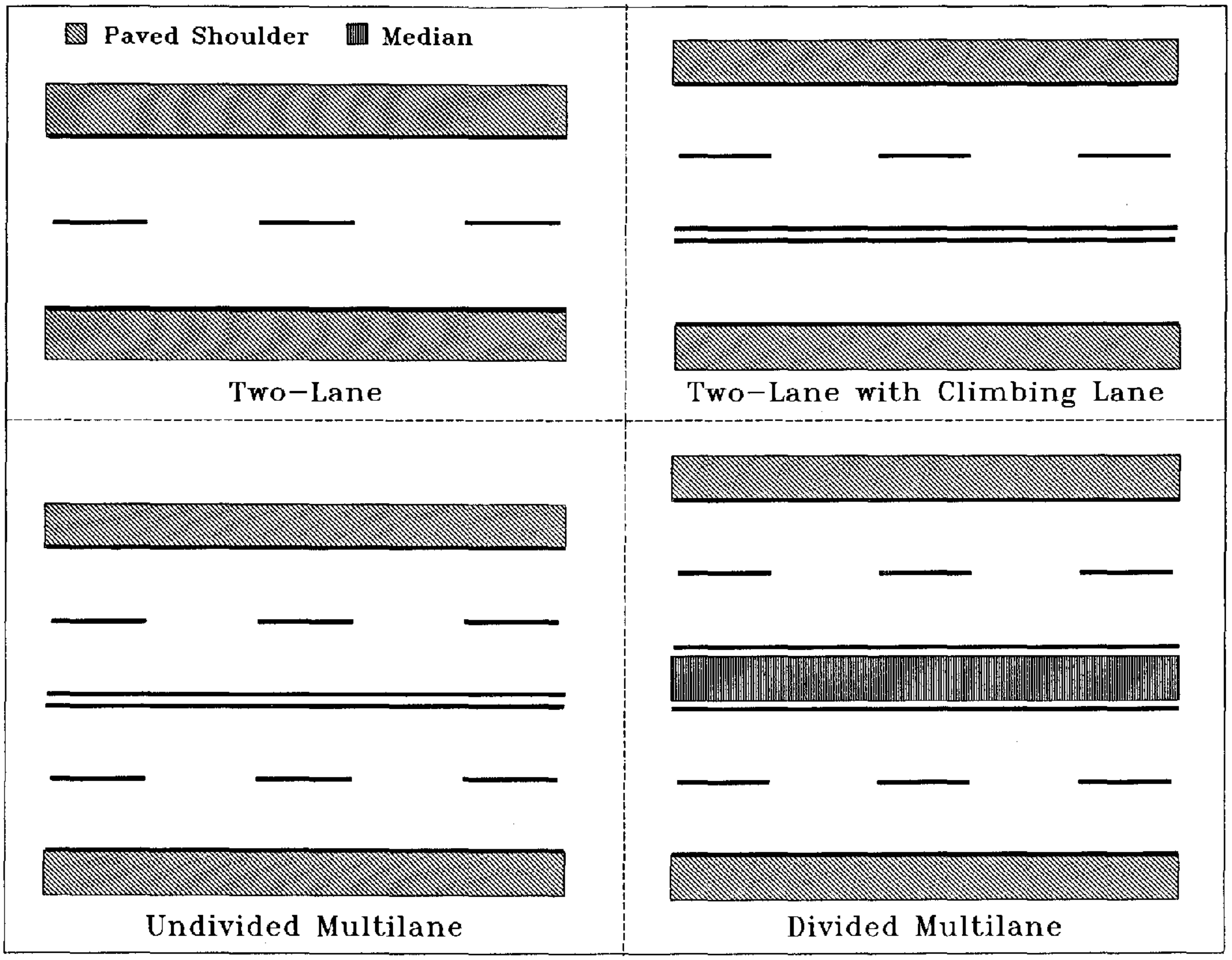


Figure 3. Roadway types selected for data collection.

- Vehicle measures - speed, lateral placement, and encroachments (edgeline, laneline, and centerline) of the vehicles being followed.

- Interaction measures - lateral placement and encroachments of opposing or passing vehicles as they interact with the vehicle being followed.

The details of the data collection procedures developed and used to obtain these operational measures are provided in the following sections.

Traffic Stream Data

The field data collection procedure for the traffic stream data as well as the control truck data consisted of the data collection van following a truck (or car) traversing a preselected route as shown in figure 4. The personnel required in the van included the driver, one person to operate the video equipment, and one person to take slides of opposing or passing vehicles.

Several pieces of equipment were required to record the operations of the

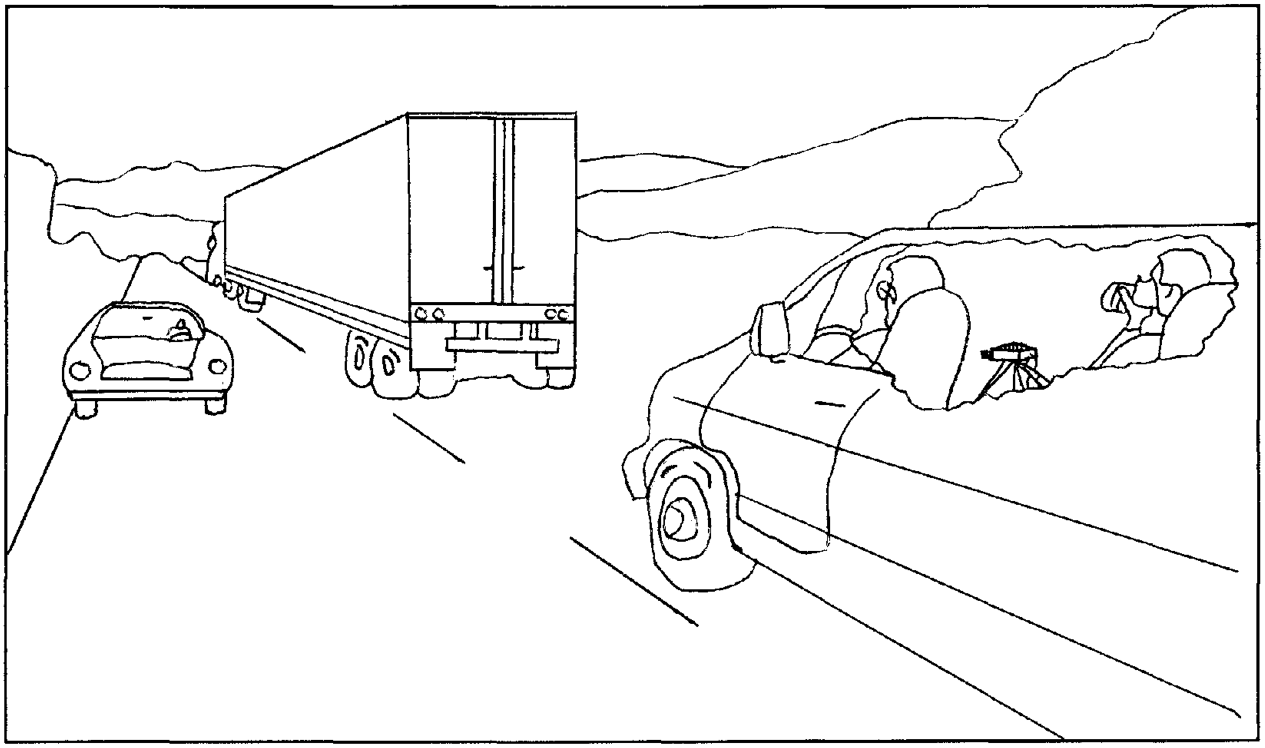


Figure 4. Data collection caravan.

vehicle being followed. A closed circuit television surveillance camera (CCTV), mounted inside the van, was focused on the rear of the followed vehicle. A second CCTV camera was focused on a distance measuring instrument (DMI) and a stopwatch inside the van. The DMI was used to record the location and speed throughout the study segment while the stopwatch simply recorded elapsed time. A signal splitter was used to connect the two cameras to a videocassette recorder and display the real-time view of the vehicle being followed along with the readings of the DMI and stopwatch on a monitor inside the van. An example of this display is shown in figure 5. All of this information was recorded on a videotape. A 35-mm camera with a wide-angle zoom lens was also used to take slides of opposing or passing vehicles at the time when they were directly beside the rear of the truck (as is the case in figure 5). Finally, a microphone was used to record verbal information concerning the run number, truck description, opposing/passing vehicle description, and any other relevant information about the run.

In order to collect unbiased data, the research team concealed the video equipment from the truck drivers' view by the use of tinted plexiglas mounted inside the van on all windows. In addition to this precaution, a CB radio was also used to monitor truck driver conversations. During the data collection task of this study, no truck drivers indicated that they were being followed and/or filmed.

At a location approximately 1 mi (1.6 km) from the beginning of the route, the data collection team parked on the roadside and waited for a truck to follow.

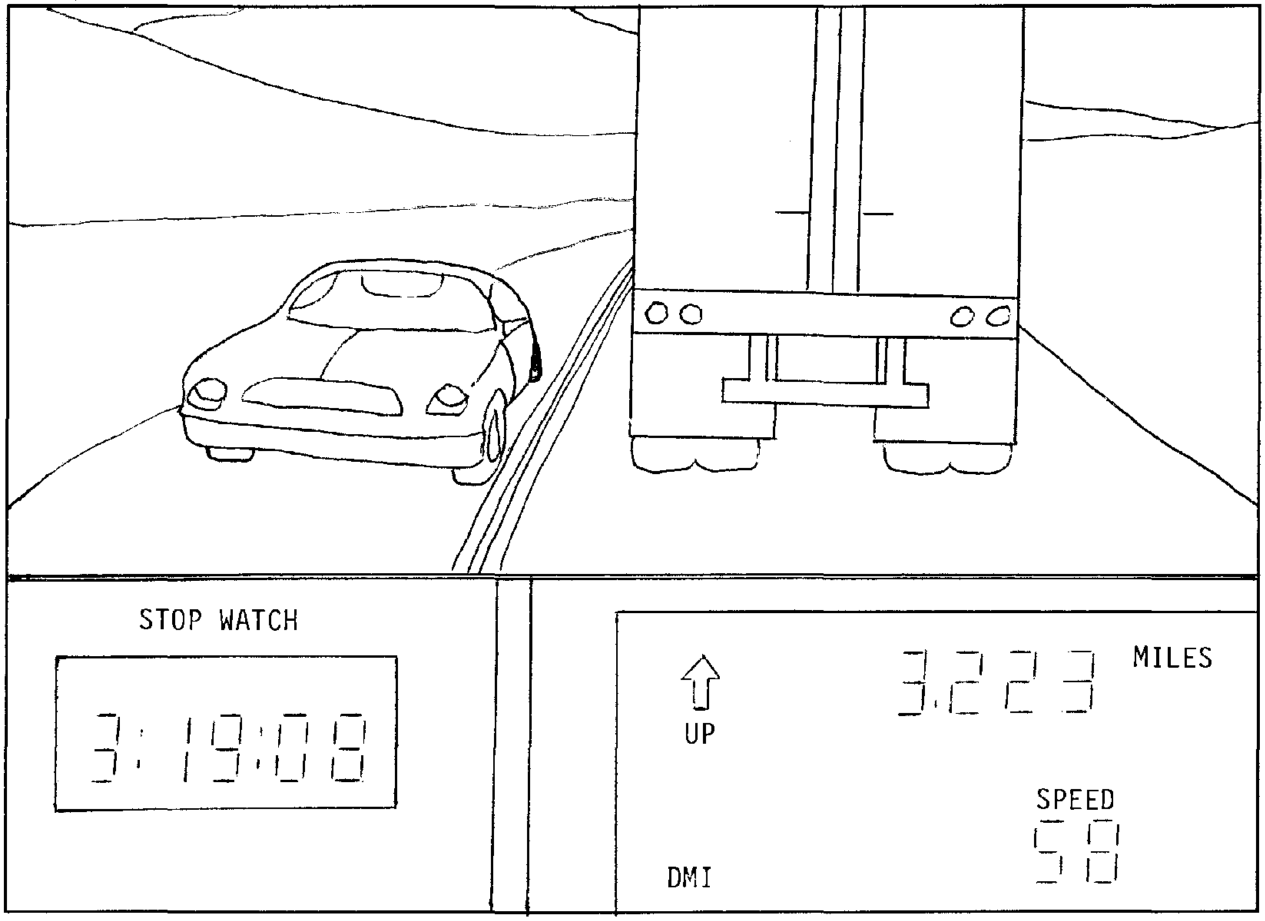


Figure 5. Real-time display of recorded data.

When a truck of interest passed, the team pulled in behind the vehicle and closed to the necessary following distance prior to reaching the start of the study segment. The run number, direction of travel, and estimated length and width of the truck was then recorded (*see appendix C*). At the beginning of the segment, the DMI, the stopwatch, and the video recorder were started and continued to run until the data collection run was completed. During the run, slides were randomly taken of the opposing/passing vehicles. For each slide, the driver of the data collection van gave a brief verbal description of the vehicle which was audibly recorded on the videotape.

The videotape provided a continuous real-time record of the operations of the vehicle being followed as it traversed a given route and allowed for the observance of encroachments in terms of speed, magnitude, and distance (time and length), with respect to any location along the route. The slides of the opposing/passing vehicle-truck interactions provided a means to precisely determine the lateral placement of the opposing/passing vehicle and the truck. Each of these items will be discussed in more detail in the section on *data reduction.*

From the four routes selected (*see table 1*), data were collected for a total of

174 trucks and 55 cars in the traffic stream. This resulted in approximately 7,400 slides and 3,600 encroachments over 3,900 mi (6279 km) of travel.

A critical part of the traffic stream data collection effort was to measure the width of all vehicles (cars and trucks) and the length of all truck trailers. The method developed to obtain trailer length incorporated two sets of posts (racks) which made up a scaling apparatus, and one video camera as shown in figure 6. The racks were 6 ft (1.83 m) and 4 ft (1.22 m) in length and consisted of 1-in (2.54-cm) diameter dowels spaced at 1-ft (.31-m) intervals. One set of racks were placed along the edge of the roadway (approximately 4 ft (1.22 m) from the travel lane within a tangent section) and were spaced at 40 ft (12.2 m). Since vehicles were being followed in both directions along a route, another set of racks was positioned on the other side of the roadway. A VHS camcorder with a wide-angle lens was centered between the racks and positioned 75 ft (22.9 m) away.

By use of a walkie-talkie, the driver of the data collection van would alert the roadside technician on site when a traffic stream truck was approaching. The technician would then record the truck as the data collection caravan passed through the roadside setup. As the truck passed, the technician recorded the run number, time of day, direction of travel, and description of the truck (color, markings, etc.) on a data collection form (*see appendix C*). This written data was used as a check to ensure that the correct length data were matched with the video and slide data

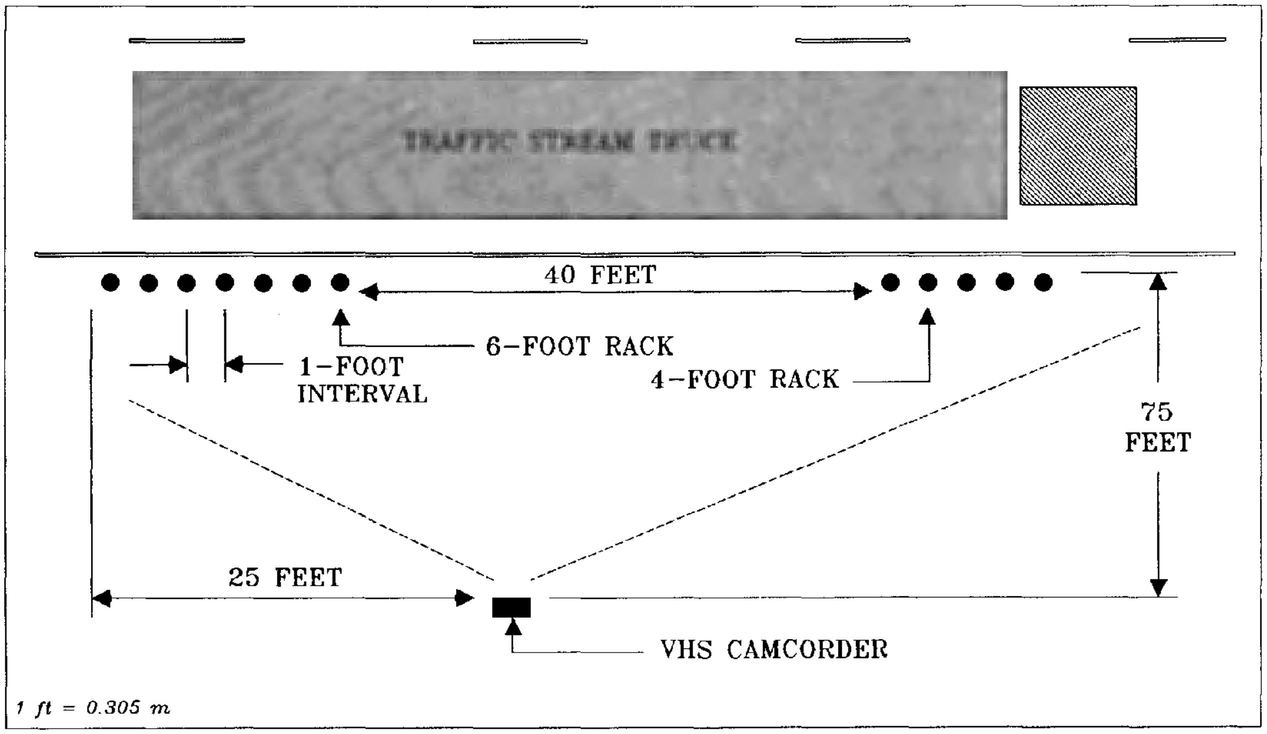


Figure 6. Roadside setup to obtain trailer length.

collected during the run. After the data collection caravan passed, the technician moved to the other side of the roadway with the camcorder and waited for the data collection caravan to return.

A videocassette recorder with freeze-frame capabilities was used to obtain the length measurements from the roadside videotape. A recorded truck was frozen on the monitor such that the front and rear of the trailer were positioned within the two racks as shown in figure 7. The 1-ft (0.3-m) intervals between the dowels were counted from the front and rear of the trailer and added to the 40-ft (12.2-m) spacing between the racks to calculate the truck trailer length. Additional measures obtained from this picture were tandem spacing (i.e., distance from the rear of the trailer to the middle of the rear tandem) and kingpin position (i.e., distance from the front of the trailer to the kingpin). These values were used to compute the kingpin-to-rear axle distance.

The width of a vehicle was determined from a slide taken when the vehicle crossed several lines of tape placed on the road surface by the research team. Strips of 2-in (5.1-cm) white tape were spaced at 2-in (5.1-cm) intervals at a point on the roadway to establish a scale. Two sets of these tape markings, 30 in (76.2 cm) wide and 10 ft (3.0 m) long, were applied 6 in (15 cm) from the edgeline and centerline as shown in figure 8. The inside distance between these two sets of markings was also measured. This setup was repeated for both directions of travel.

During the vehicle following task of the data collection, the individual taking slides of the opposing vehicles took a slide of the rear tires of the vehicle being followed as it passed over the tape lines.

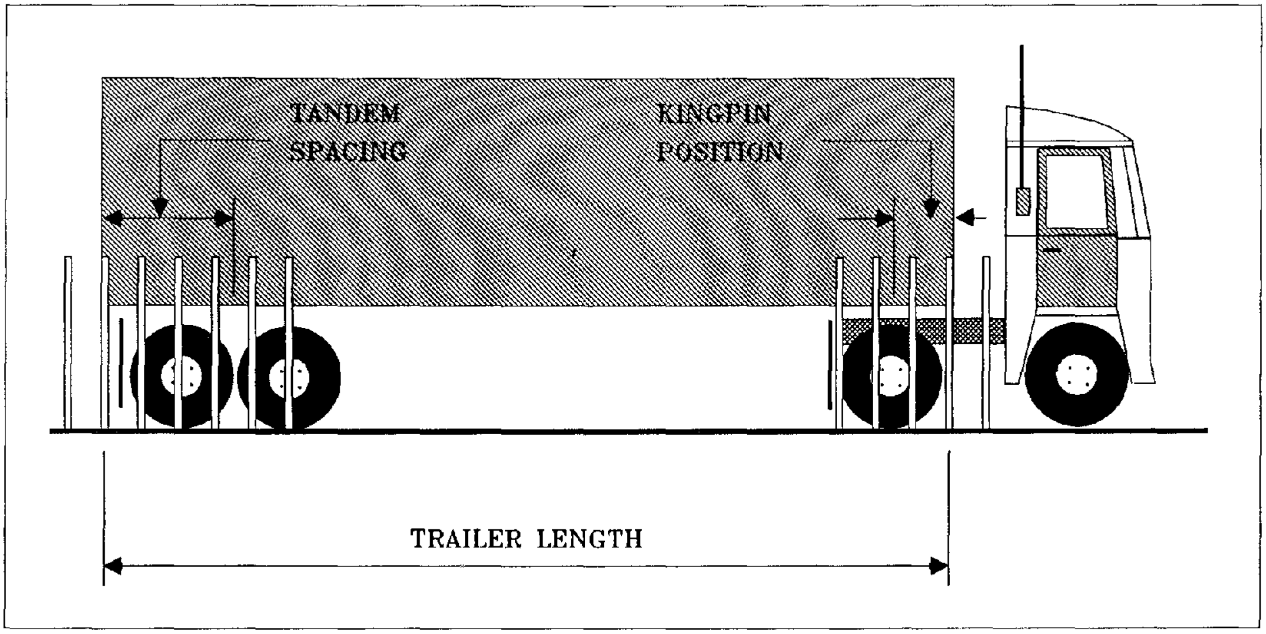


Figure 7. Measurements obtained from the roadside videotape.

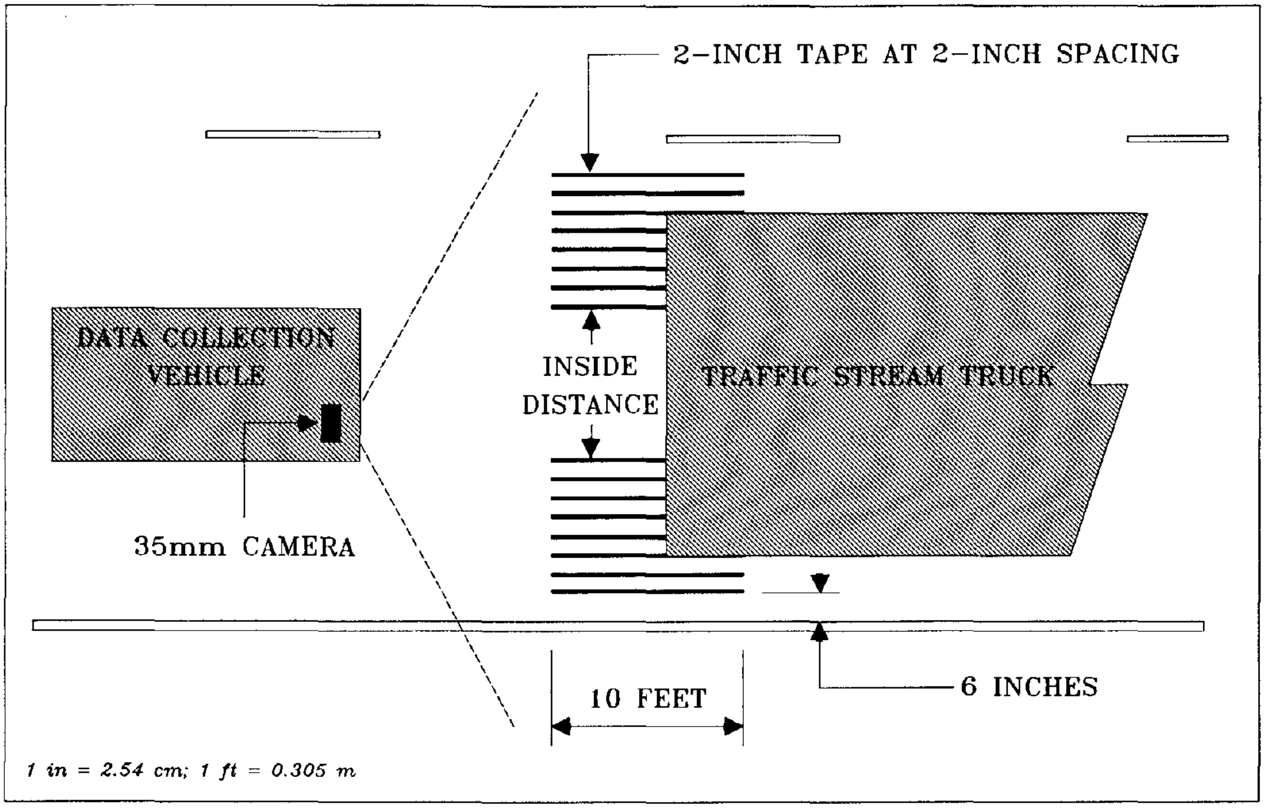


Figure 8. Setup for determining vehicle width.

From this slide, as shown in figure 9, the 2-in (5.1-cm) intervals were counted from the outside of the tires to the inside of each set of marks. These measurements were then added to the inside distance to determine the trailer width.

Control Truck Data

As previously stated in chapter 3, control truck data were collected to help focus on truck size effects by isolating the effects due to driver variance. In order to fully test the effects resulting from truck size, the route with the most severe geometrics, US 71B, was selected as the route on which control truck data were collected. The four truck configurations used were:

- 96-in (244-cm) wide, 45-ft (13.7-m) semi.
- 102-in (259-cm) wide, 48-ft (14.6-m) semi.
- 96-in (244-cm) wide, 48-ft (14.6-m) semi.
- 102-in (259-cm) wide, 28-ft (8.5-m) double.

For all four configurations, the trailer tandems were slid to the rear of the trailer to produce the worst possible offtracking patterns.

The data collection procedure was the same as the traffic stream data

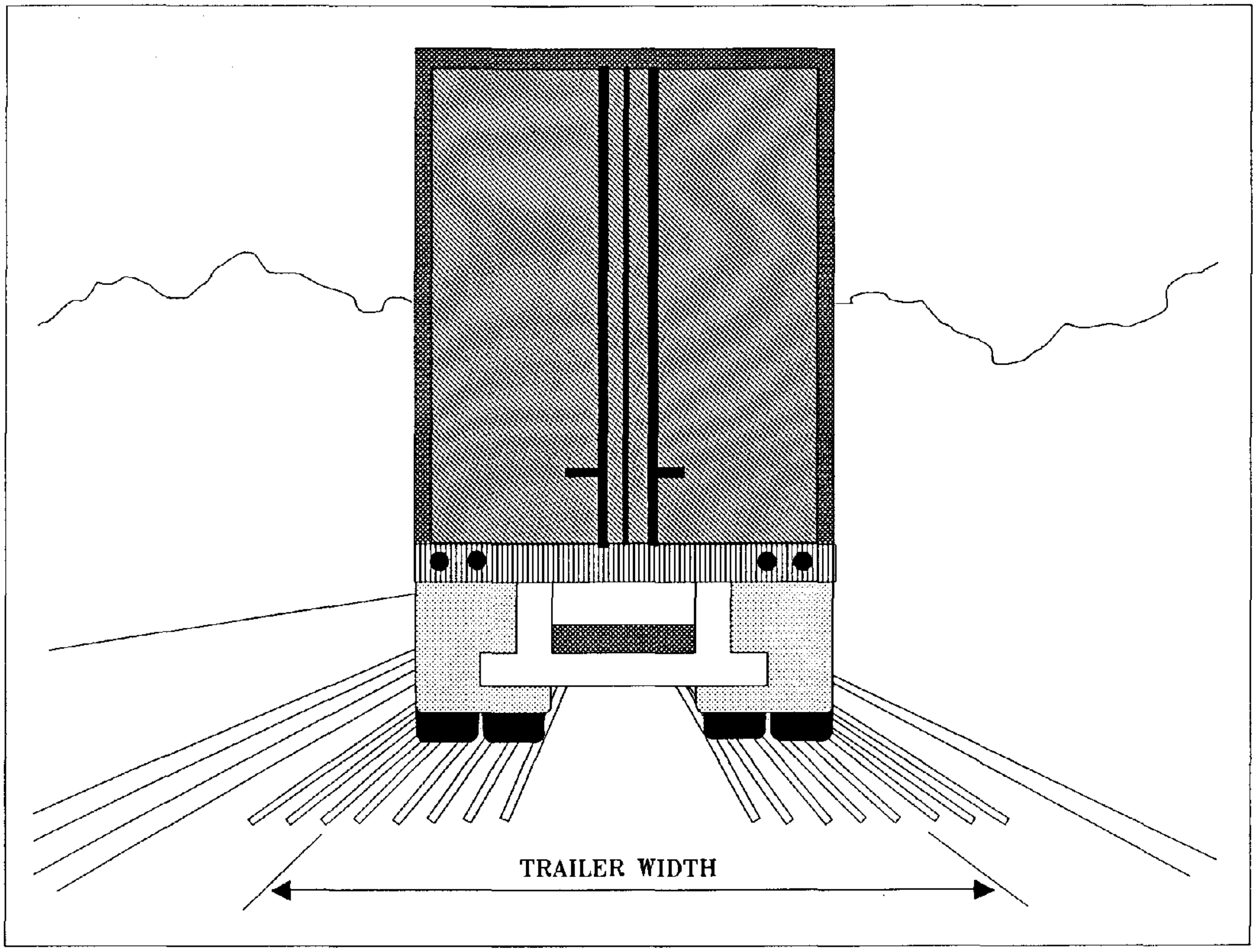


Figure 9. Example of a slide taken to determine vehicle width.

collection procedure with the exception of obtaining trailer length and width data. Since the dimensions of the trailer were known, there was no need for length and width data. Ninety-nine runs were made following the four configurations of control trucks. This resulted in 1586 slides and only 29 encroachments over 1800 mi (2898 km) of travel.

Geometric Data

For each of the four sites selected, it was important that the geometrics of the roadway be determined for the analysis. After the beginning and ending points of each route were determined, the research team made measurements at a minimum of every quarter mile. These measurements included lane widths, shoulder widths (if paved), and shoulder type (paved or unpaved). Other points where these measurements were made included transition zones, intersections, bridges, abrupt lane width changes, beginning and ending points of curves, and beginning and ending points of paved shoulders. Each measurement made was located by a milepost referenced to the start of the segment.

Highway construction plans were used to obtain the radius, degree of curve, and deflection angle for each curve. If plans were not available, aerial photographs obtained from the States or the U.S. Department of Agriculture (USDA) were used. These data were also located by milepost.

DATA REDUCTION

Reducing the data collected (both traffic stream and control truck) consisted of two basic steps:

- Recording encroachments of the vehicle being followed from the videotape.
- Recording lateral placement data from the slides for the opposing/passing vehicles and the vehicle being followed.

Recording Encroachments

The videotape provided a permanent real-time record of the operations of the truck (or car) followed along each route. The primary purpose of this technique was to be able to accurately measure encroachments of a truck and to be able to relate those encroachments to the geometrics at the sites. For purposes of this study, an encroachment was defined as occurring when the outside edge of the rear tire of the vehicle crossed the outside of the edgeline, laneline, or centerline.

The process by which encroachments were recorded was as follows. At the start of the run, the information at the top of the data encroachment reduction form was completed (*see appendix C*). This information included the route location, run number, vehicle type (car, semi, double), trailer length, and vehicle or trailer width. The video was then viewed until an encroachment was observed. The video was paused at the point where the encroachment began and the DMI value (milepost) and time (from the stopwatch) were recorded along with the information on the type of encroachment (centerline, edgeline, or laneline). The videotape was then slowly advanced forward until the vehicle ended the encroachment, i.e., when the outside edge of the rear tire returned across the outside of the edgeline, laneline, or centerline. The time on the stopwatch when the encroachment ended was then recorded along with the DMI reading. During the encroachment, the speed and the amount of encroachment (in tire widths) were observed, and the average speed and the maximum amount of encroachment were recorded. Finally, the type of opposing or passing vehicle present (e.g., car, single unit truck, etc.), if any, during the encroachment was recorded.

Recording Lateral Placement Data

The operational measures related to opposing/passing vehicle interaction data were taken primarily from the 35-mm slides with supplemental information taken from the videotapes. As the videotape was viewed for a second time, the slides for each run were sequenced in the order in which they were taken. The total opposing traffic volume was also recorded at this time to provide some measure of exposure for each vehicle followed.

For each run, information regarding the run number, route, and vehicle characteristics was recorded at the top of the opposing/passing vehicle data reduction form (*see appendix C*). For each slide examined, the event (slide) number, vehicle description and type, maneuver (opposing, passing, or being passed), speed, DMI value (milepost), and platooning characteristics (free flow, cars only, trucks only, etc.) were recorded. The DMI value and the speed were removed from the videotape at the point where the slide was taken. Other information obtained by viewing the videotape included the maneuver of the opposing/passing vehicle on the slide and the platooning characteristics ahead of the vehicle being followed.

The lateral placement data for the vehicle being followed and the opposing/passing vehicle were taken from the slides of the interactions. This was done by projecting the slides over a grid on a wall (*see figure 10*). The width of the followed vehicle was known from the slide containing the white tape lines. The zoom control on the slide projector was then used to adjust the known vehicle width on each slide to the corresponding width on the grid. For example, an 8-ft (2.44-m) trailer width would fill eight grid intervals. Thus, 1 ft (.31 m) was equal to 1 interval on the grid. The lateral placement of each vehicle was then measured using a straight edge. Each measurement was taken from the center of the roadway to the outside edge of the nearest tire. The measurements were accurate to one-eighth of a foot (3.8 cm). An indication of whether either vehicle was encroaching over the edgeline, centerline, or laneline was also recorded on the form.

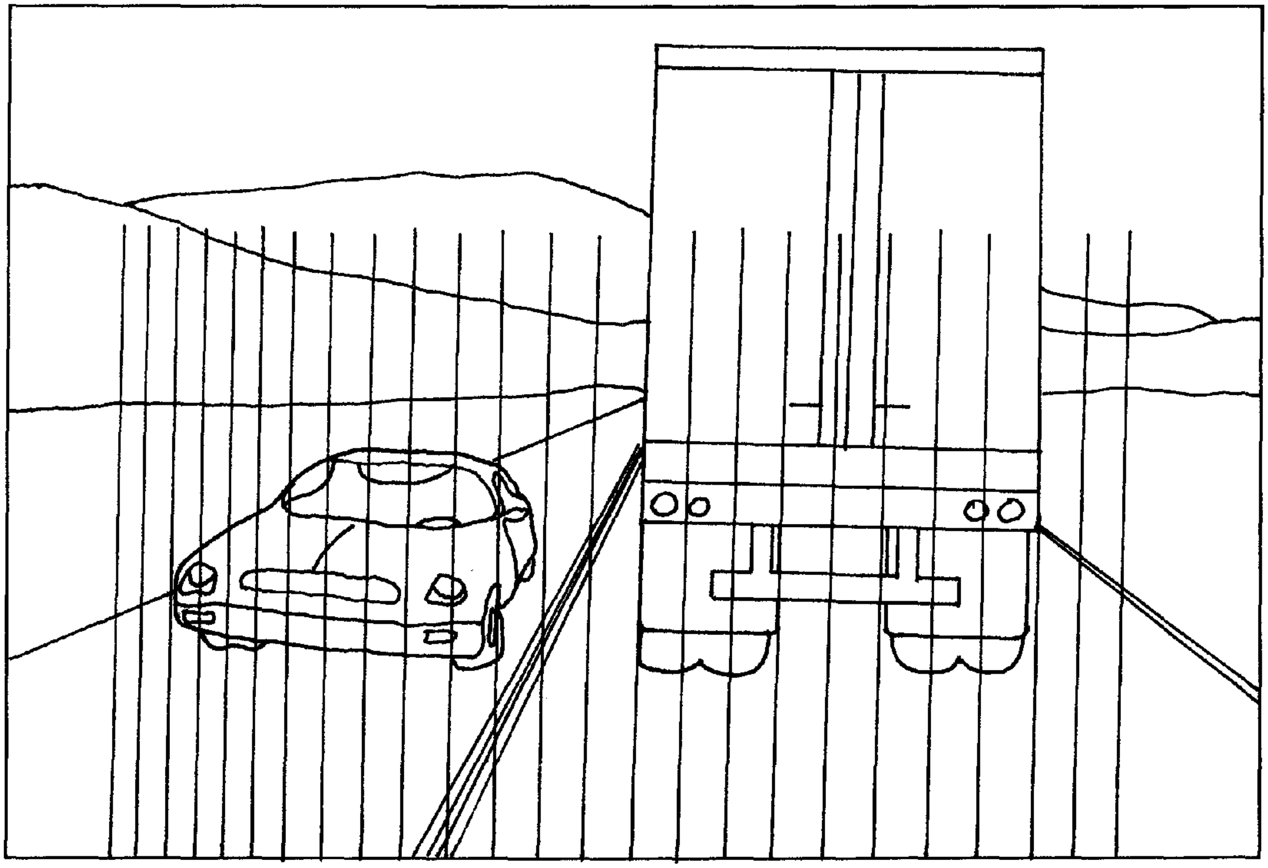


Figure 10. Example of obtaining lateral placement data from a slide.

PREPARATION FOR DATA ANALYSIS

As the data reduction was completed for each of the selected sites, quality control checks were conducted on approximately 5 percent of the data to ensure that the measurements made were accurate. Once the data were verified, it was entered into the computer in a number of spreadsheets. The lateral placement data, taken from the slides, was entered into the *lane placement file*. The encroachment data, taken from the videotape, was entered into the *encroachment file*. The lane and shoulder width data and the curve data, obtained in the field and from the construction plans and aerial photographs, were entered into the *geometric file* and *curve file*, respectively.

CHAPTER 5 - DATA ANALYSIS AND RESULTS FOR TRAFFIC STREAM TRUCKS

The truck operational data collected for this study consisted of two basic types:

- Traffic stream truck data and, for comparison purposes, traffic stream car data.

- Control truck data ,i.e., trucks of different sizes, operated by the same driver, and driven in both directions along the same route (US 71B in Arkansas).

The results of the analyses performed on the traffic stream data are presented in this chapter while chapter 6 provides results of the control truck data analyses.

As discussed in chapter 4, there were three basic types of operational data collected:

- Lane placement data on two-lane roads, as taken from 35-mm slides, when a truck being followed was directly beside an opposing vehicle in the traffic stream. Data recorded from a slide included centerline and edgeline encroachments and distance of the truck and opposing vehicle from the centerline. This information was then used to calculate the distance of the truck and the opposing vehicle from their respective edgelines and separation distance between the vehicles.

- Lane placement data on multilane roads, similar to the above, plus data on vehicles performing a passing maneuver beside the truck in the adjacent lane. Laneline encroachments were also recorded.

- Encroachment data, as recorded on videotape, included all centerline, edgeline, and laneline encroachments by the truck being followed. Thus, for this data base, each data record represented a truck encroachment with its corresponding degree of encroachment (i.e., number of tire widths over the line), length of encroachment (i.e., distance traversed while encroaching), and roadway characteristics at the point of encroachment.

For a given "run," a data collection van would follow a truck (or car) through one of four test routes (US 1, US 220, US 71A, or US 71B). If the truck never encroached over the centerline, edgeline, or laneline during the run, no encroachment data would be generated, although the truck mileage would be included for calculating overall encroachment rates. There would, however, always be lane placement data since slides were taken randomly when opposing vehicles, and same-direction passing vehicles on multilane roads, were directly beside the rear of the truck being followed.

As discussed in chapter 3, the primary issue of concern in this study was:

- What are the effects of 102-in (259-cm) wide trucks compared to 96-in (244-cm) wide trucks while accounting for other truck and driver characteristics?

Secondary issues of importance included:

- *Subissue 1* - How do the various truck configurations (e.g., semitrailers vs. doubles) compare with each other with respect to operational practices?

- *Subissue 2* - What are the effects of truck trailer length (e.g., 45 ft (13.7 m) vs. 48 ft (14.6 m)) and kingpin-to-rear axle distance on operational practices with respect to trailer width (96 in (244 cm) vs. 102 in (259 cm))?

- *Subissue 3* - How do the operational characteristics of various truck types and sizes compare with cars? In other words, to what degree are the large trucks, relative to cars, causing operational problems?

- *Subissue 4* - For a given truck type and size (e.g., 102-in (259-cm) wide, 48-ft (14.6-m) semi), how much variation in operational measures occurs due to driver differences? In other words, do all drivers handle a given truck type in relatively the same manner or in largely different manners?

- *Subissue 5* - For a given truck type and size, how much operational variation occurs for various roadway geometrics?

This chapter and chapter 6 include a series of analyses which focus on these issues. This chapter first discusses the results of the analyses of the lane placement data. This is followed by the results of the encroachment data analyses. Provided in figure 11 is an "analysis flowchart" which shows the various subissues discussed above, the statistical procedures used to address each issue, and where to find the analysis and results within the chapter.

ANALYSIS OF LANE PLACEMENT DATA ON TWO-LANE ROADS

Analyses described in this section are restricted to data collected on two-lane segments of roadway, and to situations involving the followed vehicle meeting an oncoming vehicle in the opposing lane. The intent of these analyses was, first, to describe the behavior of the vehicle being followed in terms of its position on the road, and, second, to estimate the effects that this positioning might have on the behavior of opposing vehicles. The data are organized by runs, where a run consists of data collected while following a truck, or car, from one end of a selected route segment to the opposite end of the segment or to the point where the vehicle turned off. Each run then includes a series of observations involving a specific followed vehicle. Thus, if different drivers tend to position their vehicles differently, observations on the followed vehicle would tend to be correlated within a run, while observations on the opposing vehicles should be independent of each other. Some of the analyses which follow were done using the raw data while other analyses were done with means of variables over runs, weighted by the number of observations per run.

Basic position measures of the followed vehicle which were taken from the 35-mm slides included: (1) distance from the centerline, and (2) a variable indicating whether or not the vehicle encroached over the edgeline. Two other measures, constructed from these data were: (3) distance to the edge of pavement, and (4) an indicator variable indicating when this distance was 1 ft (.31 m) or less. These latter two measures were developed since merely encroaching the edgeline may not be an unsafe or abnormal behavior where wide paved shoulders exist. Distance of the vehicle from the edge of the paved surface, however, may be more indicative of the potential for a run-off-road maneuver which may lead to an accident.

TOPIC OF ANALYSIS	RELATED SUBISSUES	STATISTICAL PROCEDURE	TABLES/ FIGURES	PAGE
LANE PLACEMENT				
<u>Followed Vehicles</u>				
• Driver variation	4	1-way analysis of variance: vehicle width vs. operational effect	table 2	33
• Characteristics of trucks	1,2	2-way analysis of variance: truck width/length and curve/tangent vs. operational effect	tables 4-7 figure 12	37-40 41-42
• Truck width and geometrics	5	Histograms and 2-way analysis of variance: truck width and geometric group vs. operational effect	figures 13-16	46-49
• Truck length and geometrics	5	2-way analysis of variance: truck width/length and geometric group vs. operational effect	tables 10-11	50-51
• Trucks vs. cars	3	2-way analysis of variance: vehicle width and curve/tangent vs. operational effect	table 12	53
• Truck configuration (doubles)	1	Descriptive analysis	table 13	55
<u>Opposing Vehicle</u>				
• Response of opposing vehicle (OV) to lane placement of followed vehicle (FV) (actual measures)	primary	Multivariable regression models: OV type, centerline distance (FV), curvature, and pavement width vs. operational effect	tables 14-16	56-58

Figure 11. Analysis flowchart for studying traffic stream trucks.

TOPIC OF ANALYSIS	RELATED SUBISSUES	STATISTICAL PROCEDURE	TABLES/ FIGURES	PAGE
• Response of opposing vehicle to lane placement of followed vehicle (distance variables)	primary	Multivariate regression models	tables 17-19	59-61
<u>Followed Vehicle</u>				
• Lane placement on multilane roads	5	Descriptive analysis	tables 20-22	62-63
ENCROACHMENT (Followed Vehicle)				
<u>Truck Width</u>				
• Severity of edgeline encroachment	primary	Chi-square on edgeline encroachment rates	table 23	65
• Length of edgeline encroachment	primary	Descriptive analysis	figure 17	67
• Edgeline encroachment rates and geometrics:	primary,5			
- lane width/shoulder type		Rate per mile	table 24	68
- curvature		Rate per mile	table 25	69
• Centerline encroachments	primary	Chi-square on centerline encroachment rates	table 26	70

Figure 11. Analysis flowchart for studying traffic stream trucks (continued).

Analysis of Effects Due to Driver Variation

Before conducting operational comparisons between various truck sizes by roadway geometrics, it seemed appropriate to first examine the extent of driver-to-driver variation (*subissue 4*). Thus, a series of one-way analyses of variance were run for each study route and vehicle width category (e.g., US 71B: 102-in (259-cm) trucks). The two width categories used for trucks were obviously 96 in (244 cm) and 102 in (259 cm). Similar statistics were generated for cars and pickups, using widths less than 96 in (244 cm), for the roadway with the most curvature, namely, US 71B. This information provided a baseline to which the effects of truck width could be compared. Both distance from the centerline and percentage of edgeline encroachments were used as dependent variables.

Some results from those analyses are presented in table 2. Each row of the table contains information on a specific subset of followed vehicles identified by location and width. The number of vehicles in the subset is indicated as the number of runs. For each subset, four parameters are given for the distance from the centerline including the mean distance for the subset, the smallest and largest mean centerline distances from among the runs in the subset, and an indication of whether or not there was statistically significant variation in mean distance from the centerline over the runs in

Table 2. Variation due to driver/vehicle for distance from the centerline and percentage of edgeline encroachments.

			Distance From The Centerline (ft)				Edgeline Encroachments (%)			
Location	Width (in)	No. of Runs	Mean	Min.	Max.	Sig.[1]	Mean	Min.	Max.	Sig.
US 1	102	21	2.22	1.72	2.92	yes	20.2	6.5	58.6	yes
	96	26	2.49	1.82	3.75	yes	8.5	0	25.7	yes
US 220	102	16	2.63	1.94	3.59	yes	14.7	0	40.6	yes
	96	24	2.89	2.09	5.27	yes	7.0	0	28.6	yes
US 71A	102	17	2.75	1.98	3.43	yes	31.8	7.7	66.7	yes
	96	21	2.90	1.89	3.39	yes	20.7	0	48.4	yes
US 71B	102	21	2.98	1.57	4.36	yes	23.7	0	61.1	yes
	96	24	3.11	2.21	3.97	yes	13.7	0	36.4	yes
	<96[2]	27	4.39	2.42	6.58	yes	5.1	0	66.7	yes

1 - Significant at .05 level using analysis of variance (ANOVA).

2 - <96 denotes cars and pickups.

1 in = 2.54 cm; 1 ft = 0.305 m

the subset. The last four columns provide similar information with respect to the edgeline encroachment variable. Since this variable was coded as a "1" when an encroachment occurred and "0" otherwise, the values in this case are converted to percentages of encroachments. For example, if a truck had encroached the edgeline in 5 of the 30 slides taken in a given run, the percentage of encroachments would be 17 percent.

To illustrate the results in table 2, consider the sample segment of US 1 where 21 runs were made by 102-in (259-cm) trucks. For each run, an average distance from the centerline was computed using the measurements taken from the lane placement slides. Each run typically consisted of approximately 20 to 30 slides. Thus, the 21 averages of distance from the centerline ranged from a minimum of 1.72 ft (0.52 m) to a maximum of 2.92 ft (0.89 m) with an overall average of 2.22 ft (0.68 m). The "yes" under the "Sig." column indicates that there was a significant amount of variation in distance from the centerline among the 21 runs for the 102-in (259-cm) trucks, which may be assumed to be caused by differences in the 21 different driver and/or truck combinations. Similar significant effects were found for each of the routes and for each truck width. Significant differences were also found for the 27 runs following cars and pickups on route US 71B labeled as "<96" under the "width" column in table 2.

As shown in the right portion of table 2, comparisons were also made regarding the percentage of edgeline encroachments. Again using 102-in (259-cm) trucks on US 1 as an example, an overall average of 20.2 percent of the trucks had edgeline encroachments based on data taken from the lane placement slides. Of the 21 runs, the minimum and maximum percentage of edgeline encroachments was 6.5 and 58.6 percent, respectively. Like distance from the centerline, there was a significant amount of variation in the percentage of edgeline encroachments for each truck size on each route. Similar results were obtained for the cars and pickups.

These results, based on vehicle placement data, clearly indicate that a wide range of driving behavior may be expected for a given route and truck type. Further, since this variation exists within a given route and for a given truck size, the different driving behavior and/or differences in vehicle handling characteristics may be assumed to be important in explaining these results.

Table 2 also indicates differences between width categories. The 102-in (259-cm) trucks were operated closer to the centerline and also had a higher percentage of edgeline encroachments than the narrower (96-in (244-cm)) trucks. This seems logical, since the 102-in (259-cm) trucks are not only wider than the 96-in (244-cm) trucks but are also typically longer. Thus, the wider truck would be expected to offtrack more (i.e., take up more space on the highway) than the narrower truck. On US 71B, cars and pickups clearly had higher average distances from the centerline and lower percentages of edgeline encroachments than trucks. This also seems logical since they are not as wide or long as trucks and therefore take up less space on the highway.

Table 2 also shows there are differences between routes. For example, mean distance to the centerline is lower on US 1 than on other routes, quite likely due to its narrower pavement width. This and other locational differences are discussed further in later sections.

It is clear from table 2 that, regardless of location, there is significant variation among drivers of a given width truck with respect to distance from the centerline and percentage of edgeline encroachments. Thus, this analysis confirmed the need for control truck data to account for the effects of varying driver influences. Chapter 6 presents the results of the control truck data analysis.

Comparisons of Truck Characteristics on Operations

The next analysis effort was directed at comparing the effects of various truck characteristics on operations. This analysis corresponds to the primary analysis issue stated previously (i.e., the operational effect of the 96-in (244-cm) truck versus the 102-in (259-cm) truck) as well as to subissue 2 (i.e., the effect of trailer length on operations). The means for both distance from the centerline and percentage of edgeline encroachments for each run within width categories were listed in rank order from highest to lowest. The runs were then labelled by certain truck characteristics -- trailer length, kingpin placement, and kingpin-to-rear axle (KRA) distance -- to see if any patterns emerged (e.g., longer trucks may be at the top of the list with respect to encroachments). No such patterns were apparent from these listings.

The next set of analyses was designed to further explore differences in lane placement due to various combinations of truck characteristics. For these analyses, each run was further subdivided into two parts corresponding to observations made on tangent sections (including mild curves of 2 degrees or less) and observations made on curves greater than 2 degrees. Curves of 2 degrees or less were grouped with tangent sections as both groups had similar outcomes for the operational measures (e.g., average distance from the centerline for 96-in (244-cm) wide trucks) which were rather different from sections with curvature greater than 2 degrees. Averages over each run by curve/tangent combination were then computed for the four dependent variables:

- Distance from the centerline.
- Percentage of edgeline encroachments.
- Distance from the edge of pavement.
- CLOSE, a variable which indicates when the vehicle is within 1 ft (.31 m) of the edge of pavement.

The means of these variables, together with the number of observations generating each mean, were then used as inputs for the subsequent analyses.

From an initial examination of 17 different categories of trucks (excluding doubles) based on length, width, and KRA distance, six broader types were selected for further analysis and are shown in table 3 as A through F.

To examine differences in lane placement among these truck types, two-way analyses of variance (ANOVA) were run with truck type and curve/tangent as class variables and distance from the centerline, percentage of edgeline encroachments, distance from the edge of pavement, and CLOSE as dependent variables. These analyses on the curve/tangent means were weighted by the number of

Table 3. Dimensions of truck types selected for analysis.

Truck Type	Width (in)	Length (ft)	Kingpin-To-Rear Axle Distance (ft)
A	96	≤46.5	
B	96	≥48	30 ≤ KRA ≤ 36
C	96	≥48	36 < KRA ≤ 40
D	102	≤46.5	
E	102	≥48	30 ≤ KRA ≤ 36
F	102	≥48	36 < KRA ≤ 40

1 in = 2.54 cm; 1 ft = 0.305 m

observations within each run. Results from these analyses are presented in tables 4 through 7. Percentages of edgeline encroachments, average distances from the centerline, average distances from the edge of pavement, and percentages for trucks within 1 ft (.31 m) of the edge of pavement (CLOSE) are illustrated in figure 12, based on the information in tables 4 through 7.

To illustrate the results shown in figure 12, consider table 4 dealing with edgeline encroachments. The ANOVA shows both truck type and curvature to be significant factors ($p<.001$) on the percentage of edgeline encroachments. The "type x curves" interaction was not significant ($p = .75$), indicating that all truck types exhibit the same behavior on curves. A review of the mean encroachments provided in the table reveals that the percentage of edgeline encroachments range from a minimum of 10.7 percent of the lane placement slides for truck type A (96-in (244-cm) trucks with trailer lengths ≤ 46.5 ft (14.2 m)) to a maximum of 25.2 percent for truck type F (102-in (259-cm) trucks having trailer lengths ≥ 48 ft (14.6 m) and a KRA distance of 37 to 40 ft (11.3 to 12.2 m)).

The ANOVA table also shows results of the hypotheses tested as to whether the differences by truck type were due to different truck lengths, truck widths, KRA distances, or by a combination of these truck factors. These hypotheses were that:

1. There is no difference in edgeline encroachments among the 96-in (244-cm) trucks (i.e., the trailer length and KRA distance do not significantly affect edgeline encroachments for 96-in (244-cm) trucks).

2. There is no difference in edgeline encroachments among the 102-in (259-cm) trucks (i.e., the trailer length and KRA distance do not significantly affect edgeline encroachments for 102-in (259-cm) trucks).

Table 4. ANOVA results for percentage of edgeline encroachments.

Significance of Class Variables

Effect	df[1]	Mean Square	p-value
Truck Type	5	2.50	< .001
Curves	1	9.72	< .001
Type x Curves	5	0.15	.75

Means by factor levels

Truck Type	Width (in)	Length (ft)	KRA[2] (ft)	Mean (%)	Curves	Mean (%)
A	96	≤46.5		10.7	Yes	28.7
B	96	≥48	30 ≤ KRA ≤ 36	16.4	No	12.8
C	96	≥48	36 < KRA ≤ 40	12.3		
D	102	≤46.5		20.2		
E	102	≥48	30 ≤ KRA ≤ 36	23.3		
F	102	≥48	36 < KRA ≤ 40	25.2		

Results of Tested Hypotheses

	Hypothesis	p-value
1.	No difference among 96-in trucks (A=B=C)	.33
2.	No difference among 102-in trucks (D=E=F)	.38
3.	No width effect (A=D, B=E, C=F)	< .001

1 - Degrees of freedom

2 - Kingpin-to-rear axle distance

1 in = 2.54 cm; 1 ft = 0.305 m

3. There are no significant differences in edgeline encroachments due to 102-in (259-cm) versus 96-in (244-cm) wide trucks.

4. There is no interaction between truck type and curvature with respect to edgeline encroachments.

A corresponding p-value of .05 or less would mean that the hypothesis is rejected meaning there is a significant difference (with 95 percent confidence or above) in edgeline encroachments caused by the truck length or width. A p-value > .05 would mean there is, in fact, no significant effect of the given truck feature on edgeline encroachments.

Table 5. ANOVA results for distance from the centerline (ft).

Significance of Class Variables

Effect	df[1]	Mean Square	p-value
Truck Type	5	13.60	.011
Curves	1	28.25	.013
Type x Curves	5	6.91	.18

Means by factor levels

Truck Type	Width (in)	Length (ft)	KRA[2] (ft)	Mean (ft)	Curves	Mean (ft)
A	96	≤ 46.5		2.81	Yes	3.04
B	96	≥ 48	$30 \leq \text{KRA} \leq 36$	2.82	No	2.61
C	96	≥ 48	$36 < \text{KRA} \leq 40$	2.63		
D	102	≤ 46.5		2.37		
E	102	≥ 48	$30 \leq \text{KRA} \leq 36$	2.63		
F	102	≥ 48	$36 < \text{KRA} \leq 40$	2.69		

Results of Tested Hypotheses

Hypothesis	p-value
1. No difference among 96-in trucks (A=B=C)	.39
2. No difference among 102-in trucks (D=E=F)	.06
3. No width effect (A=D, B=E, C=F)	<.001

1 - Degrees of freedom
2 - Kingpin-to-rear axle distance
1 in = 2.54 cm; 1 ft = 0.305 m

Again, looking at table 4, note that the p-value is .33 for hypothesis 1 (i.e., the hypothesis that trailer length and KRA distance have no significant effect on edgeline encroachments). Since .33 is *not* less than .05, the hypothesis is not rejected. Therefore, for 96-in (244-cm) wide trucks, the trailer length and KRA distance do not have a significant effect on edgeline encroachments. Similarly, hypothesis 2 is also not rejected since the p-value is .38. Thus, for the 102-in (259-cm) wide trucks, trailer length and KRA distance again had no significant effect on edgeline encroachments. Hypothesis 4 is also not rejected since p = .75. Thus, the effect of truck type on edgeline encroachment rates is the same on curve sections as on tangent sections.

Table 6. ANOVA results for distance from the edge of pavement (ft).

Significance of Class Variables

Effect	df[1]	Mean Square	p-value
Truck Type	5	86.33	.46
Curves	1	2394.35	<.001
Type x Curves	5	26.14	.92

Means by factor levels

Truck Type	Width (in)	Length (ft)	KRA[2] (ft)	Mean (ft	Curves	Mean (ft)
A	96	≤46.5		5.88	Yes	8.17
B	96	≥48	30 ≤ KRA ≤ 36	5.72	No	5.38
C	96	≥48	36 < KRA ≤ 40	6.60		
D	102	≤46.5		6.58		
E	102	≥48	30 ≤ KRA ≤ 36	4.84		
F	102	≥48	36 < KRA ≤ 40	6.61		

1 - Degrees of freedom
2 - Kingpin-to-rear axle distance
1 in = 2.54 cm; 1 ft = 0.305 m

Hypothesis 3 resulted in a p-value <.001, so that hypothesis is rejected. Therefore, there is clearly a significant influence of truck width on edgeline encroachments. Furthermore, based on a review of the percentage of edgeline encroachments by truck type in table 4, the 102-in (259-cm) trucks (types D, E, and F) have a higher percentage of edgeline encroachments than 96-in (244-cm) trucks (types A, B, and C).

A brief summary of the results given in tables 4 through 7 is presented below, along with possible explanations:

- Wider (102-in (259-cm)) trucks had significantly higher rates of edgeline encroachments than did narrower (96-in (244-cm)) trucks (table 4; p <.001 for truck type effect).

This is reasonable since 102-in (259-cm) trucks require greater swept path widths (i.e., total width used by the truck during a given maneuver) than 96-in (244-cm) trucks, all else being equal. Also, as found by Zegeer, Hummer, and Hanscom, some drivers of 102-in (259-cm) trucks (and particularly those with 48-ft (14.6-m) trailers) were more likely to "hug" the edgeline on curves to the left to avoid having the rear of their trailer encroach over the centerline.(4)

- On average, wider (102-in (259-cm) trucks tended to be operated closer to the centerline than were 96-in (244-cm) trucks (table 5; p = .011 for truck type effect).

This may be the result of two possible factors. First, the additional 6 in

Table 7. ANOVA results for the variable CLOSE indicating the percentage of trucks within 1 ft (.31 m) of the edge of pavement.

Significance of Class Variables

Effect	df[1]	Mean Square	p-value
Truck Type	5	.20	.88
Curves	1	4.03	.06
Type x Curves	5	.09	.99

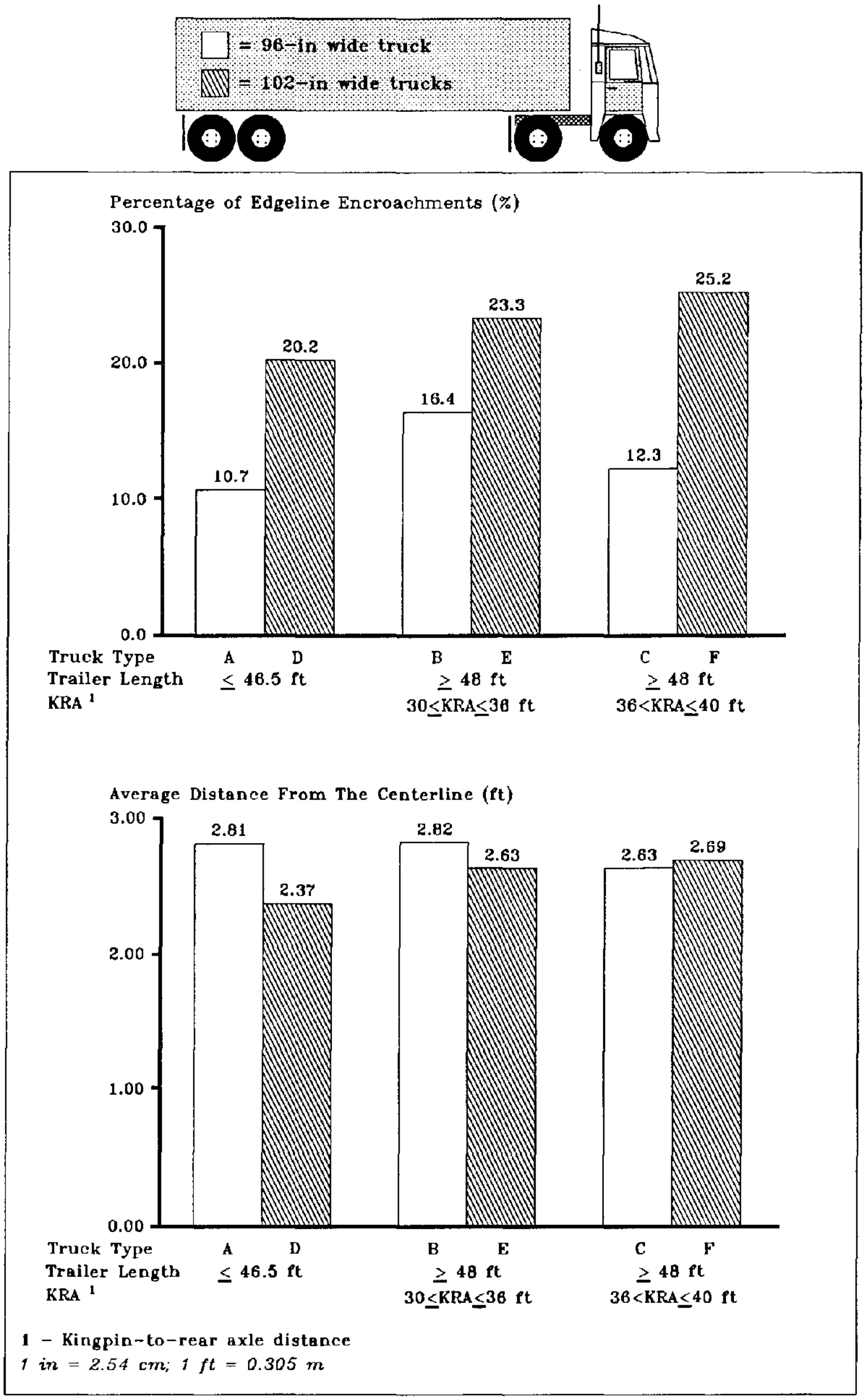
Means by factor levels

Truck Type	Width (in)	Length (ft)	KRA[2] (ft)	Mean (%)	Curves	Mean (%)
A	96	≤46.5		8.6	Yes	1.7
B	96	≥48	30 ≤ KRA ≤ 36	6.4	No	10.0
C	96	≥48	36 < KRA ≤ 40	2.8		
D	102	≤46.5		8.7		
E	102	≥48	30 ≤ KRA ≤ 36	11.9		
F	102	≥48	36 < KRA ≤ 40	6.4		

1 - Degrees of freedom
2 - Kingpin-to-rear axle distance
1 in = 2.54 cm; 1 ft = 0.305 m

(15 cm) of width for the 102-in (259-cm) trucks could result in more of them being operated closer to the centerline than the 96-in (244-cm) trucks due to their increased swept path. According to computer-generated offtracking plots of trucks on various degrees of curve, it has been shown that 102-in (259-cm) trucks can take as much as 1.5 ft (0.46 m) of additional swept path than comparable 96-in (244-cm) trucks.(4) Thus, on winding, two-lane roads, this could translate into 102-in (259 cm) trucks having a greater proportion of edgeline encroachments and being operated closer to the centerline.

The second factor relates to possible differential driving behavior for the two width categories when combined with the geometry of the test sites. If, for example, drivers of 102-in (259-cm) trucks want to "hug" the right edgeline on curved roads, one would expect a greater proportion of encroachments on roads such as US 71A and US 71B in Arkansas where wide paved shoulders existed. However, on narrow curved roads with no paved shoulders, such as US 1, drivers of the 102-in (259-cm) trucks would be limited in their ability to drive farther from the centerline unless they encroach beyond the paved roadway. Thus, because of their greater swept path on curved roads, the 102-in (259-cm) trucks would be expected to be operated closer to the centerline than the 96-in (244-cm) trucks on narrow roadways. A later analysis of the two width trucks on various geometrics lends further insights into this finding.



1 – Kingpin-to-rear axle distance

1 in = 2.54 cm; 1 ft = 0.305 m

Figure 12. Comparisons of operational measures by truck type.

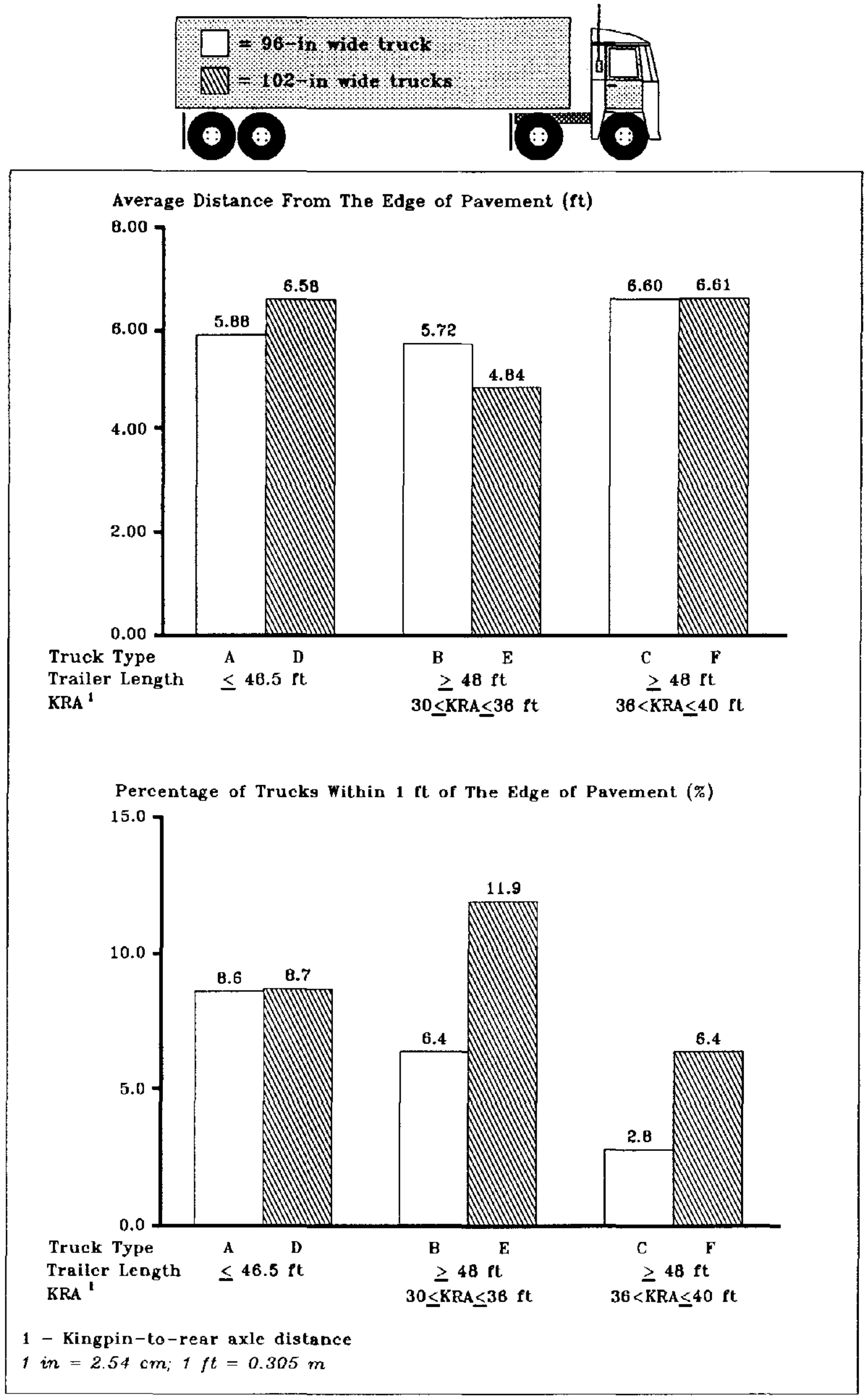


Figure 12. Comparisons of operational measures by truck type. (con't)

- No consistently significant differences were detected within width categories, in distance to the centerline (table 5; $p = .39$ and $p = .06$ for 96-in (244-cm) and 102-in (259-cm) wide trucks, respectively) or percentage of edgeline encroachments (table 4; $p = .33$ and $p = .38$ for 96-in (244-cm) and 102-in (259-cm) wide trucks, respectively).

This finding is unexpected since semis with longer trailers, and particularly longer KRA distances, would be expected to take greater swept paths on curves than semis with shorter trailers and KRA distances. Of course, on tangent sections, the trailer length and KRA distance have little or no effect on swept path since the swept path is basically the truck width.

The finding might be related to the driving skill of drivers of 102-in (259-cm) trucks versus 96-in (244-cm) trucks. For example, if drivers of longer trucks (i.e., 48-ft (14.6-m) semis) were more skilled at handling their trucks than drivers of shorter trucks (i.e., 45-ft (13.7-m) semis), then this improved handling capability could help compensate for the added operational impacts of the greater trailer length and/or greater KRA distance.

- Both 102-in (259-cm) and 96-in (244-cm) trucks tended to have higher rates of edgeline encroachments and be farther from the centerline on curves than on tangents (tables 4 and 5; $p < .001$, and $p = .013$, respectively).

This finding is perhaps the result of truck drivers using caution when driving around curves; that is, where the pavement is of sufficient width on curves, they try to increase their clearance distance to opposing traffic.

- No significant interactions were found between truck type and curvature (indicated as the class variable "truck type x curves") with respect to any of the outcome measures (e.g., table 4, $p = .75$ for edgeline encroachments).

- No significant effects due to truck type were found with respect to either average distance to the edge of pavement or the percentage of times the truck was CLOSE (1 ft (.31 m) or less) to the edge of pavement (tables 6 and 7; $p = .46$ and $p = .88$, respectively).

This may indicate that truck drivers of all truck types try to maintain their trucks a safe distance from the edge of pavement.

- Even though edgeline encroachments were higher on curves than on tangents, the average distance to the edge of pavement was, in fact, greater on curves than on tangents (table 6; $p < .001$, with curve and tangent means of 8.17 ft (2.49 m) and 5.38 ft (1.64 m), respectively).

This last finding suggests paved surfaces were wider on curves than on tangent sections. Based on the geometric files for each segment studied, this was, in fact, true. Table 8 shows characteristics of pavement width (i.e., width of lane plus paved shoulder in each direction), lane width, and paved shoulder width on both curves greater than 2 degrees and tangent sections for each of the four routes.

Table 8. Pavement width, lane width, and paved shoulder width on tangents and curves.

Width Category	Tangents (degree of curve ≤ 2°)			Curves (degree of curve > 2°)		
	Mean	Min.	Median	Mean	Min.	Median
Lane Width (ft)	11.54	10.34	11.62	11.84	10.61	11.87
Paved Shoulder Width (ft)	4.84	0	4.25	7.63	0	8.00
Pavement Width (ft)	16.38	10.34	16.15	19.47	10.61	19.81

1 ft = 0.305 m

Effect of Truck Width and Roadway Geometrics

To further explore the effects of geometric characteristics (which corresponds to subissue 5 given previously) on the lane placement of trucks, cross-tabulations of lane width, shoulder width, and curvature were examined. These tabulations showed that nearly all observations on curves occurred on roadways with lane widths greater than 11 ft (3.4 m) and some paved shoulder. Based on these tabulations, five geometric categories were established as shown in table 9. Analyses were then carried out by splitting the runs into sections corresponding to the five geometric categories, computing means of the operational measures (e.g., percentage of edgeline encroachments) for each subset, and then examining weighted ANOVA's of the means cross-classified by truck width or truck type.

Table 9. Roadway geometric categories.

Category	Lane Width (ft)	Shoulder Type	Curvature
1	≤ 11	None	Mostly Tangents
2	≤ 11	Paved	Mostly Tangents
3	> 11	None	Mostly Tangents
4	> 11	Paved	Tangents
5	> 11	Paved	Curves

1 ft = 0.305 m

Two additional operational measures were also considered: (1) percentage of trucks within 1.75 ft (.53 m) of the centerline, and (2) percentage of trucks within 3.5 ft (1.07 m) of the opposing vehicle. Two-way ANOVA's (with geometric category and truck width as factors) were carried out for each operational measure. The results of these analyses are summarized in figures 13 through 16. ANOVA tables are included at the bottom of each figure while the graphs show predicted values of the operational measure for both truck widths within each of the five geometric categories. These predicted values were estimated from a model containing no interaction terms when the interaction term was not statistically significant.

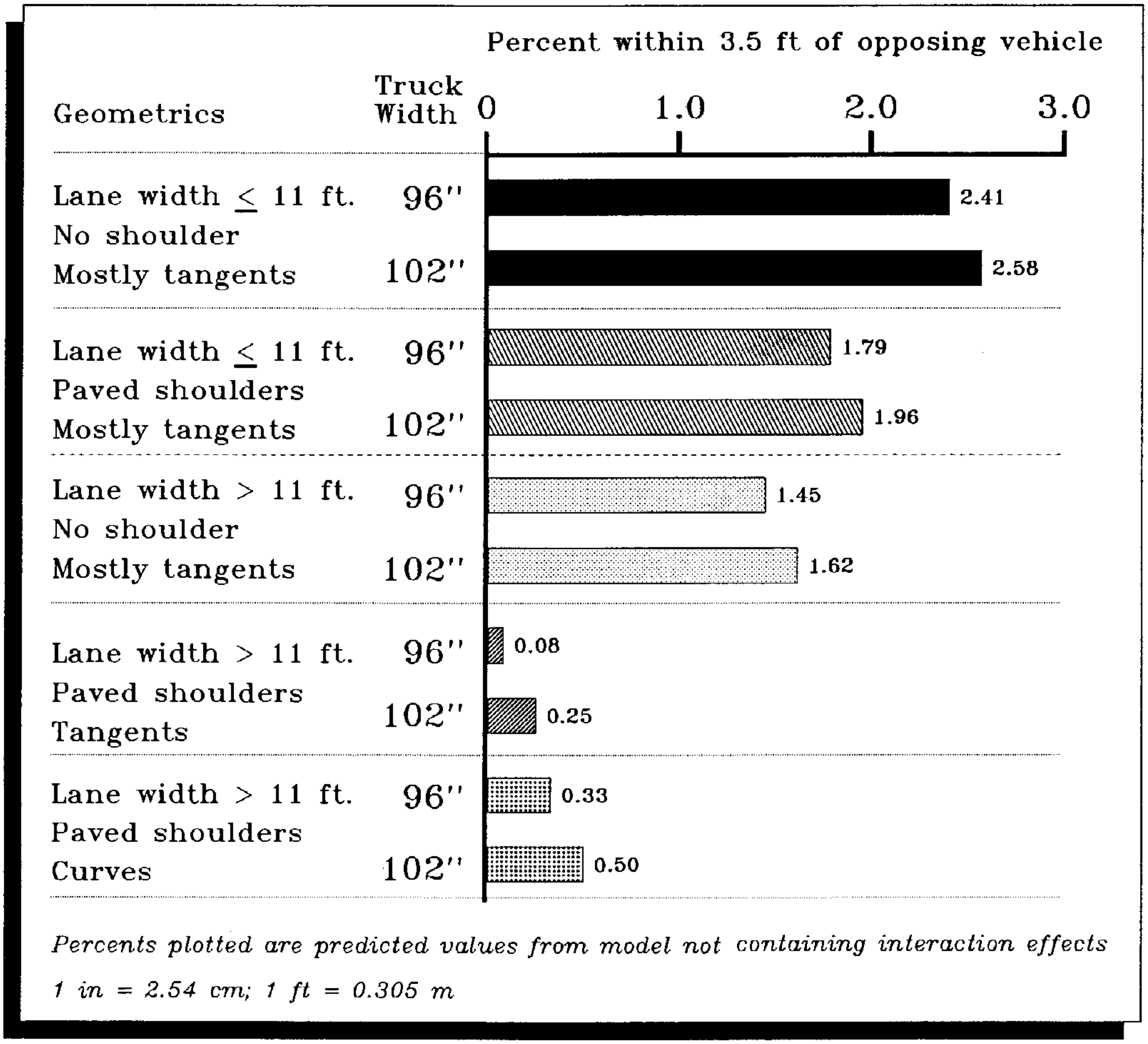
Each operational measure is seen to vary significantly over the geometric categories. The percentage of trucks within 3.5 ft (1.07 m) of the opposing vehicle *(see figure 13)* does not differ significantly between the 96-in (244-cm) and 102-in (259-cm) trucks, and the difference between truck widths with respect to the percentage within 1.75 ft (.53 m) of the centerline is only marginally significant ($p = .07$; *see figure 14*). Both of these operational measures tend to increase with decreasing pavement width. Thus, based on the operational measures, the percentage of trucks within 1.75 ft (.53 m) of the centerline and the percentage of trucks within 3.5 ft (1.07 m) of opposing vehicles, no clear differences were found between the two width trucks for the various roadway conditions tested.

However, large, highly significant differences in edgeline encroachments due to truck width can be seen from figure 15, where 102-in (259-cm) trucks have greater rates of edgeline encroachments than 96-in (244-cm) trucks for all roadway conditions ($p < .001$). The lack of significant interactions implies truck size differences are essentially constant across the geometric categories. It is also interesting to note that edgeline encroachments tend to increase with increasing pavement width, especially on curves. This is probably a result of the fact that curves had wider paved shoulders.

The percentage of trucks within 1 ft (.31 m) of the edge of pavement (*see figure 16*) is relatively high on roads with no paved shoulder, significantly greater for 102-in (259-cm) trucks relative to 96-in (244-cm) trucks on these roads, and essentially zero in the presence of paved shoulders. This results in the significant effects ($p < .001$) shown for truck width, roadway geometrics, and their interactions in figure 16.

Effect of Truck Length and Various Geometric Conditions

The analysis above compared only two truck sizes: the 96-in (244-cm) and the 102-in (259-cm) wide trucks for five groupings of roadway geometrics. However, there was also a need to compare operational effects of truck lengths and kingpin-to-rear axle (KRA) distances because the amount of offtracking by a truck, when driving around a curve, is directly proportional to the KRA distance and the amount of curvature. In other words, for a given truck width, the swept width of a truck increases for longer KRA distances and also for sharper curves. One might expect that greater operational problems (e.g., higher rates of edgeline and centerline encroachments) would result on curves for trucks with longer trailers and/or longer KRA distances compared to shorter trailers and/or KRA distances. This analysis was considered relevant to subissue 2 listed earlier. Thus, in these next



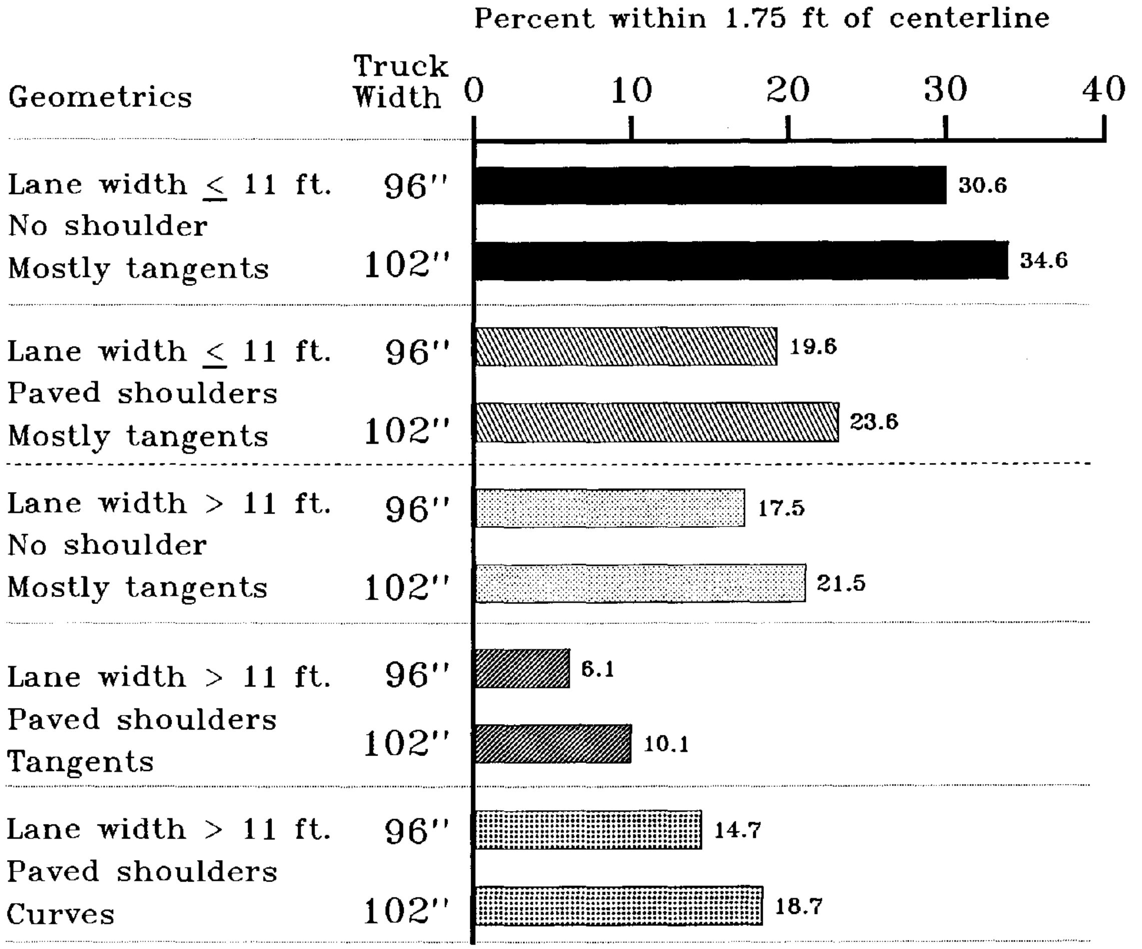
Percents plotted are predicted values from model not containing interaction effects

1 in = 2.54 cm; 1 ft = 0.305 m

Analysis of Variance Results

Effect	Degrees of Freedom	Mean Square	p
Truck size	1	.001	.90
Geometrics	4	.046	<.001
Interaction	4	.002	.87

Figure 13. Percentage of trucks within 3.5 ft (1.07 m) of opposing vehicles as a result of road geometrics and truck width.



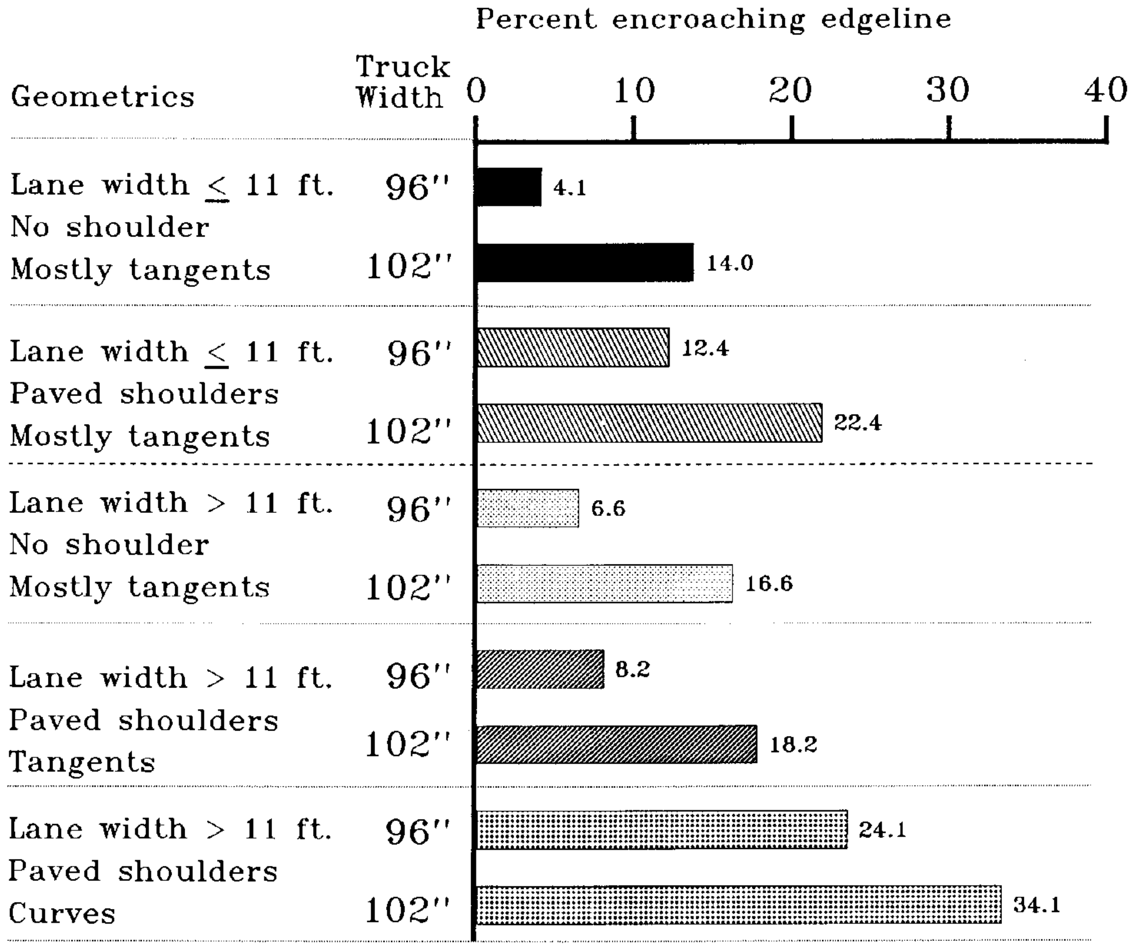
Percents plotted are predicted values from model not containing interaction effects

1 in = 2.54 cm; 1 ft = 0.305 m

Analysis of Variance Results

Effect	Degrees of Freedom	Mean Square	p
Truck size	1	.80	.07
Geometrics	4	4.57	<.001
Interaction	4	.14	.69

Figure 14. Percentage of trucks within 1.75 ft (.53 m) of the centerline as a result of road geometrics and truck width.



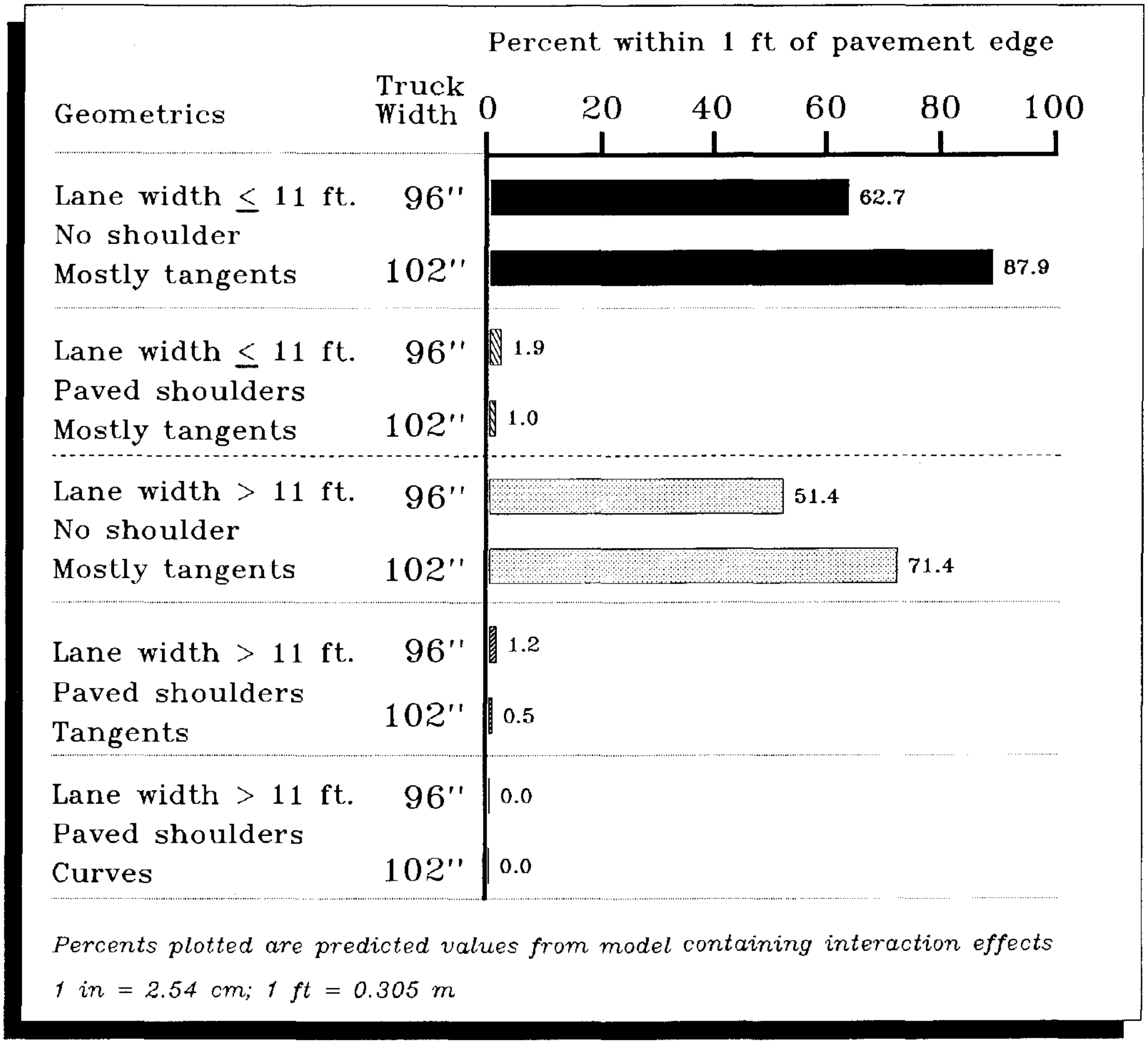
Percents plotted are predicted values from model not containing interaction effects

1 in = 2.54 cm; 1 ft = 0.305 m

Analysis of Variance Results

Effect	Degrees of Freedom	Mean Square	p
Truck size	1	3.92	<.001
Geometrics	4	5.06	<.001
Interaction	4	.08	.85

Figure 15. Percentage of trucks encroaching edgeline as a result of road geometrics and truck width.



Percents plotted are predicted values from model containing interaction effects

1 in = 2.54 cm; 1 ft = 0.305 m

Analysis of Variance Results

Effect	Degrees of Freedom	Mean Square	p
Truck size	1	2.65	<.001
Geometrics	4	53.33	<.001
Interaction	4	1.28	<.001

Figure 16. Percentage of trucks within 1 ft (.31 m) of the edge of pavement as a result of road geometrics and truck width.

set of analyses, trucks were again split into the six truck type categories *(see table 3)* and analyzed across the five geometric categories *(see table 9)* for each of the four operational measures used in the previous analyses. The results of these analyses are presented in tables 10 and 11.

As indicated in table 10, the 102-in (259-cm) trucks encroached the edgeline more than the 96-in (244-cm) trucks (range of 10.4 to 16.2 percent versus 19.9 to 25.0 percent, respectively). There were also significant differences across the geometric categories ($p < .001$), but no evidence of differences across types within widths ($p = .54$ and $p = .32$ for 96-in (244-cm) trucks and 102-in (259-cm) trucks, respectively). In other words, the 102-in (259-cm) trucks (types D, E, and F) were again found to have a higher percentage of edgeline encroachments than 96-in (244-cm) trucks (types A, B, and C). The percentage of encroachments varied significantly depending on the geometric condition. However, truck length and KRA distance were not found to have a significant effect on mean encroachments for a given truck width.

Table 10. Effects of truck type and geometrics on edgeline encroachments.

Significance of Class Variables

Effect	df[1]	Mean Square	p-value
Truck type	5	1.98	<.001
Geometrics	4	4.60	<.001
Contrast	df	Mean Square	p-value
96's all same	2	.14	.54
96's vs. 102's	3	1.23	.001
102's all same	2	.26	.32

Means By Factor Levels

Truck Type	Width (in)	Length (ft)	KRA[2] (ft)	Mean Encroachments (%)
A	96	≤46.5		10.4
B	96	≥48	30 ≤ KRA ≤ 36	16.2
C	96	≥48	36 < KRA ≤ 40	12.4
D	102	≤46.5		19.9
E	102	≥48	30 ≤ KRA ≤ 36	22.8
F	102	≥48	36 < KRA ≤ 40	25.0

1 - Degrees of freedom
2 - Kingpin-to-rear axle distance
1 in = 2.54 cm; 1 ft = 0.305 m

Table 11. Effects of truck type and geometrics on percent within 1.75 ft (.53 m) of the centerline.

Significance of Class Variables

Effect	df[1]	Mean Square	p-value
Truck type	5	1.18	<.001
Geometrics	4	4.80	<.001
Contrast	**df**	**Mean Square**	**p-value**
96's all same	2	.53	.10
96's vs. 102's	3	1.86	<.001
102's all same	2	1.70	<.001
A=B=C=E=F	4	.34	.21

Means By Factor Levels

Truck Type	Width (in)	Length (ft)	KRA[2] (ft)	Mean Percent within 1.75 ft of Centerline
A	96	≤46.5		10.9
B	96	≥48	30 ≤ KRA ≤ 36	9.0
C	96	≥48	36 < KRA ≤ 40	16.3
D	102	≤46.5		25.9
E	102	≥48	30 ≤ KRA ≤ 36	11.4
F	102	≥48	36 < KRA ≤ 40	4.1

1 - Degrees of freedom

2 - Kingpin-to-rear axle distance

1 in = 2.54 cm; 1 ft = 0.305 m

With respect to driving near the centerline (*see table 11*), the major difference among truck types was that type D (width of 102 in (259 cm), length ≤ 46.5 ft (14.2 m)) had a significantly higher rate (25.9 percent) than the other types (*see also figure 15*). This can be seen by the overall significant effect due to truck type and the non-rejection of the hypothesis A=B=C=E=F. The higher rate for type D also causes the contrasts comparing the three 102-in (259-cm) trucks among themselves and also the 102-in (259-cm) trucks with the 96-in (244-cm) trucks to be significant.

This finding is consistent with earlier results since longer semis (48 ft (14.6 m)) tended to be driven farther away from the centerline than shorter semis (≤ 46.5 ft (14.2 m)). Thus, one might expect that the shorter semis would more often be driven within 1.75 ft (.53 m) of the centerline as compared to the longer semis.

Figure 16 shows that trucks are operated within 1 ft (.31 m) of the edge of pavement only when there are no paved shoulders. Thus, there are no differences between truck types on roads having paved shoulders. On roads without paved shoulders, the data were too sparse to make any valid comparisons within width categories.

Similarly, operation of any truck within 3.5 ft (1.07 m) of an opposing vehicle occurred very seldom, less than 1 percent of the time on wide roads with paved shoulders. For other geometric conditions, the data were too sparse to detect any differences due to truck type within width categories. There was also no significant difference due to width ($p = .90$).

In summary, these results confirm the earlier results. No significant effect was found in operational measures based on truck length, but the 102-in (259-cm) trucks generally had higher rates of edgeline encroachments. In addition, on roads with no paved shoulders, wide trucks were operated slightly more often closer to the centerline and closer to the edge of pavement, which could be the result of their greater swept width on curves. When paved shoulders were present, drivers of the wider trucks tended to use this extra roadway width considerably more than those driving narrower trucks in order to position themselves away from the centerline. This was especially true on curves. No consistent differences in behavior were found that could be attributed to truck length or kingpin placement.

Operational Differences between Trucks and Cars

In addition to analyzing operational measures involving various truck sizes and types, it is also useful to compare operational characteristics of large trucks against some baseline. This is needed to determine the degree to which large trucks are causing operational problems. In this study, cars and pickups, hereafter referred to as cars, were used as the baseline for the comparison (*see subissue 3*).

As summarized in table 12, significant differences were found between cars and both width trucks for all four operational measures tested. The CLOSE measure proved to be the least significant with p-values of .035 and .009 when cars were compared to 96-in (244-cm) and 102-in (259-cm) trucks, respectively. This is most likely due to a great majority of all type vehicles being operated within 1 ft (0.3 m) of the pavement edge on US 1, which has no paved shoulder.

Table 12 also shows that cars had fewer edgeline encroachments, greater mean distances from the centerline, and travel at greater distances from the edge of pavement than trucks. This may be expected because of the greater size of trucks compared to cars. As will be seen later, the magnitude of these differences is informative in interpreting the differences between the two width trucks. The p-values were $< .001$ for all car/truck comparisons for the other three operational measures indicating significant differences in the expected direction between cars and both 96-in (244-cm) and 102-in (259-cm) semis.

The non-significant "width x curves" interaction for each operational measure indicates that the vehicle width effects are the same on curve sections as on tangent sections and thus not a function of roadway alignment.

From this lane placement data, it can be seen that cars encroached the edgeline in 4.9 percent of the cases when meeting opposing vehicles, compared to 11.8 percent for 96-in (244-cm) trucks and 22.7 percent for 102-in (259-cm) trucks. Mean

Table 12. Comparisons of cars and trucks.

Effects	Percentage of Edgeline Encroachments (%)	Mean Distance from the Centerline (ft)	Mean Distance from the Edge of Pavement (ft)	Percent Within 1 ft of the Edge of Pavement (CLOSE)
DESCRIPTIVE STATISTIC				
Vehicle Type:				
Cars	4.9	3.96	7.76	1.5
96-in Semis	11.8	2.81	5.92	8.2
102-in Semis	22.7	2.60	5.95	9.6
Curvature:				
Tangent	10.2	2.94	5.78	8.4
Curve	24.3	3.39	8.55	1.7
ANALYSIS OF VARIANCE	p-value	p-value	p-value	p-value
Effects:				
Vehicle Width	<.001	<.001	<.001	.025
Curves	<.001	<.001	<.001	<.001
Width x Curves	.13	.24	.83	.15
Contrasts:				
Cars vs 96-in Semis	<.001	<.001	<.001	.035
Cars vs 102-in Semis	<.001	<.001	<.001	.009

1 in = 2.54 cm; 1 ft = 0.305 m

distance from the centerline was 3.96 ft (1.21 m) for cars, compared to 2.81 ft (0.86 m) for 96-in (244-cm) trucks and 3.60 ft (1.1 m) for 102-in (259-cm) trucks. The fact that 102-in (259-cm) trucks travelled an average of .79 ft (0.24 m) farther from the centerline than 96-in (244-cm) trucks is consistent with earlier findings regarding their tendency to place their vehicles away from the centerline. Cars, of course, may be expected to be driven farther from the edgeline and also farther from the centerline than trucks because of their smaller size.

The mean distance of cars from the edge of pavement was 7.76 ft (2.37 m), compared to 5.92 ft (1.80 m) and 5.95 ft (1.81 m) for 96-in (244-cm) and 102-in (259-cm) trucks, respectively. This indicates that all three vehicle types maintained a substantial distance from the edge of pavement. Also, only 1.5 percent of the cars were CLOSE to the pavement edge as opposed to 8.2 percent and 9.6 percent for the 96-in (244-cm) and 102-in (259-cm) trucks, respectively. This provides an indication of the potential for run-off-road events by wider trucks.

A review of the four operational measures for all vehicle types on tangents versus curves revealed the following:

- The percentage of edgeline encroachments was more than twice as high on curves (24.3 percent) as on tangents (10.2 percent).

- The average distance from the centerline was higher on curves (3.39 ft (1.03 m)) compared to tangents (2.94 ft (0.89 m)). This is no doubt due to drivers moving farther from the centerline around a curve to avoid opposing vehicles and the presence of wider paved shoulders (almost 3 ft (.91 m)) on curves.

- Distance from the edge of pavement was considerably greater on curves (8.55 ft (2.61 m)) compared to tangents (5.78 ft (1.76 m)) even though vehicles on curves were also farther from the centerline than on tangents. This seemingly illogical finding is the result of wider paved shoulders on curves than on tangents along the study segments.

- Vehicles are less likely to travel within 1 ft (.31 m) of the edge of pavement on curves (1.7 percent) than on tangents (8.4 percent). Again, this is the result of wider shoulders on curves compared to tangents.

Comparison of Semis versus Doubles

The analyses described above involved only trucks with single trailers. As a part of subissue 1, there was also interest in comparing truck operations of semis with doubles. During the data collection period, it was feasible to obtain traffic stream data on only eight doubles. Thus, no classification by width·was possible. However, the performance on curves was compared with that on tangents and no significant differences were found. Mean and standard deviations are given in table 13 for the previously discussed dependent variables.

Looking at only mean values, doubles were operated slightly farther from the centerline (2.93 ft (0.89 m) and slightly closer to the edge of pavement (4.39 ft (1.34 m)) than the semis, which ranged from 2.37 to 2.82 ft (0.72 to 0.86 m) and 4.84 to 6.61 ft (1.48 to 2.01 m), respectively. Based on past research studies and computer plots of doubles versus semis, it is clear that, on curved road sections, doubles can generally offtrack less than longer 48-ft (14.6-m) semis. This

Table 13. Lane placement characteristics of doubles.

Variable	Mean	Standard Deviation
Edgeline encroachments (%)	20.0	16.2
Distance from centerline (ft)	2.93	.36
Distance from pavement edge (ft)	4.39	2.38
Percent within 1 ft of edge (%)	13.9	22.6
Percent within 1.75 ft of centerline (%)	3.9	7.5
Percent within 3.5 ft of opposing vehicle (%)	0	0

1 ft = 0.305 m

occurred because doubles have increased maneuverability due to their two short trailers (26 to 28 ft (7.9 m to 8.5 m)). The fact they were driven closer to the edgeline and farther from the centerline may be reflecting nothing more than the driving habits of those eight doubles' drivers -- too small a sample size to draw any significant conclusions -- especially when considering the large standard deviations shown in table 13.

Analysis of Opposing Vehicle Data

Lane placement data on two-lane roads included not only operations of the trucks being followed, but also the maneuvers of opposing vehicles. This data was critical for determining how the various truck sizes influenced opposing vehicles.

As mentioned in an earlier section, observations on the opposing vehicles constitute independent observations and thus the analyses could be applied to the raw observations rather than to quantities summarized over runs or portions of runs. This fact, plus the fact the distance of the followed vehicle from the centerline (a key factor with respect to influencing the behavior of the opposing vehicle) was measured on a continuous scale, led to the choice of regression analysis as the method for analyzing these data. It should be noted, however, that the purpose of these analyses is to determine whether certain characteristics and behaviors of the followed vehicles have statistically significant impacts on the behavior of the opposing vehicle. The modest R^2 values ($R^2 = 0.284$ and $R^2 = 0.083$ for tables 14 and 15, respectively) do not limit these analyses of associations or relationships. However, these values do indicate that the models developed do not account for a large amount of explained variance and thus, should not be used for prediction purposes.

Three classes of opposing vehicles were considered in these analyses:

- Cars and pickups.
- Single unit trucks.
- Semis and doubles.

The behavior measures of the opposing vehicle were again taken to be (1) percentage of edgeline encroachments and (2) distance from the centerline. The analyses involved fitting multivariable regression models to the complete set of observations. Two such models are summarized in tables 14 and 15.

In these models, OV2 and OV3 are dummy variables indicating an opposing vehicle that is a single unit truck or a semi or double, respectively. Both OV2 and OV3 are equal to zero in cases where the opposing vehicle is a car or a pickup.

Tables 14 and 15 show that all of the variables in the regression model are significant at $p < .001$. In other words, all of the variables contribute significantly to the variation in distances from the centerline of the opposing vehicle, CDOV.

The results shown in table 14 can alternatively be expressed as:

CDOV = distance of opposing vehicle from the centerline

$$= 3.002 - .610(OV2) - 1.069(OV3) - .237(CDF) + .119(DC) + .096(PW)$$

where:

OV2 =1 if the opposing vehicle is a single unit truck
=0 otherwise

OV3 =1 if the opposing vehicle is a semi or double
=0 otherwise

CDF =distance of the followed vehicle from the centerline

DC =degree of curve

PW =pavement width

Table 14. Regression analysis results for distance from the centerline (ft) for opposing vehicles (CDOV).

Variable	Model Coefficient	p-value
Intercept	3.002	<.001
Single unit truck vs car or pickup (OV2)	-.610	<.001
Semi or double vs car or pickup (OV3)	-1.069	<.001
Centerline distance (ft) of followed vehicle (CDF)	-.237	<.001
Degree of curve (DC)	.119	<.001
Pavement width (ft) (PW)	.096	<.001

1 ft = 0.305 m

Table 15. Regression analysis results for edgeline encroachments (%) for opposing vehicles.

Variable	Model Coefficient	p-value
Intercept	-3.7	.11
Single unit truck vs car or pickup (OV2)	10.1	<.001
Semi or double vs car or pickup (OV3)	6.2	<.001
Centerline distance (ft) of followed vehicle (CDF)	-4.0	<.001
Degree of curve (DC)	2.2	<.001
Pavement width (ft) (PW)	1.2	<.001

1 ft = 0.305 m

Thus, holding everything else constant, if the opposing vehicle is a semi or a double, it would be an average 1.069 ft (0.33 m) closer to the centerline than would a car. Likewise, for every increase in curvature of 1 degree, CDOV would increase by 0.119 ft (0.04 m).

Similar interpretations can be made for table 15. Holding everything else constant, the rate of edgeline encroachment increases by 10.1 percent if the opposing vehicle is a single unit truck compared to a car. Similarly, edgeline encroachments increase by 2.2 percent for each additional degree of curve.

In both models, the behavior of the vehicles under consideration depended on the distance of their opposing vehicle (the followed vehicle) from the centerline. The models show that, when the followed vehicle moves closer to the centerline (i.e., its distance decreases), the opposing vehicle moved farther from the centerline (*see table 14*) and its percentage of edgeline encroachments increased (*see table 15*). As discussed earlier, 102-in (259-cm) trucks tend to operate closer to the centerline than 96-in (244-cm) trucks; in fact, by an average of 0.21 ft (0.06 m). This suggests it is more often the 102-in (259-cm) trucks which caused opposing vehicles to drive across their edgeline, although this translates into an increase of less than 1 percent in opposing vehicle edgeline encroachments caused by the 102-in (259-cm) trucks over that produced by 96-in (244-cm) trucks.

Other variables which were examined for inclusion in the regression models included: (1) a dummy variable which indicates that the followed vehicle is a semi versus a car or pickup, and (2) a dummy variable which indicates a twin trailer truck. Neither variable was a statistically significant predictor of edgeline encroachments. Both, however, were statistically significant when included in the model for distance from the centerline (*see table 16*).

Other models were developed using three additional operational measures for opposing vehicles: (1) opposing vehicle within 1 ft (.31 m) of the edge of pavement, (2) opposing vehicle within 1.75 ft (.53 m) of the centerline, and (3) opposing vehicle within 3.5 ft (1.07 m) of the followed vehicle. The results are shown in tables 17 through 19 and may be summarized as follows:

- The lane placement of the opposing vehicle (e.g., within 1 ft (.31 m) of the edge of pavement; within 3.5 ft (1.07 m) of the followed vehicle) was always significantly related to its pavement width and the distance of the followed vehicle from the centerline. This is consistent with earlier models.

- Pavement width was negatively correlated with each of these three operational measures implying that, as pavement width increased, the vehicle could position itself away from the edge of pavement, the centerline, and an opposing vehicle, respectively (*see tables 17 through 19*). In other words, most trucks were

Table 16. Expanded regression analysis of distance from the centerline (ft) for the opposing vehicle (CDOV).

Variable	Model Coefficient	p-value
Intercept	3.081	<.001
Single unit truck vs car or pickup	-.606	<.001
Semi or double vs car or pickup	-1.065	<.001
Centerline distance (ft) of followed vehicle	-.252	<.001
Followed vehicle: Semi vs. car or pickup	-.093	.02
Followed vehicle: Double vs. car or pickup	.278	.002
Degree of curve	.121	<.001
Pavement width (ft)	.096	<.001

1 ft = 0.305 m

Table 17. Regression analysis results for opposing vehicle within 1 ft (.31 m) of the edge of pavement.

Variable	Model Coefficient	p-value
Intercept	.329	<.001
Single unit truck vs car or pickup	.102	<.001
Semi or double vs car or pickup	.086	<.001
Centerline distance (ft) of followed vehicle	-.007	<.001
Followed vehicle: Truck vs. car or pickup	.0003	.96
Followed vehicle: Double vs. car or pickup	-.002	.88
Degree of curve	.004	<.001
Pavement width (ft)	-.018	<.001

1 ft = 0.305 m

driven close to the center of their lane. As the followed vehicle moved closer to the centerline, the opposing vehicle tended to be farther from the centerline resulting in more edgeline encroachments. However, on average the opposing vehicle did not move as far towards the edgeline as the truck did towards the centerline, thus there was a higher likelihood that the two vehicles would be closer together (within 3.5 ft (1.07 m)).

- Trucks, either single unit or semis, tended to be farther from the centerline than cars and, hence, more likely to encroach the edgeline or be near the edge of pavement.

- There were no significant differences between the estimated effects for single unit or semi/double trucks compared with cars with the exception of opposing vehicles within 1 ft (.31 m) of the edge of pavement. For this case (see table 17), opposing single unit trucks, semis, and doubles were more likely to be within 1 ft (.31 m) of the edge of pavement than were cars.

- As the degree of curve increased, the opposing vehicles tended to move farther from the centerline on average, though they were also more likely to be within 1.75 ft (.53 m) of the centerline, to encroach more often, and to more often be near the edge of pavement.

Table 18. Regression analysis results for opposing vehicle within 1.75 ft (.53 m) of the centerline.

Variable	Model Coefficient	p-value
Intercept	.238	<.001
Single unit truck vs car or pickup	-.023	.15
Semi or double vs car or pickup	.011	.23
Centerline distance (ft) of followed vehicle	.015	<.001
Followed vehicle: Truck vs. car or pickup	-.004	.62
Followed vehicle: Double vs. car or pickup	-.061	.003
Degree of curve	.022	<.001
Pavement width (ft)	-.014	<.001

1 ft = 0.305 m

These results may indicate some mixed driving behaviors of opposing vehicles when beside a truck on a curve. The fact that, on average, opposing vehicles are farther from the centerline and more often near the edge of pavement for sharper curves may simply be the result of oncoming drivers steering away from trucks on the sharper curves (i.e., they perceive the danger of a head-on collision with a truck and choose to steer even farther away from the truck).

On the other hand, motorists are also more likely to be within 1.75 ft (.53 m) of the centerline on sharper curves, which seems contrary to the earlier statements. One possible explanation is that the driving path of some drivers on curves is governed more by the sharpness of the curve than the opposing vehicle. For example, on a sharp curve to the right, an oncoming driver approaching at a moderately high rate of speed may be unwilling or unable to oversteer in order to "hug" the right shoulder when passing a truck. Thus, some percentage of motorists appear to be passing closer to trucks on sharp curves than on tangents. The potential danger, of course, lies with those opposing vehicles which approach the sharp curve too fast and cross over the centerline into the path of the truck (or the truck crossing the centerline).

Table 19. Regression analysis results for opposing vehicle within 3.5 ft (1.07 m) of the vehicle being followed.

Variable	Model Coefficient	p-value
Intercept	.029	<.001
Single unit truck vs car or pickup	-.003	.38
Semi or double vs car or pickup	.003	.12
Centerline distance (ft) of followed vehicle	-.004	<.001
Followed vehicle: Truck vs. car or pickup	-.0007	.76
Followed vehicle: Double vs. car or pickup	-.0056	.29
Degree of curve	.00007	.84
Pavement width (ft)	-.0007	.015

1 ft = 0.305 m

- When the followed vehicle was a double versus a car, the opposing vehicle tended to be moved farther from the centerline, and less often to be within 1.75 ft (.53 m) of the centerline.

This finding is both logical and agrees with the findings of Zegeer, Hummer, and Hanscom.(4) For example, there is some evidence that many drivers, when approaching a truck, cannot readily tell the difference between a 96-in (244-cm) and a 102-in (259-cm) wide truck or between a 45-ft (13.7-m) and a 48-ft (14.6-m) long semi. According to an earlier analysis, motorists react mainly to the closeness of the opposing truck from the centerline and may move closer to their edgeline when trucks are relatively close to the centerline.

On the other hand, motorists are much more likely to recognize a double as a *large* truck due to its length and double trailers, and may take action to drive farther away from the centerline than when they approach a semi. In fact, Zegeer, Hummer, and Hanscom found that, in some situations, motorists do react more when passing a double compared to a semi.(4)

ANALYSIS OF LANE PLACEMENT DATA ON MULTILANE ROADS

All of the previous analyses related to the operations of trucks or opposing vehicles on two-lane roads. However, since some data were available, a separate analysis was conducted on multilane roads.

Tables 20 through 22 contain tabulations of several characteristics of the lane placement of followed vehicles on these roads. No attempt was made to partition the data further by geometric differences nor were any statistical tests carried out due to the limited sample sizes. When the followed vehicle is passing another vehicle or

Table 20. Lane placement characteristics of the followed vehicle when meeting opposing vehicles on multilane segments.

Followed Vehicle	Opposing Vehicle	Within 1.75 ft of Centerline			Within 3.5 ft of Opposing Vehicle		
		No	Yes	%	No	Yes	%
Car	Car	27	0	0	27	0	0
	Truck	16	1	5.9	17	0	0
96-in truck	Car	22	5	18.5	27	0	0
	Truck	10	2	16.7	11	1	8.3
102-in truck	Car	17	5	22.7	22	0	0
	Truck	7	0	0	7	0	0

1 in = 2.54 cm; 1 ft = 0.305 m

Table 21. Lane placement characteristics of the followed vehicle when passing on multilane segments.

Vehicle Followed	Passed Vehicle	Laneline Encroachments			Within 1.75 ft of Centerline			Within 3.5 ft of Other Vehicle		
		No	Yes	%	No	Yes	%	No	Yes	%
Car	Car	53	1	1.9	52	2	3.7	41	13	24.1
	Truck	37	0	0	35	2	5.4	27	10	27.0
96-in truck	Car	41	6	12.8	32	15	31.9	41	6	12.8
	Truck	24	7	22.6	28	3	9.7	20	9	31.0
102-in truck	Car	31	1	3.1	20	12	37.5	24	8	25.0
	Truck	18	0	0	15	3	16.7	7	11	61.1

1 in = 2.54 cm; 1 ft = 0.305 m

Table 22. Lane placement characteristics of the followed vehicle when being passed on multilane segments.

Vehicle Followed	Passing Vehicle	Edgeline Encroachments			Within 1.75 ft of Laneline			Within 1 ft of Edge of Pavement			Within 3.5 ft of Passing Vehicle		
		No	Yes	%	No	Yes	%	No	Yes	%	No	Yes	%
Car	Car	36	0	0	35	2	5.6	30	0	0	30	5	14.3
	Truck	5	0	0	5	0	0	4	0	0	2	3	60.0
96-in truck	Car	172	5	2.8	139	38	21.5	157	5	3.1	110	66	37.5
	Truck	20	5	20.0	21	4	16.0	22	1	4.4	14	10	41.7
102-in truck	Car	93	16	14.7	77	32	29.4	97	5	4.9	63	43	40.6
	Truck	13	1	7.1	13	1	7.1	12	1	7.7	6	7	53.9

1 in = 2.54 cm; 1 ft = 0.305 m

meeting an opposing vehicle, it was in the left-hand or inside lane, as was the opposing vehicle. When the followed vehicle was being passed, the followed vehicle was in the right-hand lane.

Operational measures involving distance or separation between vehicles were based on 3.5 ft (1.07 m) as a minimal acceptable distance between opposing vehicles, as separations less than 3.5 ft (1.07 m) are fairly rare (*see table 20*). Separations of less than 3.5 ft (1.07 m) for same direction passing situations seem to be much more acceptable as shown in tables 21 and 22. As might be expected, drivers apparently feel more comfortable with a clearance distance less than 3.5 ft (1.07 m) when passing a truck in the same direction than when passing a truck in the opposing direction. In addition, differences between cars and trucks stand out in many of the operational measures. Differences between 96-in (244-cm) and 102-in (259-cm) trucks are much more subtle and less consistent, though there is some evidence that 102-in (259-cm) trucks, since they take up more room than 96-in (244-cm) trucks, are slightly more likely to be closer to the edge of pavement when being passed (*see table 22*), closer to the centerline when passing (*see table 21*), and closer to the other vehicle in both situations.

ANALYSIS OF ENCROACHMENT DATA

Effect of Truck Width

All of the previous analyses discussed in this chapter utilized data from the *lane placement file*; that is, vehicle position, including encroachments of the traffic stream trucks and opposing vehicles taken from 35-mm slides. A video camera was also used to record encroachment events; that is, an event was coded each time the vehicle being followed encroached over the centerline, edgeline, or laneline along the route. Data were recorded on the length of the encroachment, the maximum amount of encroachment (i.e., 1 tire width, 2 tire widths, etc.), and the geometric characteristics where the encroachment began.

The first set of analyses involved comparisons of 96-in (244-cm) wide and 102-in (259-cm) wide semis on two-lane roads. Results from several of these analyses are summarized in table 23, where encroachment rates per traveled mile are presented for each of the four routes separately and for all routes combined. Encroachment rates are given for: (1) all encroachments (overall), (2) encroachments greater than one tire width, (3) greater than two tire widths, and (4) greater than three tire widths. For each rate comparison, a 1 degree of freedom chi-square (X^2) statistic is computed under the hypothesis of equal encroachment rates for the two truck widths. In every instance, the encroachment rate is equal to or higher for the 102-in (259-cm) truck than for the 96-in (244-cm) truck. The rates for all encroachments differed significantly ($p < .005$) on each route and for all routes combined. For each amount of encroachment, the rates also differed significantly ($p < .005$) when route data were combined. Within routes, some of the rate differences by amount of encroachment were significant ($p < .05$) while others were not.

Consider, for example, the "all routes" row in table 23. Ninety-one data runs, covering 963.67 mi (1552 km) were made by 96-in (244-cm) trucks. A total of 748 encroachments occurred over those 963.67 mi (1552 km), which corresponds to an encroachment rate of .78/mi

Table 23. Edgeline encroachments on two-lane sections.

Route	No. of Runs		Miles Traveled		EDGELINE ENCROACHMENTS											
					Overall			> 1 Tire			> 2 Tires			> 3 Tires		
	96"	102"	96"	102"	96"	102"	p[1]	96"	102"	p	96"	102"	p	96"	102"	p
US 1	24	21	326.40	296.23	139[2] (.43)[3]	240 (.81)	<.001	29 (.09)	34 (.11)	>.25	6 (.02)	7 (.02)	>.5	1 (.003)	3 (.01)	—
US 220	24	12	182.03	90.03	80 (.44)	81 (.90)	<.001	19 (.10)	21 (.23)	.01	1 (.01)	6 (.07)	.005	0 (0.0)	1 (.01)	—
US 71A	19	17	243.77	221.89	297 (1.22)	470 (2.12)	<.001	121 (.50)	188 (.85)	<.001	44 (.18)	64 (.29)	.025	13 (.05)	31 (.14)	.002
US 71B	24	21	211.47	184.18	232 (1.10)	290 (1.57)	<.001	141 (.67)	157 (.85)	.035	79 (.37)	81 (.44)	>.25	36 (.17)	43 (.23)	.15
All Routes	91	71	963.67	792.33	748 (.78)	1081 (1.36)	<.001	310 (.32)	400 (.50)	<.001	130 (.13)	158 (.20)	<.001	50 (.05)	78 (.10)	<.001

1 - p-value for chi-square statistic with one degree of freedom for testing differences in encroachment rates.
2 - Total number of edgeline encroachments for 96-in trucks on US 1.
3 - Overall edgeline encroachment rate per mile traveled for 96-in trucks on US 1.

1 in = 2.54 cm

(.48/km). This compares with a rate of1.36/mi (.84/km) for 102-in (259-cm) trucks (i.e., 1,081 encroachments in792.33 mi (1276 km)). This difference in encroachment rates is significant at the .001 level. Similar comparisons show there are, likewise, significantly higher overall encroachment rates for 102-in (259-cm) trucks than 96-in (244-cm) trucks for each of the four routes.

If one is concerned primarily with more severe encroachments (i.e., encroachments further beyond the edgeline), such comparisons are also shown in table 23. As an example, for 96-in (244-cm) trucks, there were 130 edgeline encroachments which exceeded 2 tire widths. For the 963.67 mi (1552 km), this corresponds to an encroachment rate of .13/mi (.08/km). The rate for 102-in (259-cm) trucks (.20/mi (.12/km)) was significantly higher than that of 96-in (244-cm) trucks ($p < .001$).

The length of each encroachment was also recorded. For example, if a truck encroached over the edgeline for a length of 0.1 mi (.16 km) before returning back over the edgeline, that length of 0.1 mi (.16 km) would be the encroachment length. Figure 17 shows encroachment rates based on length of encroachment. Thus, these rates are in the form of miles of encroachment per mile travelled. As shown in the figure, the overall miles of encroachment per mile travelled was .047 for 96-in (244-cm) trucks and .088 for 102-in (259-cm) trucks (significantly different, $p < .001$). Encroachment rates in this form were always greater for the 102-in (259-cm) trucks than the 96-in (244-cm) trucks for each of the four routes, although not always significantly greater.

Effect of Roadway Geometrics

The preceding analyses of encroachment rates for 102-in (259-cm) and 96-in (244-cm) trucks represented all geometric conditions combined for two-lane roads. However, it was also of interest to compare encroachment rates for the two width trucks within various categories of roadway geometry. Thus, the next analyses were aimed at examining encroachments as functions of (1) lane width, (2) paved shoulders, and (3) curvature. Four different lane width and shoulder configurations were considered:

- ≤ 11-ft (3.4-m) lanes with no paved shoulder.
- ≤ 11-ft (3.4-m) lanes with paved shoulders.
- ≥ 12-ft (3.7-m) lanes with no paved shoulders.
- ≥ 12-ft (3.7-m) lanes with paved shoulders.

Of the four routes, only US 1 had substantial amounts of two-lane roadway in each of the four configurations. US 1 also contained very few curves. In fact, less than three percent of US 1 consisted of curves of 2 degrees or more. Table 24 shows total number of encroachments, total miles travelled, and encroachment rates for 96-in (244-cm) and 102-in (259-cm) trucks for each of the four roadway geometric scenarios.

As shown in table 24, encroachment rates for 102-in (259-cm) trucks were much higher than those for 96-in (244-cm) trucks when no paved shoulders were present, but virtually the same in the presence of paved shoulders. This finding suggests a potential operational (and

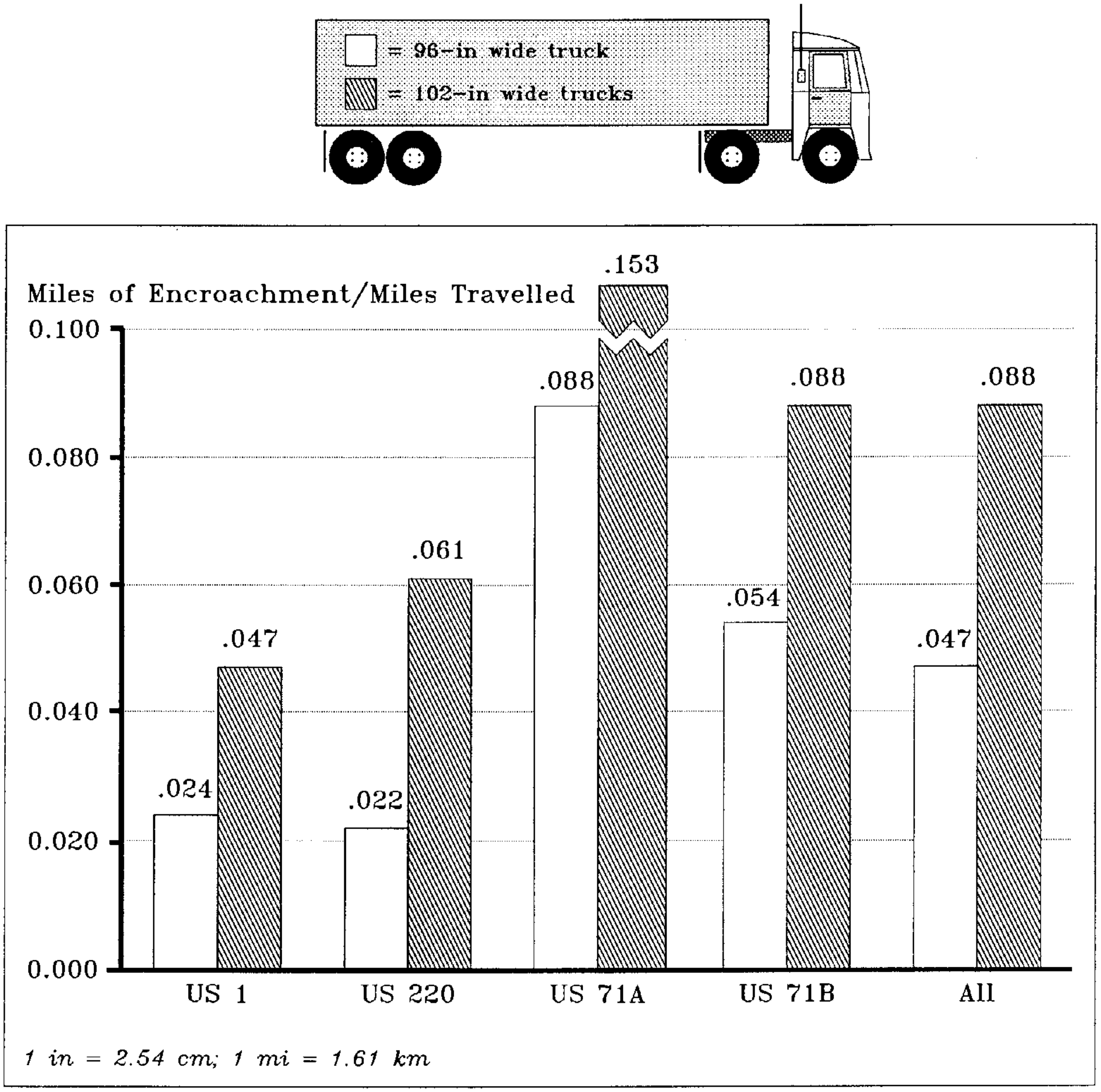


Figure 17. Length of encroachments/mi travelled for traffic stream trucks on different routes by trailer width.

Table 24. Edgeline encroachments on US 1 by lane width and shoulder type.

Lane width/ Shoulder type	Truck Type	No. of Encroachments	Miles Travelled	Rate[1]
≤ 11 ft No Shoulder	96-in	30	124.82	.24
	102-in	92	113.28	.81
≤ 11 ft Paved Shoulder	96-in	46	73.62	.62
	102-in	43	66.81	.64
≥ 12 ft No Shoulder	96-in	19	38.85	.49
	102-in	45	35.26	1.28
≥ 12 ft Paved Shoulder	96-in	44	89.11	.49
	102-in	43	80.87	.53

1 - Encroachments per mile
1 in = 2.54 cm; 1 ft = 0.305 m

perhaps safety) problem. Higher edgeline encroachments by 102-in (259 cm) trucks on this route with no shoulder correspond to the truck tires leaving the paved roadway surface which could, in turn, lead to a run-off-road event. On paved shoulders, drivers of the 96-in (244-cm) and 102-in (259-cm) trucks seemed equally likely to encroach the edgeline, using some of the paved shoulder as a driving surface.

On the other three routes, over 93 percent of the roadway fell into the fourth configuration, namely, 12-ft (3.7-m) lanes with paved shoulders. Table 25 gives encroachment rates and percentages of encroachments occurring on curves for sections with 12-ft (3.7-m) lanes and paved shoulders on each of the four routes. Encroachment rates were not computed for curves and tangents since the corresponding mileage information (or denominator data) could not be calculated because some trucks were not followed for the entire route. To calculate the mileage for each truck would have involved categorizing each segment of the mileage by the corresponding geometric combination which was beyond the scope of this study. However, the percentage of each total route consisting of curves or 2 degrees or more was estimated from the curve file which contained location, degree, and length of curve. Table 25, again, shows the 102-in (259-cm) trucks to have higher overall rates of encroachments than the 96-in (244-cm) trucks. It is of interest to note that, on the two routes with the most curvature (i.e., US 71A and US 71B), a higher percentage of the 96-in (244-cm) trucks encroached on curves than did their 102-in (259-cm) counterparts. This suggests that the driving behavior of 96-in (244-cm) truck drivers on curves may be

Table 25. Encroachments on two-lane sections with 12-ft (3.66 m) lanes and paved shoulders.

		US 1	US 220	US 71A	US 7
Percentage of Roadway with Curves ≥ 2°		2.4%	5.4%	40.3%	54.7%
96-in	No. Encroachments	44	78	287	232
	Miles Traveled	89.11	155.31	227.40	211.47
	Rate/Mi	.49	.50	1.26	1.10
Percentage on Curves		0%	6.4%	51.9%	81.0%
102-in	No. Encroachments	43	70	454	290
	Miles Traveled	80.87	76.81	207.00	184.18
	Rate/Mi	.53	.91	2.19	1.57
Percentage on Curves		0%	7.9%	41.4%	72.4%

1 in = 2.54 cm; 1 ft = 0.305 m; 1 mi = 1.61 km

more erratic than drivers of the 102-in (259-cm) trucks.

Centerline encroachments and encroachment rates are presented in table 26. The 102-in (259-cm) trucks had, generally, higher centerline encroachment rates than the 96-in (244-cm) trucks. The differences by truck width are not statistically significant on any specific route, but when the data are combined over the four routes, the overall rates of .062/mi (0.39/km) and .091/mi (.057/km) do differ significantly, ($p < .05$). This is somewhat inconsistent with earlier findings which showed 102-in (259-cm) traffic stream trucks were more likely to be steered farther from the centerline than 96-in (244-cm) trucks. However, a closer review of table 26 shows that the higher encroachment rate by the 102-in (259-cm) truck results primarily from US 1 which has a narrow (11-ft (3.4-m)) lane and no paved shoulder. Thus, since there is really little or no paved recovery area beyond the edgeline, the 102-in (259-cm) trucks on that route would be more likely to encroach the centerline simply due to their greater width.

Implications Related to Needed Paved Shoulder Width

The encroachment data were analyzed separately for 96-in (244-cm) and 102-in (259-cm) wide semis to determine the degree to which trucks encroach beyond the edgeline. (Doubles were not included in this analysis due to the small number of such trucks available on the sample sections). Such information was considered useful in determining the width of paved shoulders needed to accommodate large trucks which encroach beyond the edgeline. Distributions of edgeline encroachments were produced for the two-lane portions of the four sample segments since different roadway widths, curvature,

Table 26. Centerline encroachments on two-lane sections.

Centerline Encroachments (per mile)					
	96-in trucks		102-in trucks		
Route	Number	Rate	Number	Rate	p-value
US 1	19	.058	29	.098	.08
US 220	2	.011	0	0	--
US 71A	13	.053	17	.077	>.25
US 71B	26	.123	26	.141	>.50
All	60	.062	72	.091	.03

1 in = 2.54 cm; 1 mi = 1.61 km

and paved shoulder widths exist for each segment and such features were believed to affect truck placement (and amount of edgeline encroachment). A tire width was found to correspond to approximately 7 in (18 cm) for purposes of translating tire widths to feet of encroachment.

The smoothed distribution of the total number of edgeline encroachments by tire width is shown in figure 18 for both width trucks on US 1, which has a generally flat terrain with mild curvature and mostly no paved shoulders. About twice as many edgeline encroachments between 0 and 1 tire width were observed for 102-in (259-cm) trucks compared to 96-in (244-cm) trucks. However, little or no differences occurred between the two width trucks for more severe encroachments such as two tire widths or greater. Thus, these results suggest that on this particular route, the more severe encroachments beyond 2 tire widths (1.2 ft (0.37 m)) were rare for both truck widths. In fact, virtually no trucks encroached beyond 4 tire widths (2.3 ft (0.70 m)).

The two-lane segment of US 220 consists of mostly unpaved or narrow paved shoulders and mild to moderate curvature. The distribution of truck encroachments on US 220 (*see figure 19*) reveals that the frequencies of truck encroachments were quite similar for both width trucks. Also, very few encroachments occurred beyond 2 tire widths (1.75 ft (0.53 m)).

Encroachment distributions for both width trucks are shown for US 71A in figure 20. This segment consists of moderate to severe curvature and grades and mostly paved shoulders of 6 to 10 ft (1.83 to 3.05 m). As one might expect, the greater width of paved shoulder allows more opportunity for encroachments beyond the edgeline, and the greater curvature may result in more of a tendency for drivers to "straighten out the curves," which can result in shoulder encroachments. A greater number of edgeline

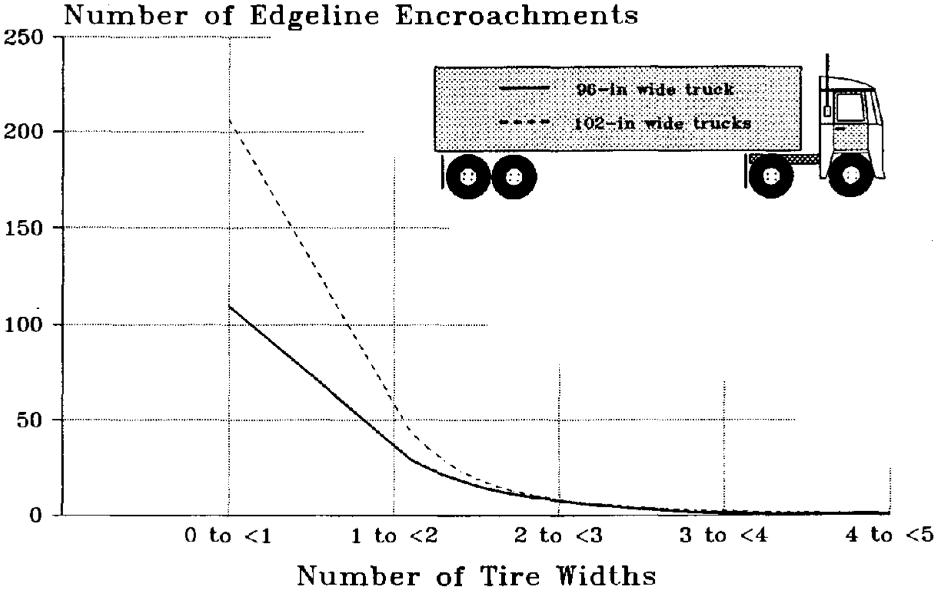


Figure 18. Distributions of edgeline encroachments for both width trucks on US 1.

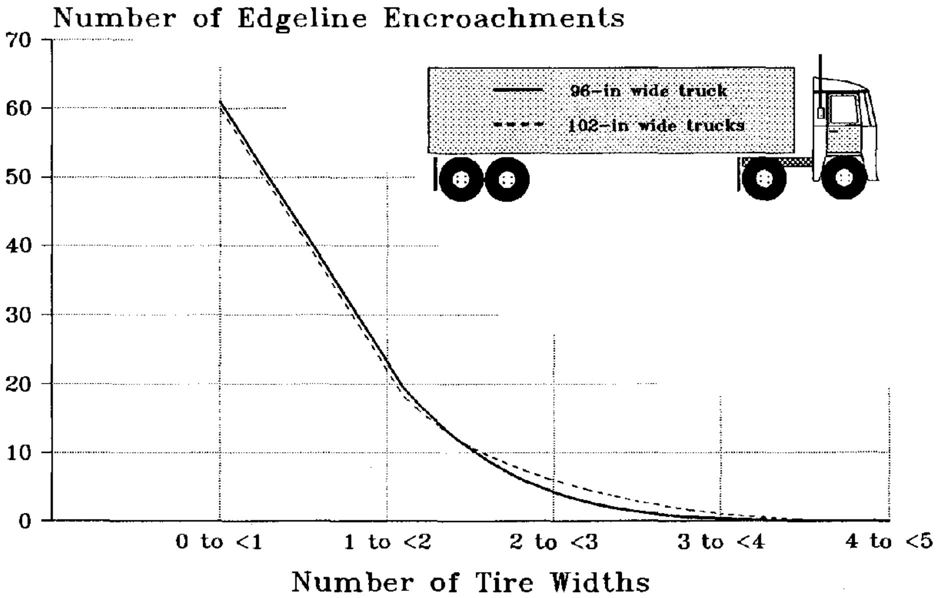


Figure 19. Distributions of edgeline encroachments for both width trucks on US 220.

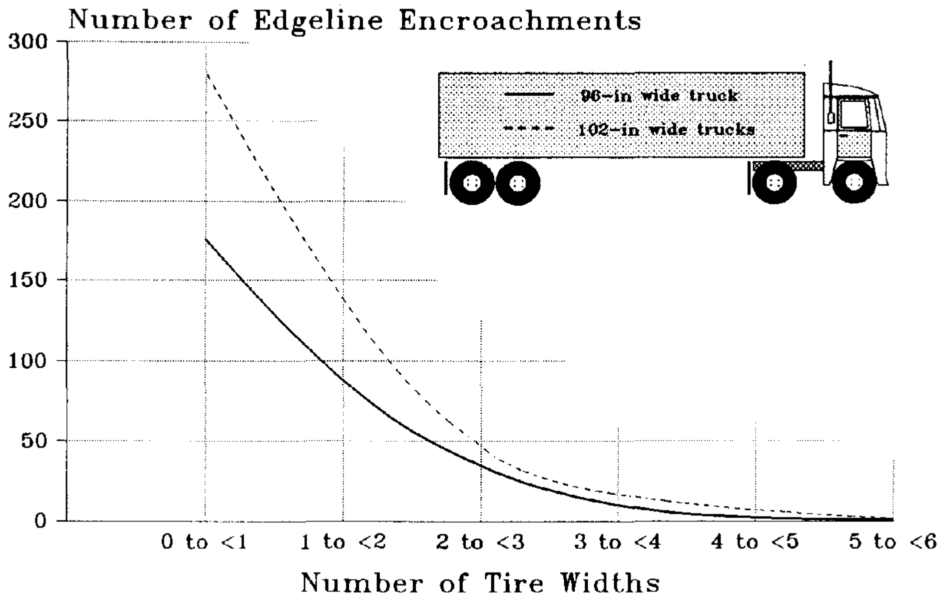


Figure 20. Distributions of edgeline encroachments
for both width trucks on US 71A.

encroachments existed for the 102-in (259-cm) truck compared to the 96-in (244-cm) truck for encroachments less than 2 tire widths (1.2 ft (0.37 m)). Encroachment frequencies between 2 and 6 tire widths (1.2 to 3.5 ft (.37 to 1.07 m)) were quite similar for the two width trucks and leveled off to near zero. Thus even on this route having mostly moderate and some severe curvature and 6 to 10 ft (1.83 to 3.05 m) shoulders, few trucks encroached beyond 3 ft (.91 m).

Of the four sample segments in this study, US 71B had the most severe horizontal and vertical curvature and also had 10 ft (3.05 m) of paved shoulder through most of the section. As shown in figure 21, encroachment frequencies just beyond the edgeline (i.e., between 0 and 1 tire width) were slightly higher for 102-in (259-cm) trucks than for 96-in (244-cm) trucks. However, little difference in encroachments existed between the two width trucks for encroachments more extreme than 2 tire widths. For both truck widths, encroachment frequencies leveled off to near 0 beyond 5 tire widths (2.9 ft (.88 m)), although a few encroachments occurred which were 7 tire widths (4.1 ft (1.25 m)).

The results of this analysis provide some insights regarding the width of paved shoulders needed to accommodate edgeline encroachments of large trucks. Trucks encroach over the edgeline more frequently and to a greater degree where wide paved shoulders exist (i.e., drivers use the paved shoulders as additional lane width). However, some trucks encroach over the edgeline even when little or no paved shoulder exists which suggests an undesirable situation from a safety, as well as an operational, perspective. The data also showed that while 102-in (259-cm) wide trucks

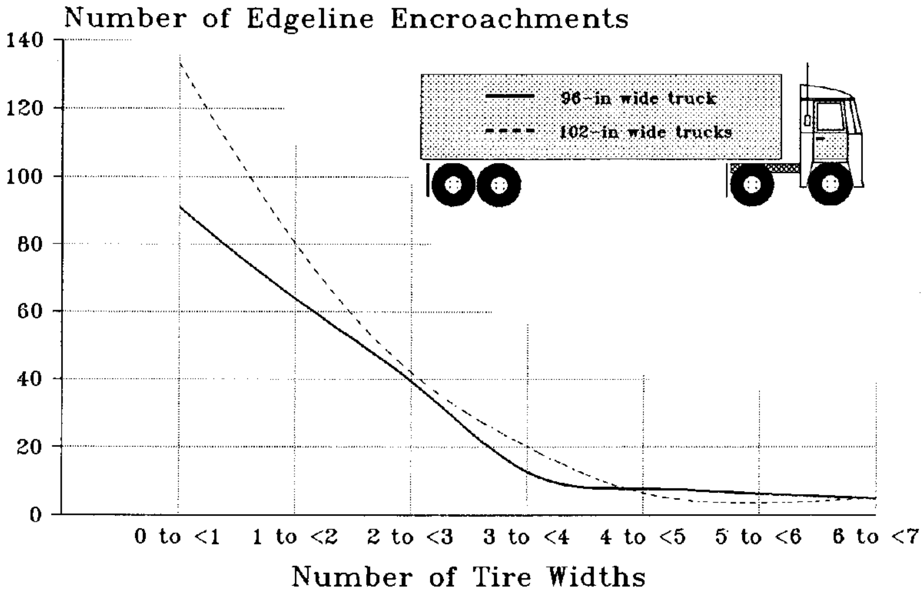


Figure 21. Distributions of edgeline encroachments for both width trucks on US 71B.

encroach over the edgeline more often than 96-in (244-cm) wide trucks, encroachments more than 3 ft (.91 m) beyond the edgeline were rare for both truck sizes for most roadway situations.

CHAPTER 6 - DATA ANALYSIS AND RESULTS FOR CONTROL TRUCKS

Chapter 5 discussed the analysis of data from following traffic stream trucks of various sizes over the four study segments. This chapter summarizes the results of the second major type of analysis, that conducted on control truck data. The term control truck refers to a driver and several truck configurations which were loaned to the research team. An experienced driver was instructed to drive the same route in each of the four configurations of trucks used:

- 96-in (244-cm) wide, 45-ft (13.7-m) semi.
- 102-in (259-cm) wide, 48-ft (14.6-m) semi.
- 96-in (244-cm) wide, 48-ft (14.6-m) semi.
- 102-in (259-cm) wide, 28-ft (8.5-m) double.

The analyses of these data involved examining differences between the four configurations.

Lane placement observations were recorded with a 35-mm camera while following each of the different trucks over the given route for a number of runs. The route chosen was US 71B, the segment with the most severe curvature. On the two-lane sections of the segment, pavement width per direction varied from approximately 14 ft (4.3 m) to 35.5 ft (10.8 m), with mean and median values of about 20 ft (6.1 m). These widths included the lane and any existing paved shoulder and climbing lane. Curves varied in degree from 0.9 degrees to 17.5 degrees with half of the observations occurring at locations with curvature greater than 3 degrees.

TWO-LANE ROADS

Table 27 shows occurrences of each of the four operational measures developed previously, cross-classified by truck configuration. As was done with the earlier traffic stream truck analyses, the situation of the control truck meeting an opposing vehicle on a two-lane road was considered first. Table 27 shows there were 2,346 observations made of the control truck meeting an opposing vehicle. In all instances the control truck was never within 1 ft (.31 m) of the edge of pavement and in only 3 cases was it within 3.5 ft (1.07 m) of the opposing vehicle. The driver of the control trucks, although encroaching the edgeline only 5 times, did come within 1.75 ft (.53 m) of the centerline 6.4 percent of the time. However, this latter measure differed significantly between truck configurations. The lowest percentage, 2.1 percent, was obtained for the 96-in (244-cm) wide, 48-ft (14.6-m) control truck. Traffic stream truck percentages for the 96-in (244-cm), 48-ft (14.6-m) truck were 9.0 and 16.3 percent for those with a short (30 to 36 ft (9.1 to 11.0 m) and long (37 to 40 ft (11.3 to 12.2 m) KRA distances, respectively. The highest percentage for the 102-in (259-cm), 48-ft (14.6-m) control truck was 11.6 percent compared with traffic stream truck percentages of 11.4 and 14.1 percent for those with short and long KRA distances, respectively.

Table 27. Control truck meeting an opposing vehicle on two-lane segments of US 71B.

Truck Configuration			Edgeline Encroachments			Within 1.75-ft of Centerline		
Type	Width	Trailer Length	No	Yes	%	No	Yes	%
Single	96-in	45-ft	687	0	0	639	48	7.0
Single	96-in	48-ft	626	1	.2	614	13	2.1
Single	102-in	48-ft	533	2	.4	473	62	11.6
Double	102-in	28-ft	495	2	.4	469	28	5.6
Total			2,341	5	.2	2,195	151	6.4
						$X^2_3 = 44.3$ p <.001		

Truck Configuration			Within 1-ft of Edge of Pavement			Within 3.5 ft of Oncoming Vehicle		
Type	Width	Trailer Length	No	Yes	%	No	Yes	%
Single	96-in	45-ft	687	0	0	686	1	.2
Single	96-in	48-ft	627	0	0	627	0	0
Single	102-in	48-ft	535	0	0	535	0	0
Double	102-in	28-ft	497	0	0	495	2	.4
Total			2,346	0	0	2,343	3	.1

1 in = 2.54 cm; 1 ft = 0.305 m

To further investigate the operational measure involving distance from the centerline, ANOVA and regression analysis models were used which treated distance from the centerline as a continuous variable. Using one-way analysis of variance, mean distances from the centerline were found to differ significantly across truck types (p < .001). The letters in the last column of table 28 show the results of Duncan's multiple range test applied to the four "near" centerline distances. As noted in the table, means having the same letter do not differ significantly, such as, for example, 96-in (244-cm), 45-ft (13.7-m) and 102-in (259-cm), 48-ft (14.6-m) trucks. The results in table 28 are consistent with those in table 27 related to being within 1.75 ft (0.53 m) of the centerline.

In a regression model fit to average distance from the centerline, truck configuration and degree of curvature were both statistically significant (p < .001), with distance from the centerline increasing as degree of curve increased. Pavement width was not statistically significant nor were any interactions involving truck configuration and degree of curve (i.e., "truck type x curve" variable).

Table 28. Mean distances from the centerline on two-lane segments of US 71B.

Truck Configuration			Mean Distance from the Centerline (ft)	Duncan Grouping
Type	Width	Trailer Length		
Single	96-in	48-ft	2.85	A
Double	102-in	28-ft	2.49	B
Single	96-in	45-ft	2.44	B C
Single	102-in	48-ft	2.41	C

1 in = 2.54 cm; 1 ft = 0.305 m

MULTILANE ROADS

For the multilane scenario, control truck data were obtained for the following three maneuvers: (1) meeting an opposing vehicle, (2) passing another vehicle, and (3) being passed by another vehicle. Occurrences of these various events are shown in tables 29, 30, and 31, respectively. Table 29 pertains to the control truck meeting an opposing vehicle when the control truck was in the inside (left-hand) lane. As was the case on two-lane roads, the maneuver of being within 1.75 ft (0.53 m) of the centerline was the only one that occurred to any extent but there were no significant truck to truck differences (p = .24).

When the control truck was passing another vehicle, it was in the left-hand lane. Table 30 shows laneline

Table 29. Lane placement characteristics of the control truck when meeting an opposing vehicle on multilane segments of US 71B.

Truck Configuration			Centerline Encroachment			Within 1.75-ft of Centerline			Within 3.5 ft of Opposing Vehicle		
Type	Width	Trailer Length	No	Yes	% Yes	No	Yes	% Yes	No	Yes	% Yes
Single	96-in	45-ft	45	0	0	37	8	17.8	43	2	4.4
Single	96-in	48-ft	52	0	0	48	4	7.7	51	1	1.9
Single	102-in	48-ft	46	0	0	37	9	19.6	46	0	0
Double	102-in	28-ft	16	0	0	12	4	25.0	16	0	0
Total			159	0	0	134	25	15.7	156	3	1.9
						$\chi^2_3 = 4.3$	p =.24				

1 in = 2.54 cm; 1 ft = 0.305 m

Table 30. Lane placement characteristics of the control truck when passing on multilane segments of US 71B.

Truck Configuration			Laneline Encroachments			Within 1.75-ft of Centerline		
Type	Width	Trailer Length	No	Yes	%	No	Yes	%
Single	96-in	45-ft	49	1	2.0	36	14	28.0
Single	96-in	48-ft	74	1	1.3	44	31	41.3
Single	102-in	48-ft	60	0	0	33	27	45.0
Double	102-in	28-ft	29	0	0	18	11	37.9
Total			212	2	.9	131	83	38.8
						X^2_3= 3.64		p =.30

1 in = 2.54 cm; 1 ft = 0.305 m

encroachments and being near the centerline for this maneuver. As before, laneline encroachments were very rare, occurring in less than 1 percent of the passing maneuvers. The table also shows that being within 1.75 ft (0.53 m) of the centerline occurred much more often, but significant differences between truck types were not found (p = .30).

Table 31 shows percentages of edgeline encroachments, being within 1.75 ft (0.53 m) of the laneline, and being within 1 ft (0.3 m) of the edge of pavement when the control truck was being passed. The first and third maneuvers did not occur during the control truck runs. In about 18 percent of the observations, the control truck was within 1.75 ft (0.53 m) of the laneline when being passed. For this maneuver, there were significant differences between trucks (p = .003). The differences were primarily between the two 96-in (244-cm) trucks, where 39 percent of the time the 45-ft (13.7-m) truck was near the centerline as compared to less than 4 percent of the time for the 48-ft (14.6-m) truck. The 102-in (259-cm), 48-ft (14.6-m) semi and the 102-in (259-cm) double behaved much more like the overall average.

The results of the control truck data on two-lane and multilane roads showed no occurrence of driving within 1 ft (.31 m) of the edge of pavement and very few occurrences of other edgeline encroachments and low clearance distances (3.5 ft (1.07 m)) for each type of control truck. It is clear that the selected driver was not only driving carefully (since he knew that he was part of the study) but was likely selected by the trucking company as one of their most competent drivers. Thus, the resulting operational problems would be expected to be less for the four truck types overall compared to the traffic stream trucks. It was hoped that this test would help to show the truck-related operational differences resulting from the four truck types, independent of driver effects. The higher incidence of near-centerline events by the 102-in (259-cm), 48-ft (14.6-m) semi (axles pulled back), as compared to the other truck types tested, was expected due to the increased swept path of the truck

Table 31. Lane placement characteristics of the control truck when being passed on multilane segments of US 71B.

Truck Configuration			Edgeline Encroachments			Within 1.75-ft of Laneline			Within 1-ft of Edge of Pavement		
Type	Width	Trailer Length	No	Yes	%	No	Yes	%	No	Yes	%
Single	96-in	45-ft	28	0	0	17	11	39.3	28	0	0
Single	96-in	48-ft	29	0	0	28	1	3.5	29	0	0
Single	102-in	48-ft	32	0	0	26	6	18.8	32	0	0
Double	102-in	28 ft	41	0	0	36	5	12.2	41	0	0
Total			130	0	0	107	23	17.7	130	0	0
						X^2_3=13.9	p=.003				

1 in = 2.54 cm; 1 ft = 0.305 m

on curves. The low number of operational problems resulting from the control truck driver operating all four truck types combined with the much higher operational problems with the traffic stream trucks suggests an interesting finding. It appears driver effects can indeed make considerably more difference in operational measures than the size and other characteristics of the trucks for the truck types tested. This same conclusion was also reached by Zegeer, Hummer, and Hanscom.(4)

ENCROACHMENTS OF CONTROL TRUCKS

All of the previous analyses discussed in this chapter used data from the *lane placement file*; that is, vehicle positions and encroachments of the control trucks taken from 35-mm slides. Additional data were obtained using a video camera. The truck path for the total route, and each encroachment over the centerline, edgeline, or laneline along the route were coded from the videotape. For each such encroachment, data were also recorded on the length of the encroachment, the maximum width of the encroachment (in tire widths), and the geometric characteristics where the encroachment occurred.

As mentioned previously, a series of runs were made using the same experienced driver and four common truck configurations. The purpose of these control truck data runs was to remove possible driver effects. As discussed below, the driver negotiated US 71B, the most challenging of the four routes, with very low encroachment rates regardless of truck configuration.

More specifically, the 96-in (244-cm) wide semi was observed while making 12 runs over route US 71B for a total of 108 mi (174 km) on two-lane sections. The truck encroached the edgeline only 4 times to yield an encroachment rate of .037/mi (.022/km). In six runs covering 59 mi (95 km), the 102-in (259-cm) wide semi had only two edgeline encroachments for exactly the same encroachment rate of .037/mi (.022/km). The 102-in (259-cm) double had a slightly higher encroachment rate of .056/mi (.035/km) based on 5 encroachments in 10 runs covering 90 mi (145 km). The comparable rates for the traffic stream trucks were considerably higher; 0.78/mi (0.48/km) and 1.36/mi (0.84/km) for 96-in (244-cm) and 102-in (259-cm) wide semis, respectively.

This finding suggests that, at least for the selected route and truck sizes tested, an experienced driver can handle a 102-in (259-cm) wide truck about as well as a 96-in (244-cm) truck. The fact that the 102-in (259-cm) traffic stream trucks had higher encroachment rates than the 96-in (244-cm) trucks suggests a different driving pattern by the traffic stream truck drivers, compared to the control truck driver. It is possible the control truck driver, knowing he was part of a test, tried to drive the 96-in (244-cm) and 102-in (259-cm) trucks more in his lane (i.e., between the centerline and right edgeline) than drivers in the normal traffic stream. This same tendency was found by Seguin et al. in their study which employed a control truck driver.(3) In their study, no significant differences were found in edgeline encroachments between the 102-in (259-cm) and 96-in (244-cm) trucks. This could indicate traffic stream drivers may be less familiar with the 102-in (259-cm) trucks than the experienced control truck driver and thus are steering farther away from opposing traffic. It could also simply be the result of the control truck driver trying to look good by staying relatively centered in his lane and therefore encroaching the edgeline less often.

In any case, it is clear from the control truck data that the four truck types tested are capable of being driven with few operational problems using a highly experienced driver with a well-maintained truck in good weather conditions, even on a segment of road with severe horizontal curvature.

The traffic stream data, however, shows that the 102-in (259-cm) trucks are not being driven like the 96-in (244-cm) trucks by the drivers currently driving trucks on these routes. The small sample of only five encroachments in 90 mi (145 km) of travel along US 71B for the doubles further indicates a low level of operational problems. This might have been expected, however, since doubles can turn curves more sharply than most 45-ft (13.7-m) and 48-ft (14.6-m) semis.

All of the encroachments for the semis occurred on curved sections of roadway with 12-ft (3.7-m) lanes and paved shoulders. This is not surprising since nearly 55 percent of the two-lane portion of US 71B consisted of curves of 2 degrees or more. Of the encroachments for the 102-in (259-cm) double, two occurred on tangent sections and three on curves.

With respect to degree of encroachment, one of the two 102-in (259-cm) semi encroachments was between 1 and 2 tire widths, while all of the others were less than 1 tire width.

For the entire set of runs, there was only one centerline encroachment observed on the two-lane section, and it involved the 102-in (259-cm) double.

Clearly, from the control truck data, an experienced driver can negotiate rather challenging sections of two-lane roads with minimal edgeline and/or centerline encroachments regardless of length and width of trailer. Also clear from the traffic stream data is the fact that drivers in the traffic stream encroach at much greater rates -- by a factor of 25 or more.

CHAPTER 7 - SUMMARY AND CONCLUSIONS

The primary objective of this study was to determine the effects of 102-in (259-cm) versus 96-in (244-cm) wide trucks on traffic operations (e.g., lane placement of trucks and opposing vehicles, and edgeline and centerline encroachments) under a variety of roadway and traffic conditions. Other truck characteristics, such as trailer length and configuration were also examined as part of this study.

A secondary objective was to investigate the feasibility of using truck fleet data from trucking companies and previous accident research studies to analyze the effects on accidents of various truck types and sizes on specific highway types. This investigation led to the conclusion that no data base was readily available from which one could compute truck accident rates by truck type and size on various roadway types. A plan is discussed in appendix B for conducting such an accident analysis study in the future. However, the remainder of this study involved analysis of the operational impacts of various truck sizes and configurations on a variety of roadway geometrics.

DATA COLLECTION AND REDUCTION

Two basic types of data collection were utilized for comparing these operational truck effects on rural roadway sections. Four roadway sections were selected in North Carolina, Arkansas, and Virginia which included a range of traffic and roadway conditions (mostly two-lane) and a sufficient volume of trucks on which data could be collected. First, traffic stream trucks of different sizes and lengths, and a smaller sample of cars and pickups, were inconspicuously followed by a data collection van, and 35-mm slides were randomly taken of opposing vehicles as they were alongside the followed vehicle. From these slides, lane placement and encroachment data of the followed and opposing vehicles, termed *lane placement data*, were recorded. Second, a video camera inside the van was used to film the path of the followed vehicle through the entire roadway section. Data concerning all encroachments of the followed vehicle through the selected routes, termed *encroachment data*, were recorded from the videotape. A second video camera at a roadside location along the route was used to obtain the length of any truck being followed. These data were then added to the two data files. Roadway geometric data (e.g., lane width, shoulder width, and length and degree of curve) were collected in the field, supplemented with data from aerial photographs, and later merged with the lane placement and encroachment data files to develop the final files used in the analysis.

In addition to following traffic stream trucks (and cars and pickups for comparison purposes), a separate data collection effort was performed using four control trucks (i.e., trucks loaned to the research team by a trucking company along with an experienced driver). The collection of control truck data served to enhance the study in two important ways. The first and most important reason for collecting control truck data is the need to control for driver effects which may vary by truck size and/or type. Assume, for example, that the larger trucks (i.e., 102-in (259-cm) wide trucks with 48-ft (14.6-m) long trailers) are generally being driven by more experienced drivers than the smaller trucks (i.e., 96-in (244-cm) wide trucks with 45-ft (13.7-m) long trailers). This could result, for example, from trucking companies assigning better drivers to handle the larger trucks (which may be more difficult to operate than smaller trucks). If this were the case, a comparison of operational effects between the two width trucks would result in not just a comparison of truck size effects, but a comparison of 102-in (259-cm) wide trucks with more experienced drivers versus 96-in (244-cm) wide trucks with less experienced drivers. Thus, having data for traffic stream trucks alone would not allow for determining if an operational difference was due to the difference in truck size alone or due to the differing driver characteristics between the truck groups or both.

Secondly, not all of the truck types were available within the traffic stream in adequate sample sizes for statistical comparison. For example, only eight doubles were observed in the traffic stream. The use of a control truck double allowed for comparisons between configurations be made within the control truck data set.

The same driver made multiple runs with different trucks on a preselected route with severe curvature. Runs were made using a double with two 102-in (259-cm) wide 28-ft (8.5-m) trailers, a semi with a 102-in (259-cm) wide 48-ft (14.6-m) long trailer, a semi with a 96-in (244-cm) wide 45-ft (13.7-m) long trailer, and a semi with a 96-in (244-cm) wide 48-ft (14.6-m) long trailer. In all data runs using control trucks, the same tractor was used and the trailers were empty as compared to the traffic stream trucks which had a variety of tractor rigs and unknown trailer weights. The rear axles on the control truck trailer were also pulled back to achieve the worst possible offtracking patterns.

The field data collected and the following conclusions relate only to rural highway sections and are not intended for extrapolation to urban roadway sections. Likewise, the results of this study cannot be extended to longer and wider trailers than those examined in this effort which include semis with widths of 96 in (244 cm) and 102 in (259 cm) and lengths up to 48 ft (14.6 m), and doubles of both widths with 28-ft (8.5-m) trailers.

SUMMARY OF RESULTS

The data collection and analyses were structured to address the primary issue:

- *What are the operational effects of 102-in (259-cm) wide trucks compared to 96-in (244-cm) wide trucks while accounting for other truck and driver characteristics?*

To answer this general question, five specific secondary issues were addressed for the rural roadway scenario since truck width could interact with truck configuration, trailer length, roadway geometrics, driver differences, and other factors in affecting operations. Following is a listing of these subissues along with a summary of the analysis results.

Subissue 1 - How do the various truck configurations (e.g., semitrailers vs. doubles) compare with each other with respect to operational practices?

There is some evidence that doubles are operated slightly farther from the centerline and slightly nearer the pavement edge than semis. For example, based on average values of traffic stream trucks, doubles were operated 2.93 ft (0.89 m) from the centerline and 4.39 ft (1.34 m) from the edge of pavement as compared to semis which ranged from 2.37 to 2.82 ft (0.73 to 0.86 m) from the centerline and 4.84 to 6.61 ft (1.48 to 2.01 m) from the edge of pavement.

Control truck doubles were used to supplement the data for the eight traffic stream doubles which were followed. The control truck data revealed that the 102-in (259-cm) double had a slightly higher encroachment rate (0.56 encroachments/mi (0.90 encroachments/km)) based on five encroachments in 10 runs covering 90 miles (145 km) compared to an encroachment rate of 0.037 encroachments/mi (0.059 encroachments/km) for 96-in (244-cm) and 102-in (259-cm) semis based on 108 miles (174 km) and 59 miles (95 km) of runs, respectively.

In addition to the lane placement of the truck itself, opposing vehicles on two-lane roads were found to be driven farther from the centerline when meeting doubles than when meeting cars or other truck types. This may be caused by the simple perception that doubles are indeed larger trucks.

Subissue 2 - What are the effects of truck trailer length (e.g., 45-ft vs. 48-ft (13.7-m vs. 14.6-m) trailers) and kingpin-to-rear axle distance with respect to trailer width (e.g., 96-in (244-cm) vs. 102-in (259-cm) on operational practices?

The lane placement data of traffic stream trucks showed no consistently significant effect of trailer length or kingpin-to-rear axle (KRA) distance on edgeline encroachments or distance to the centerline, neither on tangents or curves, for a given trailer width. However, trailer width was associated with significant differences in truck operations in many situations. Depending on trailer length and KRA distance, the percentage of edgeline encroachments for 96-in (244-cm) trucks ranged from 10.7 to 16.4 percent while 102-in (259-cm) trucks had between 20.2 and 25.2 percent edgeline encroachments. The distance of the trucks from the centerline ranged from 2.63 to 2.82 ft (0.80 to 0.86 m) for 96-in (244-cm) wide trucks and from 2.37 to 2.69 ft (0.72 to 0.82 m) for 102-in (259-cm) wide trucks.

No significant effects due to trailer length or KRA were found with respect to either average distance to the edge of pavement (i.e., distance to the outside edge of the paved shoulder if a paved shoulder exists) or the percentage of times the truck was CLOSE (1 ft (.31 m) or less) to the edge of pavement. This finding may seem somewhat surprising since offtracking for longer trailers and KRA distances is expected to be greater and thus result in more encroachments. However, one must consider the characteristics of low-speed and high-speed offtracking of vehicles with longer trailers, and particularly longer KRA distances (e.g., greater than 36 ft (11.0 m) in this study). For example, when making turns under speeds of 35 to 40 mi/h (56.4 to 64.4 km/h), trucks with longer KRA distances will have their rear trailer tires track to the inside of the path of the front tractor tires. On sharp curves this can result in severe encroachments over the centerline (on curves to the left) or the edgeline (on curves to the right). However, high-speed offtracking can cause the trailer to swing outward so the rear trailer tires more closely track the path of the front tractor tires. For example, on a curve with a 1200-ft (366-m) radius, a semi with a 48-ft (14.6-m) trailer travelling at 55 mi/h (86 km/h) will offtrack about 0.24 ft (0.073 m) to the outside of the curve. The fact that the majority of the data were collected under high-speed conditions may be the primary reason why the lane placement data for the traffic stream trucks resulted in no consistently significant effect of trailer length or KRA distance on edgeline encroachments or distance to the edge of pavement.

Two other possible explanations should also be mentioned relative to the lack of effect of trailer length and KRA distance in the analysis. First, on tangent sections, the trailer length and KRA distance have little or no effect on swept path since the swept path is basically the truck width. Many of the observations were made on tangent sections. Another possible explanation is related to the characteristics (including skill) of drivers of 102-in (259-cm) trucks versus 96-in (244-cm) trucks. For example, if drivers of longer (i.e., 48-ft (14.6-m)) trucks were more skilled at handling their trucks than drivers of shorter (i.e., 45-ft (13.7-m)) trucks, this improved truck handling could help compensate for the added operational impacts of the increased trailer length or KRA distance.

Subissue 3 - How do the operational characteristics of various truck types and sizes compare with cars? In other words, to what degree are large trucks, relative to cars, causing operational problems?

The lane placement data showed cars have fewer edgeline encroachments, greater mean distances from the centerline, and are driven at greater distances from the edge of pavement than either the 96-in (244-cm) or 102-in (259-cm) trucks. In fact, cars encroached the edgeline in only 4.9 percent of the cases when meeting opposing vehicles, compared to 11.9 percent for 96-in (244-cm) trucks and 22.7 percent for 102-in (259-cm) trucks. Mean distance from the centerline was 3.96 ft (1.20 m) for cars, compared to 2.81 ft (0.86 m) for 96-in (244-cm) trucks and 3.60 ft (1.10 m) for 102-in (259-cm) trucks. The fact that 102-in (259-cm) trucks travelled an average of 0.70 ft (0.24 m) farther from the centerline than 96-in (244-cm) trucks is consistent with earlier findings regarding the tendency of drivers of the wider trucks to place their vehicles away from the centerline.

Cars, of course, may be expected to be driven farther from the edgeline (i.e., with fewer encroachments) and also farther from the centerline than trucks because of their smaller size. The mean distance of cars from the edge of pavement was 7.76 ft (2.37 m), compared to 5.92 ft (1.80 m) and 5.95 ft (1.81 m) for 96-in (244-cm) and 102-in (259-cm) trucks, respectively. These values indicate that all three vehicle types maintained a substantial distance from the edge of pavement.

In addition, a much smaller percentage of the cars were CLOSE to the edge of pavement as compared to trucks. This is again because of the smaller size of cars than trucks. Only 1.5 percent of the cars were CLOSE to the edge of pavement as opposed to 8.2 percent and 9.6 percent of the 96-in (244-cm) and 102-in (259-cm) trucks, respectively. These values indicate a higher potential for run-off-road events for the 102-in (259-cm) trucks than for passenger cars or 96-in (244-cm) wide trucks.

Subissue 4 - For a given truck type and size (e.g., 102-in (259-cm), 48-ft (14.6-m) semi) how much variation in operational measures occurs due to driver differences? In other words, do all drivers handle a given truck type in relatively the same manner or in different manners?

A wide range of vehicle behavior was found for a given route and truck type based on vehicle placement. For example, on one route (US 1) in North Carolina, slides of the lane placements of 102-in (259-cm) trucks revealed that an overall average of 20.2 percent of the trucks had edgeline encroachments. Of the 21 runs, the minimum and maximum percentage of edgeline encroachments was 6.5 and 58.6 percent, respectively. As another example, the 24 runs of 96-in (244-cm) trucks on US 220 had an overall average distance from the centerline of 2.89 ft (0.88 m), although the range of averages among the 24 trucks included a minimum of 2.09 ft (0.64 m) and a maximum of 5.27 ft (1.61 m). Since this variation exists within a given route and for a given truck size, different driving behavior may be assumed to be important in explaining these results. This difference in driver behavior is further supported by the control truck data which indicated a given truck type can be operated consistently by the same driver in repeated runs, and different truck types can also be operated in a relatively similar fashion by the same driver.

Subissue 5 - For a given truck type, how much operational variation occurs for various roadway geometrics?

Both 102-in (259-cm) and 96-in (244-cm) trucks tended to be driven farther from the centerline and to have higher rates of edgeline encroachments on curves than on tangents. The percentage of edgeline encroachments was more than twice as high on curves (28.7 percent) as on tangents (12.8 percent). The average distance from the centerline was slightly higher on curves (3.04 ft (0.93 m)) compared to tangents (2.61 ft (0.79 m)). This finding is, perhaps, the result of truck drivers using caution when driving through curves. That is, where the pavement is of sufficient width on curves, drivers tend to move to the right, onto a paved shoulder in some cases, thus increasing their clearance distance to opposing traffic.

Distance from the edge of pavement was considerably greater on curves (8.17 ft (2.49 m)) compared to tangents (5.38 ft (1.64 m)) even though vehicles on curves were also farther from the centerline than on tangents. Trucks were also less likely to travel within 1 ft (.31 m) of the edge of pavement (i.e., outside edge of a paved shoulder if a paved shoulder exists) on curves (1.7 percent) than on tangents (10.0 percent). Again, these results are indicative of the wider paved shoulders on curves compared to tangents.

CONCLUSIONS

Operational Differences

Through examination of the above findings, the following conclusions were drawn about the operational effects of the 102-in (259-cm) wide truck compared to the 96-in (244-cm) wide truck while accounting for other truck characteristics and driver effects:

- Wider (102-in (259-cm)) trucks had significantly higher rates of edgeline encroachments than did narrower (96-in (244-cm)) trucks.

This is reasonable since 102-in (259-cm) trucks require greater swept path widths than a 96-in (244-cm) truck, all else being equal. Also, some drivers of the 102-in (259-cm) trucks (particularly those with 48-ft (14.6-m) trailer lengths) were more likely to *hug* the edgeline on curves to the left, probably to avoid having the rear of their trailer encroach over the centerline.

- On average, wider (102-in (259-cm)) trucks tended to be closer to the centerline than were the 96-in (244-cm) trucks. For all four sites combined, the 102-in (259-cm) trucks had higher centerline encroachment rates than the 96-in (244-cm) trucks, although this result was not significant for any specific route due to the small samples of centerline encroachments.

This closeness to the centerline may be the result of two possible factors. First, the additional 6 in (15.2 cm) of width for the 102-in (259-cm) trucks could result in more of them being driven closer to the centerline than the 96-in (244-cm) trucks due to their increased swept path. Thus, on winding, two-lane roads, this could translate into 102-in (259-cm) trucks having a greater proportion of edgeline encroachments as well as being closer to the centerline.

The second factor relates to differential driving behavior for the two width categories when combined with the geometry of the test sites. If, for example, drivers of 102-in (259-cm) trucks tend to hug the right edgeline on curved roads, one would expect a greater proportion of edgeline encroachments on roads where wide paved shoulders exist. However, on narrow curved roads with no paved shoulders, drivers of the 102-in (259-cm) trucks would be limited in their ability to drive farther from the centerline (unless they encroach beyond the paved roadway). Thus, because of their greater swept path on curved roads, the 102-in (259-cm) trucks would be expected to be closer to the centerline than the 96-in (244-cm) trucks on narrow roadways.

Combining the Traffic Stream and Control Truck Results

The combined results of the operational analysis for both the traffic stream and control truck data were considered to be useful in gaining a better understanding of truck size effects. It was clear that a wide range of vehicle operations existed for a given route and truck type based on traffic stream truck driver behavior. Also, the control truck driver was able to operate a given truck type consistently in repeated runs, and thus resulting encroachments by the traffic stream trucks were considerably greater than those of the control trucks.

It was also clear that the selected control truck driver was not only driving carefully (since he knew he was part of the study) but was probably selected by the trucking company as one of their most competent drivers. Thus, the resulting operational problems would be expected to be less for the four control truck types than for the traffic stream trucks.

The analyses of both the traffic stream and control trucks found some increased problems with the 102-in (259-cm) wide trucks compared to the 96-in (244-cm) wide trucks. For example, in one analysis of the control truck data, a higher incidence of near-centerline events was found for the 102-in (259-cm), 48-ft (14.6-m) semis (axles pulled back) compared with the smaller trucks. The low number of operational problems resulting from the control truck driver operating all four truck types compared with the much greater operational problems with the traffic stream trucks suggests driver effects can indeed make considerably more difference in operational measures than the size and other characteristics the trucks studied.

The encroachment data of traffic stream and control trucks also revealed some interesting findings. Using control trucks, the edgeline encroachment rates were similar (.037/mi (.023/km)) for the 96-in (244-cm) and 102-in (259-cm) wide semis, with a somewhat higher rate (.056/mi (.035/km)) for the double with 28-ft (8.5-m) trailers). The comparable rates for the traffic stream trucks were considerably higher -- .078/mi (.048/km) and 1.36/mi (.845/km) for the 96-in (244-cm) and 102-in (259-cm) wide semis, respectively. These findings suggest that, at least for the selected route and truck sizes tested, an experienced driver can handle a 102-in (259-cm) wide truck about as well as a 96-in (244-cm) truck. The fact that the 102-in (259-cm) traffic stream trucks had higher encroachment rates than the 96-in (244-cm) trucks suggests a different pattern by the traffic stream truck drivers, compared to the control truck driver. This could indicate that the traffic stream drivers may be less familiar with the 102-in (259-cm) trucks than the experienced control truck driver, and thus are steering farther away from opposing traffic. It could also simply be the result of the control truck driver trying to look good by staying relatively centered in his lane with each truck type and therefore encroaching the edgeline less often.

Whatever the combination of reasons, data in this study revealed that 102-in (259-cm) traffic stream trucks were not being driven like the 96-in (244-cm) traffic stream trucks on the selected routes, even though the control truck driver was able to handle both width trucks with very few operational problems. Perhaps differences can be reduced by improvements in driving behavior. This suggests need to further study and implement truck driver improvement programs in addition to needed roadway improvements where large trucks operate.

Several caveats should be made relative to the results discussed above. First, all of the traffic stream and control truck data were collected during daylight hours under good weather conditions (e.g., no rain, ice, or snow on the pavement). Truck operations may differ under nighttime and adverse weather conditions. Secondly, the results pertain to rural (two-lane and four-lane) highway conditions including sections on tangents and curves for semis with widths of 96 in (244 cm) and 102 in (259 cm) and trailer lengths of 45 to 48 ft (13.7 to 14.6 m), and 102-in (259-cm) 28-ft (8.5-m) doubles. The results should not be extended or extrapolated to other truck sizes or roadway conditions.

Roadway Width Implications

The results of this study provided some insights regarding the width of paved shoulders needed to accommodate edgeline encroachments of large trucks. The study found that trucks encroach over the edgeline more frequently and to a greater degree where wide paved shoulders exist (i.e., the drivers use the paved shoulders as additional lane width). However, some trucks encroach over the edgeline even when little or no paved shoulder exists which suggests an undesirable situation from a safety, as well as an operational, perspective. The data also showed that while 102-in (259-cm) trucks encroach over the edgeline more often than 96-in (244-cm) trucks, encroachments more than 3 ft (.91 m) beyond the edgeline were rare for both truck sizes for most roadway situations. There is also some evidence that trucks encroach more often on curves than tangents, although this trend could not be clearly established from the available data.

On roadway sections having severe horizontal and/or vertical alignment, wider paved shoulders may be needed to adequately provide for large trucks. The use of 12-ft (3.4-m) lanes and a minimum of 3-ft (.91-m) paved shoulders should be considered on rural roadways carrying truck traffic consisting of both 96-in (244-cm) and 102-in (259-cm) wide semis and doubles. In addition, the increased travel on such shoulders could result in shorter pavement life. In order to minimize shoulder damage and maintenance problems and help ensure a stable shoulder for encroaching trucks, consideration should also be given to increasing the pavement thickness of the shoulder.

Providing paved shoulders of 3 ft (.91 m) or more will significantly increase construction costs on many roadway sections. In addition, rebuilding shoulders or adding shoulders which are designed to travel lane standards (i.e., to accommodate frequent truck encroachments) can also correspond to substantial costs for such improvements. Ideally, a benefit/cost analysis is needed to determine the economic feasibility of such shoulder construction projects. However, such an analysis requires information on the accident effects of such improvements related to trucks and other vehicles, and such effects could not be quantified in this study.

It should also be remembered that the suggestion for a minimum of 3-ft (.91-m) paved shoulders applies only to truck sizes which existed on the sample roadway sections in this study. The sample studied did not include semis with 53-ft (16.2-m) trailers, triples (i.e., three 28-ft (8.5-m) trailers), Rocky Mountain Doubles (48-ft (14.6-m) and 28-ft (8.5-m) trailer combination), or the longer Turnpike Double (two 48-ft (14.6-m) trailers). The offtracking characteristics of these longer trucks may require more paved surface than is suggested here.

CHAPTER 8 - OTHER ISSUES

WIDER TRUCK SAFETY IMPLICATIONS

The analyses in this study were for rural two-lane and some multilane roadways and did not include urban situations. The study results indicated that there are some operational differences associated with wider (102-in (259-cm)) trucks as a result of various restrictive geometric features. Some of these operational measures may be indicative of potential run-off-road events as a result of vehicles travelling too close to the edge of pavement and potential opposite direction accidents as a result of small clearance distances between the truck and an opposing vehicle. However, as is always the case with operational studies, it is difficult to directly translate differences in operational measures, like truck placement within the travel lane and edgeline encroachments, into some predicted change in accident potential. This occurs because the link between these operational measures and subsequent accident experience has not been clearly established. But, as noted above, the operational performance data does provide some clues as to the potential safety implications of wider trucks. This is examined in more detail below.

The basic finding from the data collected in this study is that:

There are, indeed, measurable differences between the operations of the 102-in (259-cm) trucks and 96-in (244-cm) trucks that could relate to ultimate safety.

There was a wide variation between trucks, and thus between drivers, within any truck class in terms of centerline and edgeline encroachments and lane placement. The biggest difference observed was that 102-in (259-cm) trucks have 1.5 to 2 times the number of edgeline encroachments as 96-in (244-cm) trucks. However, tempering this finding is the fact that many of these edgeline encroachments were on sections of roadway where there were paved shoulders. This finding is verified by the fact that no differences were found between the two different widths of trucks in terms of either the distance from the edge of pavement or the percentage which were within 1 ft (0.3 m) of its edge. Thus, the fact that a truck crosses the edgeline may not necessarily result in more crashes if there is a paved shoulder present.

On curves, both width trucks were operated farther from the edge of pavement than on tangents even though edgeline encroachments on curves were greater. This probably occurred because there were generally wider paved shoulders on curves. There was only a minor difference in the potential for either type truck to run off the road. The 102-in (259-cm) truck drivers, in general, placed their vehicles closer to the edgeline but not to the edge of pavement (where paved shoulders existed). While they tended to use the paved shoulders somewhat more as a driving area than did drivers of 96-in (244-cm) trucks, this, in itself, would not appear to be a major safety factor (although this could be a pavement design problem).

Centerline encroachments provide a measure for potential head-on accidents with oncoming vehicles. In this study, the 102-in (259-cm) trucks were operated slightly closer to the centerline than the 96-in (244-cm) trucks, but the difference was only 2.5 in (6.35 cm). This difference corresponds closely to 3 in (7.62 cm), which is half of the 6-in (15.24-cm) width increase of the 102-in (259-cm) truck compared to the 96-in (244-cm) truck. However, operation of either truck close to the centerline did affect the operation of opposing vehicles. Regression analysis techniques indicated that opposing vehicles do indeed encroach more on their own edgelines when meeting trucks being driven closer to the centerline, but less than 1 percent more when meeting wider trucks being operated 2.5 in (6.35 cm) closer to the centerline. Edgeline encroachments of opposing vehicles where paved shoulders are present do not necessarily indicate a significant increase in the probability of running off the pavement. A more significant increase in edgeline encroachments occurred when an opposing vehicle met a double, perhaps due to the fact, as stated earlier, that doubles are viewed as larger trucks than are singles of the same width.

In general, the operational data results indicated there are statistically significant differences in traffic operations between truck widths, although the results of such differences may be minimized if lanes are wide and there are paved shoulders present. It must be noted the analyses were restricted to two lane-width categories -- lanes greater than 11 ft (3.4 m) wide and lanes 11 ft (3.4 m) and less. No statistically significant differences were found between the two categories. There were very few roadway segments with lanes narrower than 11 ft (3.4 m) where a significant sample of large trucks could be observed. Therefore, the bulk of observations made were on lane widths of 11 ft (3.4 m) and 12 ft (3.7 m). In the presence of the wider lanes, both width trucks averaged one edgeline encroachment every 2 mi (.61 km) Also, curves tended to be over represented in the number of encroachments as compared to tangents.

Given the fact that on curves semis and doubles tend to be driven over the edgeline and truck drivers use the full width of paved shoulders where available, there is a need to examine the current roadway design practices.

RECOMMENDATIONS

To directly relate the truck behaviors observed in this study to accidents requires that a comprehensive study be conducted of truck crashes and corresponding truck exposure for various truck sizes and geometric conditions. A study plan, as originally proposed by McGee and Morgenstein, for accomplishing this effort is discussed in appendix B of this report.(9) The study should be performed to further identify any potential safety problems with wider and longer trucks. This effort is needed since previous truck studies have indicated that large trucks of all widths and lengths have trouble with certain specific types of roadway geometry like sharp curves, narrow lanes, and steep grades.

The high toll of truck crashes on some roadways also dictates that each State should carefully review the truck crash frequency, rate, and severity of all routes on the National Network for trucks. Such a statewide review has been conducted of high-crash sites in North Carolina by Council and Hall which yielded a listing of roadway segments with high concentrations of crashes involving large trucks.(18) Roadway sections identified with an abnormally high incidence of truck accidents should be investigated to determine the probable cause of these crashes. Based on this detailed review of truck crashes, as well as the traffic and roadway characteristics of these sites, consideration should be given to improving the section through geometric and/or other roadway improvements. Examples of such improvements may include widening the lanes and/or paved shoulders; reconstructing one or more sharp curves and/or upgrading the superelevation on curves where needed; resurfacing the road to provide better pavement skid properties; and use of improved signs, signals, and markings.

If roadway improvements cannot be economically justified, consideration then should be made to prohibit the larger trucks (102-in (259-cm) doubles and semis longer than 45 ft (13.7 m)) on selected roadways with inadequate geometry. If the roadway in question is part of the National Network for trucks, Title 23, Code of Federal Regulations (CFR), Part 658 - Truck Size and Weight, Route Designations - Length, Width, Weight Limitations should be consulted. This section of the CFR contains procedures and factors that need to be addressed for deleting a section of highway from the National Network for trucks. Alternative routes should also be considered for providing reasonable access to the prohibited trucks. Transportation Research Board Special Report 223 provides some general guidance for providing truck access.(10) This guidance includes a discussion of current access policies, accident risk as related to highway design, traffic operations and safety, and the impact on the highway infrastructure.

The results of this study clearly show a wide range of driving behavior by traffic stream truck drivers for a given truck size on selected routes. This suggests the importance of driver performance as a critical factor in the operation of trucks in addition to roadway and truck characteristics. Thus, measures to improve truck driver performance (e.g., driver training programs) should also be considered and further studied as another potential method to improve truck operations and safety.

APPENDIX A - DETAILED LITERATURE REVIEW OF STUDIES RELATED TO WIDER TRUCK OPERATIONS

There have been very few studies conducted in which width of the truck was a primary variable. Therefore, the literature in which the effects of width are documented is sparse. Below is a detailed review of several studies which have examined vehicle width in the conduct of the research which was performed. A summary of the type of data collected and the results, with respect to vehicle width, is given for each study.

Seguin et al. Study

Seguin et al. studied effects of truck sizes in specific traffic situations including:(3)

- Passing of trucks on two-lane rural roads.
- Truck impacts on traffic from freeway entrances.
- Effects of truck size on opposite-direction passing on narrow bridges.
- Effects of truck size on mainline (main roadway) lane changing behavior.

The first situation, passing of trucks on two-lane roads, was the only one relevant to the current study and is summarized below.

A controlled field study was used to investigate the effects of various truck widths on passing vehicles. The roadway was a two-lane, two-way tangent section approximately 1.3 mi (2.1 km) in length with excellent sight distance throughout. The lane width varied from 10.5 to 12 ft (3.2 to 3.7 m), the shoulder width averaged 9 ft (2.8 m) (3 ft (0.9 m) paved), and the mean speed on the section was approximately 55 mi/h (89 km/h). The passing vehicle condition was staged by allowing free-flowing vehicles to be sandwiched between the control truck and a data collection van. The passing maneuver was then invoked by slowing the control truck speed to 40 mi/h (64 km/h). For each car-truck interaction, time and distance measures were obtained at four points (two fixed and two variable) as shown in figure 22. In addition to these points, photographs, times, and speeds of the opposing vehicles were recorded with respect to the rear of the control truck. The truck width was varied from 96 to 114 in (244 to 290 cm) using 6-in (15-cm) increments. Only passenger cars and small pickup trucks were included in the study. Thus, no attempt was made to observe the effects of large trucks passing the control truck.

Five hundred one experimental trials were attempted which resulted in 434 successful trials. The data base characteristics, by truck width, are given in table 32. These successful trials were used in the statistical analysis of passing time, distance, and speed by truck width as shown in table 33. The authors observed no major differences in passing behavior when the truck width was changed since the average times and speeds of the passing maneuvers were similar.

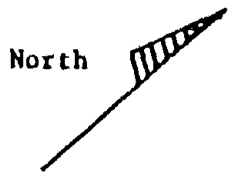
Since the drivers executed the passing maneuver with such similarity, the opposing vehicles were investigated to

Legend:

BPZ - Begin Passing Zone
EPZ - End Passing Zone
PI - Pass Initiation
PC - Pass Completion

V - Data Collection Van
P - Passing Vehicle
T - Experimental Vehicle Truck
O - Oncoming Vehicle

1 mile = 1.609 kilometers



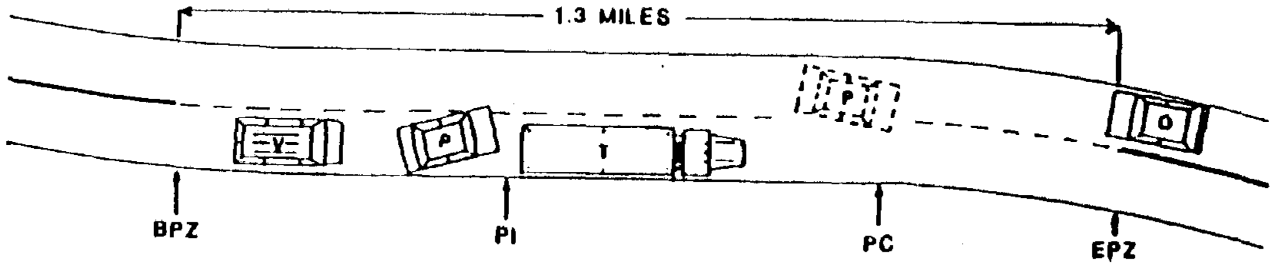


Figure 22. Schematic of experiment site showing measurement points.

Table 32. Summary of passing study data base.[3]

Length (in)	Trials	Captures	Aborted Trials	Usable TES Trials	Pass Trials	No-pass Trials	Usable Photo Trials
96	126	100	26	93	81	12	87
102	109	103	6	100	86	14	83
108	107	101	6	94	84	10	84
114	159	130	29	109	99	10	113

1 in = 2.54 cm

observe their behaviors. The speeds of 1,292 oncomers were monitored and the results are presented in table 34. Although similar, there did exist more variation among the oncomers than the overtakers. As for truck width effects, the 96-in (244-cm) versus the 108-in (274-cm) truck proved to be significant. However, it was concluded that the oncomer speeds did not suppress the effects of truck width on the overtaker's behavior.

To further investigate the intimidation effect of truck width, the examination of acceptable gap size for all truck widths was undertaken. The acceptable gap size was defined by the summation of decision time, passing time, and time margin. The results of this analysis are presented in table 35. The findings of this approach were that the decision time was not affected by truck width, time margins decreased as truck widths increased, and the gap size for 102-in (259-cm) and 108-in (274-cm) width trucks was significantly less than for the 96-in (244-cm) truck. Additional analysis results showed that the average rejected and accepted gaps steadily decreased until the largest truck was encountered. Further research on gap acceptance was conducted and the results are presented in table 36. No systematic effect of truck width on the probability of small gap acceptance was found.

Analysis of overtaker headways resulted in an increase as the truck width increased. The authors speculated that this effect was due to the driver needing to compensate for the reduced sight distance associated with increased truck width. They further concluded that the drivers were sensitive to truck width but their actions did not result in any safety hazards.

Lateral separation between the truck and the passing or opposing vehicle was found to decrease as truck width increased. However, the frequency of shoulder encroachments by the vehicles did not increase with truck width. Thus, the drivers appeared to discriminate between size and corrected their placement accordingly.

The passing drivers did tend to space themselves away from the truck with respect to width when the lane width was held statistically constant. Thus, the implication of the intimidation effect on

Table 33. Summary of passing time, distance, and speed by truck width.[3]

	TRUCK WIDTH											
	96 inches			102 inches			108 inches			114 inches		
	$\bar{X}$	σ	N	$\bar{X}$	σ	N	$\bar{X}$	σ	N	$\bar{X}$	σ	N
PASSING TIME (sec)	10.3	2.4	81	10.3	2.5	85	11.0	2.8	84	10.7	2.7	98
PASSING DISTANCE (ft)	786.1	184.5	81	786.7	185.9	86	843.1	200.0	84	814.0	164.7	97
PASSING SPEED (ft/sec)	76.7	8.1	81	76.6	6.3	85	76.8	5.6	84	77.1	7.8	97

1 in = 2.54 cm; 1 ft = 0.305 m

Table 34. Average speed (ft/sec) of 1292 oncomers.[3]

	TRUCK WIDTH			
	96 inches	102 inches	108 inches	114 inches
MEAN	79.3	80.5	81.6	80.5
ST. DEV.	12.2	11.3	9.8	8.4
N	280	378	321	313

1 in = 2.54 cm; 1 ft = 0.305 m

Table 35. Summary of decision time, time margin, and accepted gap size statistics by truck width.(3)

	TRUCK WIDTH							
	96 inch		102 inch		108 inch		114 inch	
(sec)	X̄	σ	X̄	σ	X̄	σ	X̄	σ
DECISION TIME	7.3	8.1	5.6	7.6	6.3	6.5	8.1	9.5
PASSING TIME	10.3	2.4	10.3	2.5	11.0	2.8	10.7	2.6
TIME MARGIN	29.9	18.1	24.6[1]	16.7	24.9[1]	14.5	24.8[1]	15.0
ACCEPTED GAP SIZE	47.4	20.5	40.4[1]	18.6	38.3[1]	17.9	43.6	20.2

1 - significant at or beyond p = .05 when compared to 96 inch value.
1 in = 2.54 cm

Table 36. Summary of effects of truck width on gap size acceptance.(3)

	Mean Gap Size (sec)		
Truck Width (in)	Accepted	Rejected	Difference
96	45.52	14.20	31.32
102	39.91	13.39	26.52
108	38.68	12.06	26.62
114	40.96	16.80	24.15

1 in = 2.54 cm

passing drivers was apparent but did not pose a safety problem.

Zegeer et al. Study

Zegeer et al. studied the effects of various truck configurations with respect to roadway geometry, traffic operations, and safety.(4) The truck sizes and configurations of concern were semis with 40-ft (12.2-m), 45-ft (13.7-m), and 48-ft (14.6-m) trailers and 28-ft (8.5-m) twin trailer trucks with widths of 96 in (244 cm) and 102 in (259 cm). The research environment was confined to lower-designed arterials and collectors as opposed to freeways and high-design arterials.

Before field data collection was performed, various truck configuration offtracking patterns were investigated using the FHWA/UMTRI Vehicle Offtracking Model and computer simulation software to define critical intersection and roadway geometrics. The five truck types selected for this analysis were:

- Semi with 48-ft (14.6-m) trailer.
- Semi with 55-ft (16.7-m) trailer.
- 65-ft (19.8 m) autotransport.
- Double (28-ft (8.5-m) trailers).
- Triple (28-ft (8.5-m) trailers).

Each of the five truck types were analyzed using both 96-in (244-m) and 102-in (259-m) trailer widths. The tested curve geometrics consisted of various radii for intersections with deflection angles of 60, 70, 90, 105, and 120 degrees and for roadway section curves exhibiting 20-, 30-, 40-, 50-, 60-, and 180-degree deflective angles. The offtracking analysis produced 205 plots.

From the plots generated, the maximum offtracking was measured and are presented in table 37 (intersection curve) and table 38 (roadway section curve). For the intersection curves, the results were summarized as follows:

"Wider trucks (102-in (259-cm) width) generally exhibited greater maximum offtracking distance (usually 0.5 to 1.5 ft (0.15 to .46 m)) than 96-in (244-cm) trucks. In general, the magnitude of the difference in offtracking between 96-in (244-cm) and 102-in (259-cm) versions of a truck type increased slightly with a decreasing radius of curvature. Analyzing the maximum offtracking pattern by curve geometrics, it appears that any intersection curve with less than a 60-ft (18.3-m) radius will present some problems for most truck types -- especially wider (102-in (259-cm)) trucks. This 60-ft (18.3-m) minimum radius is especially critical for a turn of 70 to 120 degrees."

The results of the roadway section curves were summarized as follows:

"The truck types exhibited the same general rank of maximum offtracking for the roadway section curves as had occurred for the intersection curves. Wide (102-in (259-cm)) trucks generally exhibited 0.5 to 1.0 ft (0.15 to 0.3 m) greater maximum offtracking. A minimum radius of curvature of 300 ft (91 m) would be necessary to avoid lane encroachment conflicts on 12-ft (3.7-m) lanes for the most critical truck types -- the semi 55 and semi 48."

Lastly, lane encroachment was investigated for the intersection geometrics. Table 39 reflects the findings from examining the offtracking plots. In general, encroachments were large for all truck types traversing the turns of 70 to 120 degrees with 60-ft (18.3-m) radii or less. The results implied that large trucks require multilane approaches with large curve radii.

In their identification of candidate study conditions, truck-length issues were given priority over truck-width issues. The research team concluded, based on a literature review and the offtracking results, that the length and configuration of the trucks would promote more of a hazard than width. While both 96-in (244-cm) and 102-in (259-cm) width trucks were used in both the urban and rural studies, references pertaining only to length were cited.

Table 37. Maximum offtracking dimensions (ft) through intersection curves.(4)

Geometrics of Curve / Truck Type (ft)	Intersection Curve														
	angle = 60°			angle = 70°			angle = 90°			angle = 105°			angle = 120°		
	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'
Semi 48	23.5	21.0					31.0	25.5	22.0	35.0	28.0		39.0	29.0	
Semi 48 wide	24.0	22.0					31.0	26.0	22.5	35.0	28.0		39.5	29.5	
Semi 55		23.0	21.0	28.0	25.0	22.5	33.5	28.5		38.0	31.0		43.0	33.5	
Semi 55 wide		23.5	22.0	29.0	26.0	23.0	34.0	29.0	25.5	38.5	31.5		43.0	34.0	27.5
65 Autotrans		17.0	15.0	21.0	18.0	16.0	23.0	19.0		26.0	20.0		28.0	20.5	
65 Autotrans wide		17.5	16.0	21.0	18.0	16.5	24.0	20.0	17.0	26.5	20.5		28.5	21.0	17.5
Double 28	20.0	17.5	16.0	21.5	18.5	16.5	25.0	20.0		28.0	21.0	17.0	30.0	22.0	17.5
Double 28 wide		18.0	16.0	22.0	18.5	16.5	25.5	21.0	18.0	28.0	21.5		30.5	22.5	18.0
Triple 28		20.5	18.0	25.0	22.0	19.0	30.0	25.0		33.0	26.0		37.0	28.0	
Triple 28 wide		21.0	19.0	26.0	22.5	20.0	31.0	25.5	21.5	34.0	27.0		39.0	28.0	

1 ft = 0.305 m

Table 38. Maximum offtracking dimensions (ft) through roadway section curves.(4)

Geometrics of Curve / Truck Type (ft)	Roadway section Curve									
	angle = 20°		angle = 30°		angle = 40°		angle = 50°		angle = 60°	
	R=200'	R=300'	R=200'	R=300'	R=200'	R=300'	R=200'	R=300'	R=200'	R=300'
Semi 48										
Semi 48 wide	12.0	11.5	13.0	11.5	13.0	11.5	13.0	11.5	13.0	12.0
Semi 55		11.0		11.5		12.0		12.0		
Semi 55 wide		12.0		12.0		12.0		12.5		
65 Autotrans				10.0		10.0		10.0		
65 Autotrans wide		10.0		10.0		10.0		10.0		
Double 28				10.0		10.0				
Double 28 wide		10.0		10.5		10.5				
Triple 28				11.0		11.0		11.0		
Triple 28 wide		11.0		11.0		11.0				

1 ft = 0.305 m

Table 39. Lane encroachment (ft) for trucks turning through intersection curves.(4)

Geometrics of Curve / Truck Type (ft)	Intersection Curve														
	angle = 60°			angle = 70°			angle = 90°			angle = 105°			angle = 120°		
	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'	R=20'	R=40'	R=60'
Semi 48	22.0	21.0					27.0	22.0	19.0	27.0	22.5		28.0	21.5	
Semi 48 wide	23.5	21.5					26.0	22.0	20.0	27.5	22.5		27.5	22.0	
Semi 55		22.5	19.0	27.0	24.0	20.5	30.0	26.0		32.0	27.0		33.5	26.0	
Semi 55 wide		22.5	20.5	27.5	25.0	21.0	29.5	26.0	23.0	31.0	26.0		33.0	25.0	21.0
65 Autotrans		15.0	14.0	18.5	16.0	15.0	19.5	17.0		20.5	17.0		20.0	15.0	
65 Autotrans wide		16.0	14.0	20.0	17.0	15.0	20.0	17.5	16.0	21.0	17.0		20.0	16.0	13.5
Double 28	18.5	16.5	14.0	20.0	17.0	15.0	20.0	17.0		21.5	17.0		20.5	15.5	12.5
Double 28 wide		17.0	15.0	20.5	17.0	15.0	21.0	17.0	15.0	22.0	18.0		21.5	17.0	14.0
Triple 28		18.5	16.5	22.5	20.0	16.5	25.0	20.5		26.5	21.5		24.5	19.5	
Triple 28 wide		19.0	17.0	24.0	20.5	16.5	25.0	21.0	18.0	27.0	22.0		24.5	20.0	

1 ft = 0.305 m

Parker Study

Parker used a traffic conflict technique to assess the safety problems associated with oversized loads.⁽⁵⁾ The loads were 12-ft (3.7-m) to 14-ft (4.3-m) wide housing units. A traffic conflict was defined as:

> "...an evasive maneuver, as evidenced by a brake-light indication, taken by a driver operating a vehicle in the vicinity of a wide load. The definition also was taken to include evasive maneuvers by a driver pulling a wide load in the vicinity of other traffic or narrow roadside obstructions (fixed objects). It did not include braking because of traffic-control devices (such as traffic signals and stop signs) or conflicts between wide loads and their escort vehicles (because escorts were considered to be integral components of the load). In addition, violations of the traffic, e.g., driving to the left of a double solid centerline, were not taken as constituting conflicts. No attempt was made to define the severity of conflicts because the objective of the study was to identify all hazards."

Cameras mounted on the research vehicles were used to record conflicts between the vehicle transport and other vehicles. After data reduction, the data included 737 conflicts for the 12-ft (3.7-m) wide units and 832 for the 14-ft (4.3-m) wide units. Even though these samples were considered insufficient for the analysis purposes, the conclusion was drawn that narrow pavements (mainly two-lane roads) should be avoided when transporting these oversized loads.

Kakaley and Mela Study

The Kakaley and Mela study involved investigating the effect of MC-6 (102-in (259-cm) width) and MC-7 (96-in (244-cm) width) buses.⁽⁶⁾ The five topics covered were:

- Aerodynamic disturbances, characteristics, and effects.
- Lateral placement.
- Lateral stability.
- Offtracking on sharp curves.
- Accident data analysis.

The second and fourth topics are discussed here since they are more relevant to the current study.

Lateral placement measures along the path of a passing or opposing vehicle were made for each control bus type by using three synchronized cameras on the left side of the buses. Two-lane and multilane highways were examined under no crosswind or negative crosswind conditions.

The data produced no significant differences between 96-in (244-cm) and 102-in (259-cm) wide buses regardless of wind conditions or highway type. The mean effect of the adjacent vehicle was about 1 to 1.5 ft (0.3 to 0.46 m) to the left of the centerline. No significant differences were observed on six- to eight-lane highways when the passing or opposing vehicle was separated by at least one lane from the bus. However, more variation existed in lateral separation on two-lane cases than for multilane cases.

Lateral placement of 96-in (244-cm) and 102-in (259-cm) wide buses were determined by placing three movie cameras on an overpass crossing the New Jersey Turnpike. Data were collected and analyzed only for the middle and right shoulder lanes since buses were not permitted to operate in the median lane. The data summary is presented in table 40. Measurements were taken using the centerline of each lane as 0.00 ft (0.00 m). The differences between the centerline of the buses and the centerline of the lanes was not significant except for the 102-in (259-cm) wide buses in the middle lane. Also, no significant difference between the lateral separation of the two bus types was found for either of the lanes.

The swept-width was computed for varying degrees and radii of horizontal curvature known to be common on the Interstate Highway System for several known 96-in (244-cm) and 102-in (259-cm) wide bus configurations. The 102-in (259-cm) wide bus (MC-6) exceeded the 12-ft (3.7-m) lane width on a curve of 27 degrees. The 96-in (244-cm) bus (MC-7) did not exceed the 12-ft (3.7-m) lane width until a curve of 31 degrees was reached.

Gericke and Walton Study

A study conducted by Gericke and Walton examined the effects of the increase in legal truck limits on highway geometric design elements for the Texas highway system in order to upgrade design standards to produce safe and efficient operations. The authors used American Association of State Highway and Transportation Officials' (AASHTO) standards and formulas to identify these effects.(8)

An evaluation of present geometric design standards identified the following elements which may be affected by the larger or heavier trucks:

Design Elements

- Stopping sight distance.
- Passing sight distance.
- Pavement widening on curves.
- Critical lengths of grades.

Table 40. Lateral placement of buses on New Jersey Turnpike.(6)

Lane	Bus Width (in)	Difference between Bus Centerline and Lane Centerline (ft)		Number of Buses
		Mean	Standard Deviation	
Shoulder	102	0.10 right	0.68	27
Shoulder	96	0.02 left	0.81	62
Middle	102	0.25 left	0.72	29
Middle	96	0.00	0.64	81

1 in = 2.54 cm; 1 ft = 0.305 m

Cross-Section Elements

- Lane width.
- Width of shoulder.

Intersection Design Elements

- Minimum design for turning radii.
- Widths for turning lanes.
- Sight distances for at-grade intersections.
- Median openings.

Four different truck configuration scenarios (A,B,C,D) were used and are shown in figure 23. Based upon AASHTO design standards, the authors determined which, if any, truck configurations would call for geometric improvements. In addition, other studies performed in Utah, Texas, California, and Alberta, Canada were used validate their findings.

A summary of the elements that involve truck width is discussed here since this was the primary concern of the current study.

Passing sight distance based on AASHTO's equation does not consider width since length produces the most adverse effects on sight distance.

Pavement widening on curves was found to be required for scenarios B,C, and D. The authors pointed out that configuration and length were the primary factors in AASHTO's pavement width formula. They did note that the 102-in (259-cm) truck (which are maximum limits under AASHTO) would aid in pavement widening since the state of Texas presently designed for 96-in (244-cm) wide trucks.

Lane width design standards should be strictly followed if an increase in width is allowed. AASHTO requires two-lane rural highways to consist of 11- to 13-ft (3.4- to 4.0-m) lanes. The authors stated that 10-ft (3.0-m) lanes were inadequate and that 11-ft (3.4-m) lanes should be gradually widened to at least 12 ft (3.7 m) to ensure safe and tension-free operation of 102-in (259-cm) wide trucks.

Shoulder widths, under AASHTO design standards, should be strictly enforced to promote safe clearance of parked 102-in (259-cm) wide trucks.

Minimum design for sharpest radii, width for tuning roadways, and median openings were recognized in terms of truck configuration, length, and width. In all cases, additional pavement width would be required if the scenarios of B, C, and D were allowed.

Overall, Gericke and Walton concluded that scenarios B, C, and D may require upgrades in the Texas highway network. For future research on width characteristics, the authors recommended attention be directed toward lane width, shoulder width, vehicle width, and safety to better current design standards if 102-in (259-cm) trucks are allowed.

Weir and Sihilling Study

Weir and Sihilling studied the passing effects of vehicles overtaking two types of buses, MC-6 (102-in (259-cm) width) and MC-7 (96-in (244-cm) width).(7) The test environment consisted of two-lane and multilane highways with rural flat terrain. Crosswinds and no-wind conditions were studied, lane widths were 12 and 13 ft (3.7 and 4.0 m), and the average bus speed was 50 to 55 mi/h (81 to 89 km/h). The data were obtained with synchronized cameras mounted inside the windows on the left

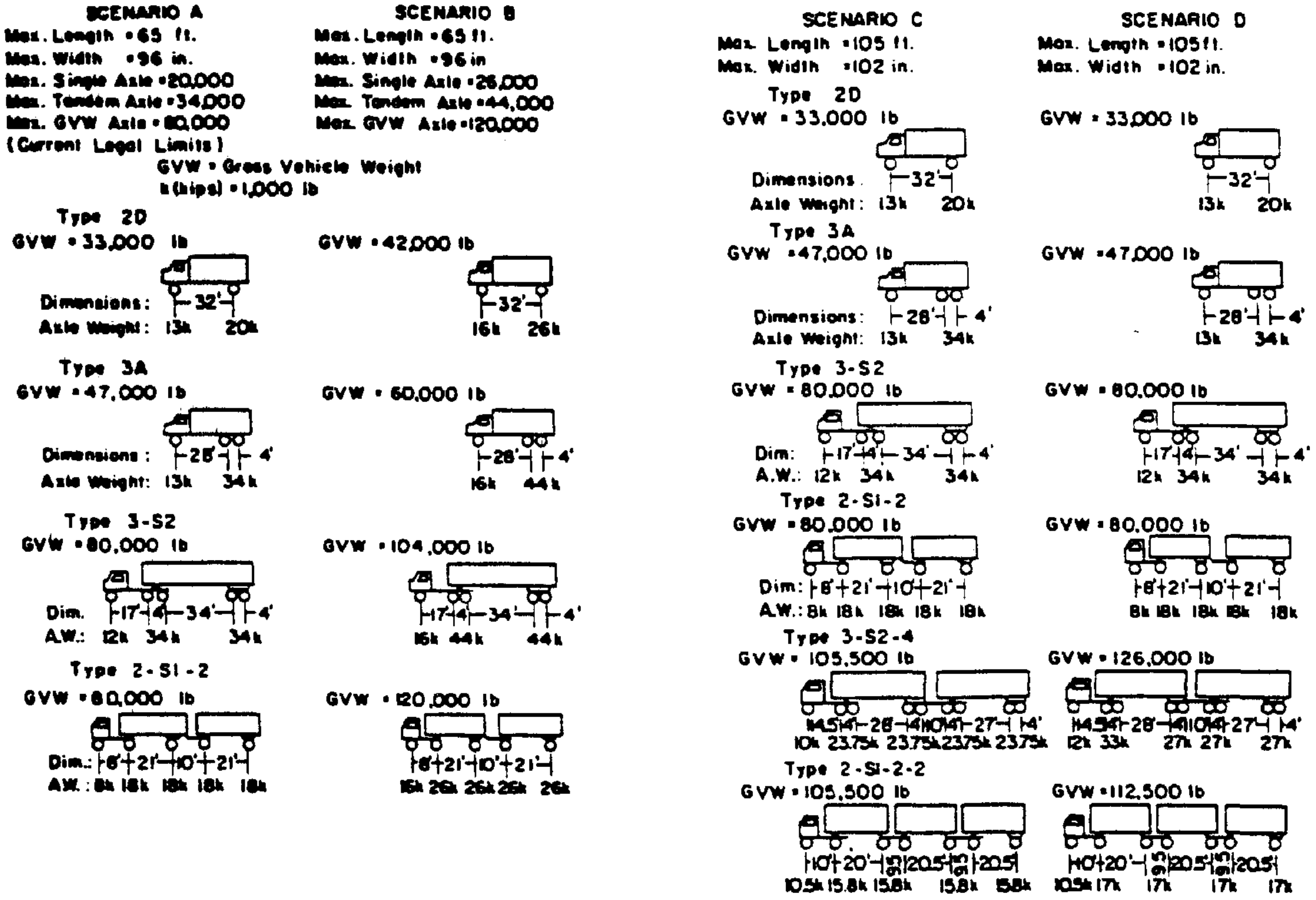


Figure 23. Vehicle configurations for scenarios A, B, C, and D.

side. Data reduction produced car/bus relative speed, car speed, lane placement of the bus, car/bus lateral separation, and lane placement of the car involving about 1100 passing encounters.

The data indicated no difference in the passing vehicle's lane placement between the two types of buses. The passing vehicle's centerline offset when adjacent to the bus was about 1 to 1.5 ft (0.3 to 0.46 m) to the left. This offset was encountered regardless of bus type. This shift of the passing vehicle did not occur when traveling in lanes further from the bus. Lastly, the car/bus relative speed data showed the passing vehicle to slow down beside side the bus. This slower speed was attributed to the aerodynamic drag by the bus.

APPENDIX B - FEASIBILITY OF ACCIDENT ANALYSIS USING TRUCK FLEET DATA

The primary objective of this study involved determining the effects of truck size on vehicle *operations*. However, another objective of the study involved determining the feasibility of using existing data from truck fleets (i.e., from trucking companies) and previous research studies to analyze the effects on *accidents* of various truck types and sizes on specific highway types. The efforts of this feasibility study are discussed in the following sections:

- Key issues and data requirements.
- Candidate truck fleet data bases.
- Candidate truck research data bases.
- Usefulness of the data bases.
- Accident analysis plan.

KEY ISSUES AND DATA REQUIREMENTS

Before reviewing candidate truck data bases, specific research questions must be stated to define the needed data elements. In this feasibility examination, the general analysis question of interest is:

"What are the effects of truck size (i.e., length, width, and configuration) on accident frequency and severity for different traffic and roadway conditions?"

To properly answer this question, one needs truck accident data and exposure (mileage) data stratified by numerous truck classifications and roadway characteristics. More specifically, the following variables, as listed by McGee and Morganstein, are most critical and relevant for conducting truck accident research:(9)

- Truck type - single-unit truck with or without trailer, tractor with semitrailer, tractor with double or triple trailer, or special truck sizes such as the Turnpike Double, Rocky Mountain Double, etc.
- Truck length - total truck length, length of tractor and trailer(s), length between kingpin and rear trailer axle and other truck dimensions such as height, underbody clearance, etc.
- Truck trailer type - van, tanker, platform (i.e., flatbed), bulk commodity (e.g., coal or gravel trucks), and other cargo body types.
- Truck gross weight - which can affect truck operation, stopping potential, maneuverability, and momentum in a crash.
- Truck driver type - For example, owner-operator, leased operator (driver is leased to a fleet operator for a trip or time period), or employed driver (driver is employed for a company on a regular basis) are categories suggested by McGee. This would be important, since there is some evidence that the owner-operator trucks have considerably higher accident experiences than larger carriers. In addition, since there is strong evidence that young (below 21 years of age) and less experienced drivers have higher accident rates than older, more experienced drivers,

driver age and years of experience would be important information to obtain.

- Truck highway type - For example, functional class, access control, number of lanes, divided or undivided, urban vs. rural, roadway width, curvature, or other features. Accident rates are higher on two-lane roads than on Interstate routes, and doubles typically travel a higher proportion of their mileage on Interstates, compared to semis or straight trucks. Thus, one must account for travel route differences when comparing accident rates between truck types.

- Traffic volume - The chance of a truck having a multivehicle accident is increased if most of its travel mileage is on a high-volume rather than a low-volume route (all other factors being equal).

In addition, although not specifically mentioned by McGee and Morganstein, truck width is another factor of interest.

Note that these variables listed above need to be available for the truck accidents and truck exposure on common routes. In addition, numerous other truck accident data variables of concern include accident severity, number of people killed and injured, driver characteristics (e.g., age, condition), collision type, weather and environmental conditions, type of location, time of day, number and type of other vehicles involved, contributing circumstances, and others. It would also be important to have the exposure data in terms of driver characteristics, times of travel, weather conditions, etc.

Unfortunately, virtually no State accident records currently contain accident details on truck length, truck width, trailer size, truck driver type and/or gross truck weight, although many States do classify a truck accident as involving a straight truck, tractor with semitrailer, double, or other such truck classes. North Carolina is one of the few States which now codes trailer length and width for up to two trailers per truck for trucks involved in an accident). Thus, to conduct a thorough accident study, additional information would be needed on truck size and truck driver characteristics to supplement data on typical police accident reports.

Even more critical, however, is the fact that no State collects truck *exposure data* categorized by truck size and weight. Indeed, it is virtually impossible to obtain mileage estimates for singles and doubles, much less for tankers or vans. Exposure data stratified by driver characteristics or time of day are also not routinely collected by State forces. For these reasons, truck fleet data and previous truck research data bases were examined.

CANDIDATE TRUCK FLEET DATA BASES

Certain trucking companies have, in the past, provided accident data to support investigations into truck safety issues. Therefore, use of such truck fleet data on accidents and mileage were considered worthy of further consideration for truck accident analyses.

Numerous telephone contacts were made with officials of various trucking companies and with others who work in the truck area. Information was also received on truck fleet accident rates from correspondence sent to the Federal Highway Administration (Legislative and Regulations Division) in response to *FHWA Docket, No. 87-1 on Truck Size and Weight; Reasonable Access*. This information was useful since it provided accident rates by truck type, and revealed the truck types/sizes for which accident and mileage data are available. Ten different trucking companies responded by letter to the Docket.

Most companies provided accident rates in accidents per million vehicle miles (MVM) by truck type which included comparisons between doubles and semis. However, no truck size information (length and width) was usually given for semis. Semis were used, in most cases, to refer to any and all sizes of single trailers used with tractors by a particular company.

In terms of the overall findings reported by these trucking companies, doubles were consistently reported to have accident rates equal to or less than the rates of semis. Of course, none of these statistics appeared to have controlled for the types of routes travelled by doubles versus semis or any possible differences between truck drivers operating the two truck types. Only one company produced accident rates separately for 45-ft (13.7-m) semis versus 48-ft (14.6-m) semis, and they found little difference.

Another interesting finding is the large differences in accident rates for a given truck type by different companies. For example, reported accident rates for doubles range from 0.13 to 1.96 accidents per MVM. Rates for semis by the same 10 trucking companies ranged from 0.22 to 1.59 accidents per MVM. A discussion of the usefulness of these fleet data bases for further analysis in the current study is given in a later section.

TRUCK RESEARCH DATA BASES

In addition to truck fleet data, truck research data bases were also considered to have possible usefulness for determining effects of truck types and sizes on accidents. Of the many accident research studies conducted on large truck safety in recent years, eight of the most prominent ones are summarized in table 41, as taken from Transportation Research Board (TRB) Special Report 223.(1) The table lists the authors and study date, principal finding, accident involvement rate ratio of twins (doubles) to semis, and the data base and methodology used in each study.

Each of the eight studies attempted to compare accident rates between twins and semis. Three of the eight studies (Glennon, Chira-Chavala, and Yoo) found no difference in accident involvement rates between twins and semis.(11,12,13) Jovanis found twins to have a lower rate than semis, while Campbell et al. and Stein and Jones found twins to be over-involved in accidents.(14,15,16) Graf and Archuleta concluded that twins have higher accident involvement rates than semis on rural roads, but a lower involvement rate on urban roads.(17) Based on a synthesis of other studies, the 1986 TRB study concluded that twins are slightly over-involved in truck crashes, but this is offset by an expected nine percent reduction in truck travel due to greater capacity of twins.(1)

While the results of such studies are of considerable interest, the focus of this effort was primarily on the data bases on which these studies were based. The following is a brief summary of the data sources and information used in these studies, based largely on the information contained in TRB Special Report 223. In the next section, each of these research data bases is

Table 41. Summary of studies examining accident rates by truck configuration.(10)

Study	Principal Finding	Involvement Rate Ratio: Twins to Tractor-Semi-trailers (by VMT)[2]	Base Data and Method
Campbell et al. 1988	Twins have a 10 percent higher fatal accident involvement rate than tractor-semitrailers when accident rates are adjusted for differences in travel by road class, time of day, and area	1.10	1980-1984 UMTRI[3] accident file; 1986 exposure data; medium and heavy trucks >10,000 lb
Stein and Jones 1988	Twins are overinvolved in crashes compared with tractor-semitrailers by a factor of two to three regardless of accident type, truck operating characteristics, driver characteristics, and enviromental and road conditions.	2.00 to 3.00	Case-control methodology; 1984-1986 large truck (>10,000 lb) accidents and control sample on two Interstate highways in Washington
Jovanis et al. 1988	Twins had lower accident involvement rates than tractor-semitrailers over a 3-year period and the differences were statistically significant for travel on Interstate, state and local roads	Statistically less than 1.0	Matched-pair analysis; large LTL[4] general freight carriers; 1983-1985 data
TRB 1986	Twins are slightly overinvolved in truck crashes, but a projected 9 percent reduction in truck travel from twins' greater capacity will offset any accident increase; no net safety decrement	0.98 to 1.12	Synthesis of prior studies for accident rates and independent travel forecast
Graf and Archuleta 1985	Twins have higher[1] accident involvement rates than tractor-semitrailers on rural roads and lower involvement rates on urban roads	1.12 (rural) 0.79 (urban)	California data; 1979-1983 accident information and 1982 traffic counts
Glennon 1981	No statistically significant difference in accident involvement between twins and tractor-semitrailers	1.06	Pennsylvania data-1976 to 1980; matched pair analysis; large LTL general freight carriers
Chira-Chavala and O'Day 1981	No statistically significant difference in accident involvement rates between twins and tractor-semitrailers	0.98	Bureau of Motor Carrier Safety 1977 accident data from the Truck Inventory and Use Survey (U.S. Census); ICC[5]-authorized carriers only
Yoo et al. 1978	No statistically significant difference in accident involvement rates between twins and tractor-semitrailers	1.01	California data; 1974 accidents and travel counts

1 - Data from multiple sites have been combined to compute the rates shown with weights equal to total (semitrailer plus multitrailer) mileage at each site (TRB 1986, 130 and Appendix F).
2 - Vehicle miles travelled.
3 - University of Michigan Transportation Research Institute.
4 - Less than truck load.
5 - Interstate Commerce Commission.

discussed in terms of its usefulness for further analysis in this study.

Jovanis et al. Study

The study by Jovanis et al. made use of accident records and exposure data from Consolidated Freightways and Yellow Freight for the 3-year period 1983-1985.(14) Routes with truck terminals used by both twin trailer trucks (doubles) and 45-ft (13.7 m) semis were chosen primarily in the East, Midwest, and South. Randomly selected terminal pairs were selected which served both vehicle types in an attempt to control for differences in truck travel patterns. The TRB study reported that Jovanis et al. used no control for driver characteristics or time of day, and the results may have been affected by the authors' elimination of routes with low travel volumes after the random pairs were initially selected.(10) The study included Interstate, State highways, and local street routes.

Glennon Study

Another research study using data from trucking companies was conducted by Glennon in 1981.(11) Paired trips were selected for twins and semis using data from Pennsylvania provided by Consolidated Freightways. The data were analyzed to ensure that no large variation existed in day/night conditions or in driver characteristics (e.g., driving experience and accident records) for the two vehicle types.(10,11)

Stein and Jones Study

Stein and Jones investigated the relative accident rates for twins versus semis using a case-control study data base of crashes on two Interstate highways in Washington State involving large trucks (over 10,000 lb (4540 kg)). Accidents were included in the analysis if they resulted in personal injury or property damage of $1,500 or more. Sampling of the first three trucks to pass was conducted at the crash sites 1 week after the crash to estimate relative involvement rates.(16) Use of this sampling procedure have raised doubts about applying the results to sites other than the ones where data were collected.(11)

Campbell et al. Study

The data base used by Campbell et al. consisted of 5 years of national fatal truck accident data (1980-1984) and truck travel survey data collected in 1986. Trucks with gross vehicle weights above 10,000 lb (4540 kg) and involved in an accident in the 48 contiguous States were included in the study.(15) The use of only fatal accidents is one limitation of the data base. Sampling of exposure during 1986 was also thought to result in appropriately low accident rates for twins since the proportion of twins was expected to be much higher in 1986 than for the 1980 through 1984 accident period. This inflated volume of twins was expected to cause artificially low accident rates for twins.(10)

Other Studies

The TRB study on "Twin Trailer Trucks" synthesized information from other studies and thus did not involve development of a separate data base.(1) The studies by Yoo et al. and Graf and Archuleta both used California accident and travel counts to compare accident rates between twins and semis.(13,17) The study by

Yoo et al. used ton-miles as one measure of exposure, while the study by Graf and Archuleta included operating environment (urban vs. rural) as one of the factors in their analysis. Finally, the 1981 study by Chira-Chavala and O'Day made use of 1977 Bureau of Motor Carrier Safety (BMCS) accident data and 1977 travel data from the Truck Inventory and Use Survey of the U.S. Census.(12) This study included only Interstate Commerce Commission authorized carriers, not private carriers.

USEFULNESS OF DATA BASES

Conducting a thorough and technically sound study requires the availability of truck accident types, truck exposure, and roadway variables discussed earlier. Since we are concerned with determining accident differences for various truck types (e.g., semis vs. twins), lengths (e.g., 45-ft (13.7-m), 48-ft (14.6-m), 53-ft (16.2-m) trailers), and widths (96-in (244-cm) vs. 102-in (259-cm)), it is clear that accident and exposure data stratified by these truck characteristics must be available. Also, since truck accidents are clearly affected by traffic and roadway characteristics, and mileage of various truck types differs by road class, it is important to properly control truck accident rates by important roadway features (e.g., select study sites which have each truck type to be studied). Further, if the truck driver characteristics (e.g., age and driving experience) differ for the various truck types (e.g., older, more experienced drivers are operating doubles more than semis), then it is important to control for key driver factors to the extent possible.

The truck fleet data sources and research data bases discussed earlier were reviewed in terms of their usefulness for further analysis as part of the current study. The following is a summary of that review.

Truck Fleet Data Sources

While numerous trucking companies compile various types of information on accidents and mileage for various truck types, our efforts were focused on three major companies, termed here as companies A, B, and C. These were the companies which were most often mentioned as having the most complete data for use in computing truck accident experience. Information obtained from officials of those companies has led us to the following assessment of their data bases:

- Company A - Accidents are summarized by 28-ft (8.5-m) doubles versus semis versus triples, but not by trailer size. Although some mileage data are available, it apparently is not very accessible. These two data limitations would prevent the use of this company's data for this study.

- Company B - They also have no information on truck trailer size prior to 1989, and can only classify accidents by semis versus doubles. Starting in 1989, they have begun to code trailer numbers onto accident reports, which will eventually allow for determining sizes of accident-involved trailers. Unfortunately, travel mileage is not separated by semis versus doubles, nor by road type. Such limitations with mileage data would prevent the use of this data for analyses of accident rates by truck size and road type.

- Company C - Data appear to be the most promising in terms of feasibly computing accident rates by truck types (semis versus twins). However, since 90 percent of their fleet is twins, nearly 10 percent 45-ft (13.7-m) semis, and only a few 48-ft (14.6-m) semis, the sample sizes of the semis would not be very large. By carefully selecting routes common to both truck types (doubles and 45-ft (13.7-m) semis), a reasonable experimental design would be possible. Of course, the only possible comparison would be for twins (two 102-in (259-cm) wide, 28-ft (8.5-m) trailers) versus 96-in (244-cm) wide, 45-ft (13.7-m) semis. Driver differences, which could influence the results, could not easily be controlled.

It seems apparent that, of the three carriers contacted, only Company C had accident and mileage data with the potential for a useful analysis, assuming the time and money were available to obtain route information and to select proper routes common to both truck types. However, the only possible comparison would be twins versus 45-ft (13.7-m) semis while no comparison could be made of truck length (45-ft (13.7-m) versus 48-ft (14.6-m) versus 53-ft (16.2-m)) or width (96-in (244-cm) versus 102-in (259-cm)) for similar truck types.

Another point worthy of mentioning is the limitation of any truck analysis involving one or two major trucking companies. Such large companies are likely to generally use better equipment, which is newer and better maintained, and more qualified drivers than many of the small owner-operator companies. For example, Company C has their own safety personnel who, among other activities, use radar to monitor their own drivers. Company B has their own company drug testing program to minimize the drug problem among their drivers.

While these are admirable programs, it raises questions about the representativeness of an accident analysis involving one or two of these elite trucking companies. As discussed earlier, there seems to be a wide variation in truck accident rates between trucking companies for the same type of truck. Such large differences in accident rates might be partly explained by differences in driver characteristics, condition of the trucks, differences in types of routes travelled (e.g., some companies may travel a greater proportion of urban mileage than other companies), and differences in their accuracy and procedures in defining "accidents" or recording mileage. In any case, it is likely that the sampling of truck accidents and mileage across the full traffic stream, and not just one or two companies, would give more realistic results, even though this approach would most likely be much more expensive.

Truck Research Data Bases

Of the eight research studies discussed earlier, each was designed to compare accident rates between twins and tractor semitrailers. Thus, each made use of truck accident data for those two truck classes and some sample of exposure for the same two truck groups. However, none of the studies reported accident rates separately by truck width or length. Only the Glennon study attempted to account for possible driver differences between the two truck types of concern.(11) Thus, these data bases would not appear to be appropriate for analyzing effects of truck width or length on accidents because of the lack of data on a number of critical variables.

There were some other features of several of these data bases which are of interest. For example, Glennon and Jovanis et al. used matched pair analysis, which controls for the effect of roadway and traffic features.(11,14) The data base used by Graf and Archuleta stratified data by area type (rural versus urban), and the Jovanis et al. study utilized samples on Interstate, State, and local roads.(14,17)

The data base developed by Campbell et al. is unique from the others in several respects.(15) First of all, it is a national data base of truck accidents, although it only includes fatal accidents. The exposure data is from the National Truck Trip Information Survey conducted by the University of Michigan Transportation Research Institute (UMTRI). Even though accident and exposure data are not classified by truck size, factors do include truck configurations, travel category (road type, urban/rural, access control and day/-night), and gross combination weight. Exposure data was on a per trip basis and not annual vehicle mileage. Although the presence of only *fatal* truck accidents was thought to be a limitation (thus not giving an indication of the complete accident differences between truck types), the other features of the database made it of interest for further analysis. The data base, however, was not available for use in this study.

In summary, none of the research databases were considered appropriate for accident analysis in this current FHWA study (i.e., to study accident rates by truck size and type on various roadway types) since:

● None had information on truck length or width.

● Only one of the studies (Glennon) attempted to account for driver characteristics.

● Most of the data bases had one or more serious limitations such as:

- Only containing fatal truck accidents.
- Having no control for roadway type.
- Eliminating low-volume sites after selecting a random sample.
- Utilizing a questionable truck sampling scheme which was thought to make the results only valid for the particular sample sites.

The next section discusses a proposed data analysis plan which would be more desirable than using existing truck fleet or available truck research data bases.

ACCIDENT ANALYSIS PLAN

The previous discussions have dealt with many of the requirements for conducting a proper truck accident study and some of the problems and limitations found with existing truck fleet data and available truck research data bases. At this point, one conclusion seems clear. *There is no readily available data base on truck accidents and exposure to allow proper comparison of accident rates by truck type and size on various roadway types.*

To develop a truck data base with the necessary truck, roadway, and driver factors discussed previously, a carefully planned data collection and analysis plan is needed. A 1986 study by McGee and Morganstein entitled, *"Development of a Large Truck Safety Data Needs Study Plan"* involved determining data needs for addressing truck safety issues. The authors' recommended sampling plan calls for collecting accident and exposure data from a sample of highways within a geographically representative group of jurisdictions. Primary Sampling Units (PSU's) should be selected for collection of accident and exposure data for trucks, where a PSU consists of a county or group of counties.(9)

According to the proposed plan, police accident data would be combined with other necessary truck data by the police investigator on a supplemental form. As an alternative, outside investigators could make contact with the truck owner or driver and obtain needed information. Exposure data would be obtained from three sources:

- Existing State traffic and classification counts (to develop average daily traffic values and some truck exposure).

- Weigh stations (to obtain truck weight data, truck size information, and driver classification).

- Manual 24-hour (or 48-hour) classification counts (to get truck exposure by truck and trailer type). Counts would be made throughout the year to get seasonal representation.

The plan suggests the collection of highway-type data for the following features:

- Functional class (Interstate and other freeways and expressways, other principal arterials, minor arterials, and collectors).

- Access control (full control, partial control, or no control).

- Number of lanes (two-lane, more than two-lane).

- Divided or undivided.

- Urban versus rural area.

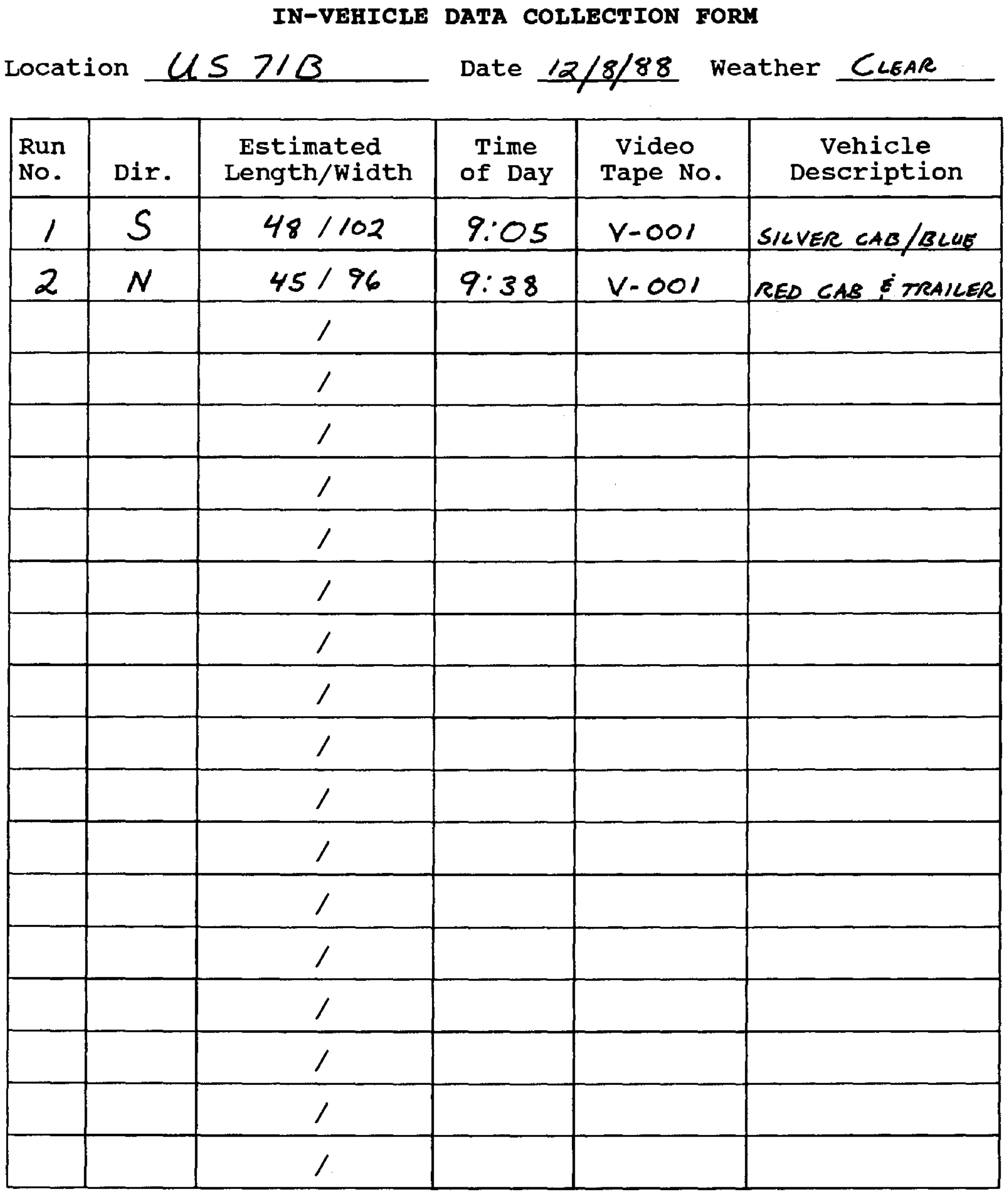
The sample size should be sufficient to detect statistically significant differences in accident rates between certain truck types. The factors which influence the required sample size include the desired confidence level, the expected accident rate of various truck types, and the desired percent of difference to be detected. Assuming that the analysis needs to detect a 10 to 15 percent difference in accident rates between truck types, the authors estimated that approximately 300 jurisdictional sampling units would be needed and this would cost $1.85 million over a 1-year period. Further details of that proposed plan are available within McGee and Morganstein's Executive Summary and Research Report.(9)

Based on the information described above, it was concluded that obtaining and analyzing truck accident and exposure data bases was not feasible for analysis purposes in this study. This is based on the current lack of a suitable database to determine the accident rate differences between various truck types and sizes on various roadway types.

APPENDIX C - DATA COLLECTION AND REDUCTION FORMS

Contained in this appendix are examples of the forms used during the data collection and reduction tasks of this study. Each form shown has been partially completed to illustrate the type of information actually recorded. Figure 24 is the in-vehicle data collection form and was used by the data collection crew in the van to record the trucks being followed on any given day. As shown on the form, each vehicle followed was identified by a run number, direction of travel and a brief description. The time of day, estimated length and width, and the videotape number were also recorded. The form used by the individual filming from the roadside is shown in figure 25. The information recorded on this form was similar to that recorded by the crew in the van. These two forms were used together to ensure that the correct length data were being used with the correct data obtained when following the vehicles.

Figure 26 is an example of a form used for recording encroachment data from the video. Information recorded at the top of the form was used to identify the truck (or car) by location. For each encroachment, represented as an event, the type of encroachment, DMI values, stopwatch values, maximum amount of encroachment, average speed, and characteristics of the traffic stream in which the vehicle being followed was travelling (V) were recorded. The final form, shown in figure 27, was used to record the lateral placement data from the slides. Again, identifying information was recorded at the top of the form. For each event, or slide, a brief description was recorded of the opposing, passing, or passed vehicle along with the vehicle type (car, truck, etc.), maneuver, DMI value, and platooning characteristics of the opposing traffic stream. The lane placement of both vehicles in the slide was then recorded as follows. Under the columns labeled "C", the distance of the vehicle from the centerline was recorded. Under the columns labeled "E", information was entered indicating if the vehicle was encroaching over the edgeline.



IN-VEHICLE DATA COLLECTION FORM

Location US 71B Date 12/8/88 Weather CLEAR

Run No.	Dir.	Estimated Length/Width	Time of Day	Video Tape No.	Vehicle Description
1	S	48 / 102	9:05	V-001	SILVER CAB/BLUE
2	N	45 / 96	9:38	V-001	RED CAB & TRAILER
		/			
		/			
		/			
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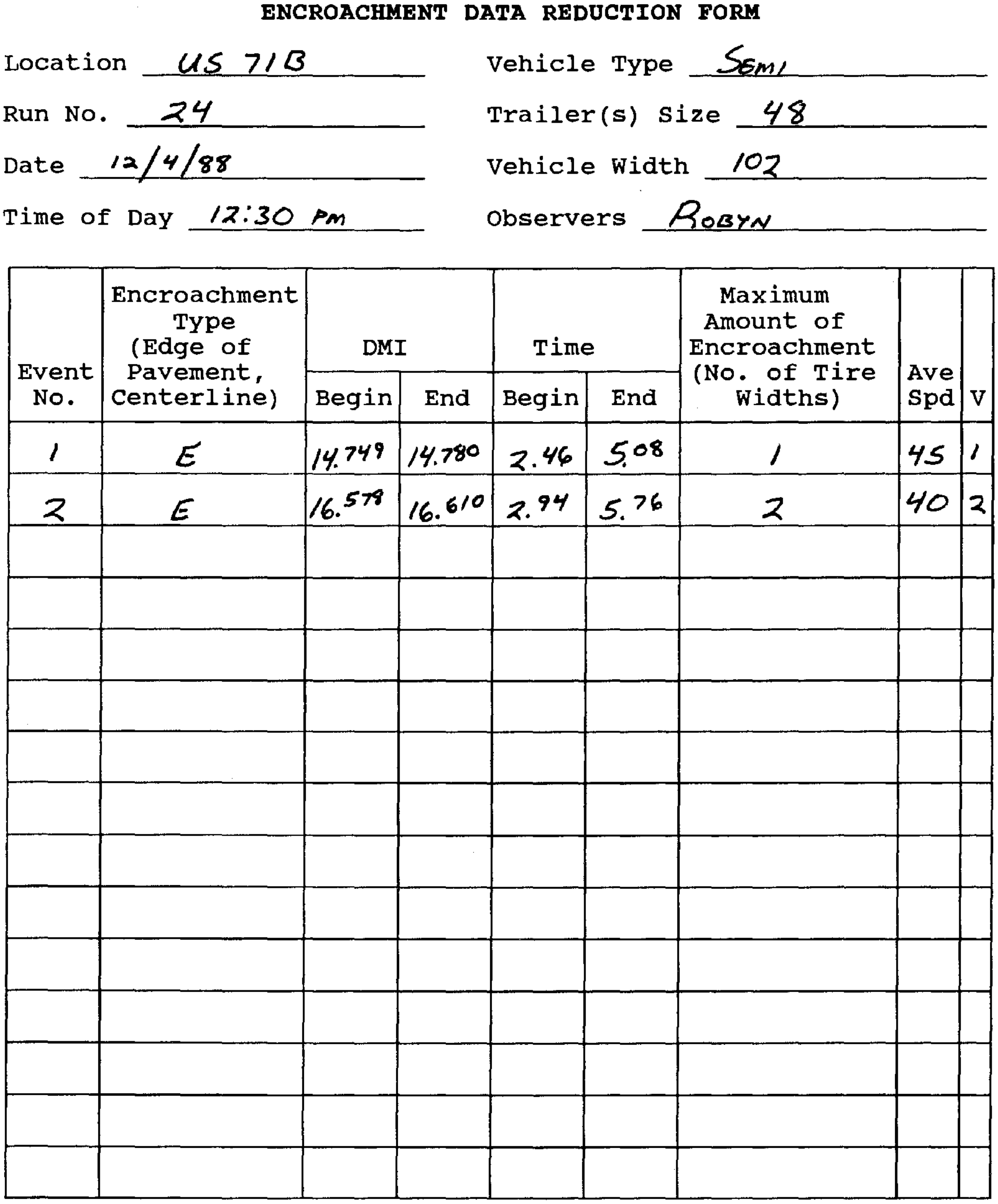
Figure 24. In-vehicle data collection form.

ROADSIDE DATA COLLECTION FORM

Location US 71B Date 12/8/88 Weather CLEAR

Run No.	Dir.	Estimated Length	Time of Day	Video Tape No.	Truck Description
1	S	48	9:15	C-001	SILVER/BLUE
2	N	45	9:47	C-001	RED CAB/TRAILER

Figure 25. Roadside data collection form.



ENCROACHMENT DATA REDUCTION FORM

Location US 71B

Vehicle Type Semi

Run No. 24

Trailer(s) Size 48

Date 12/4/88

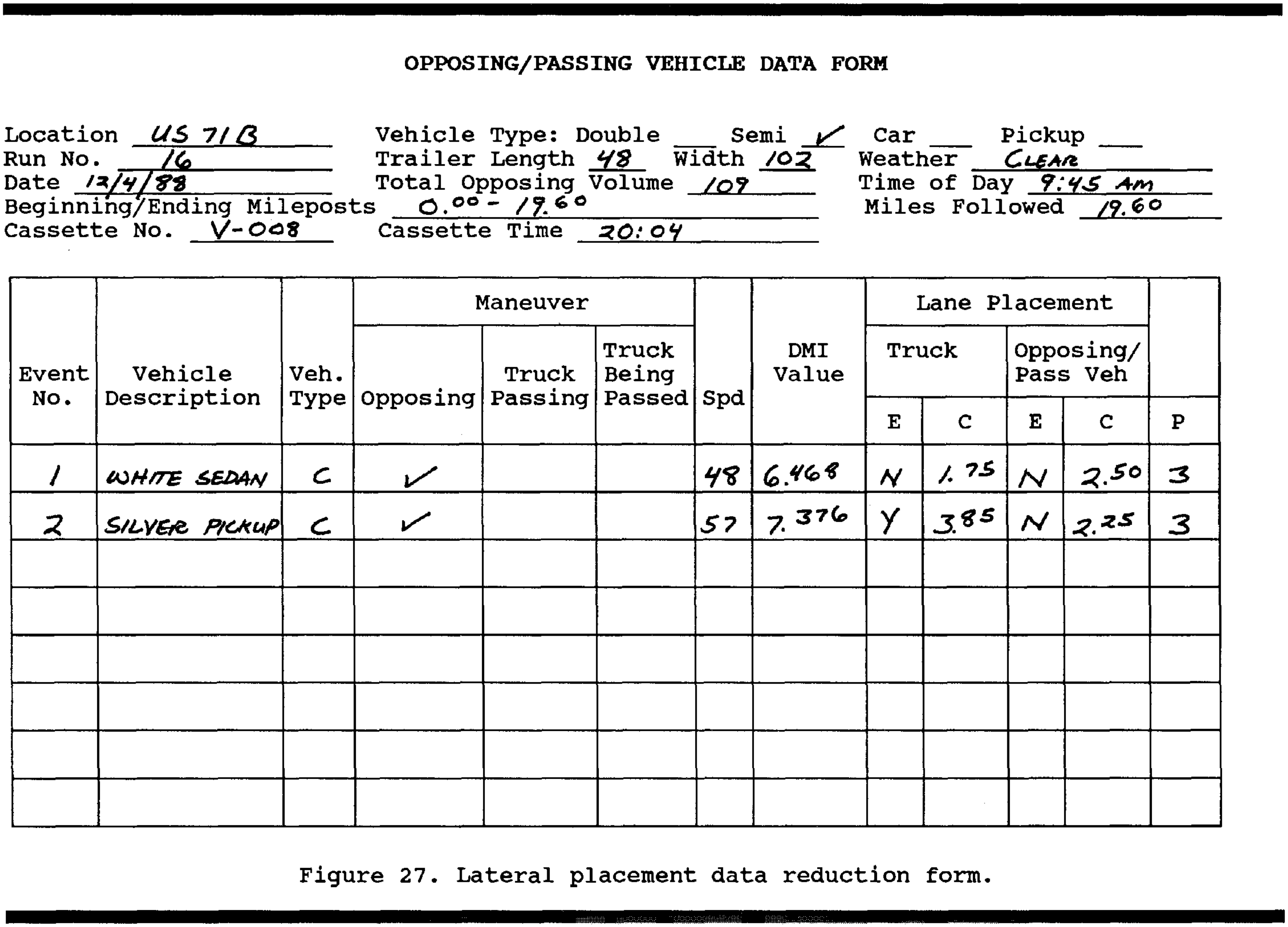
Vehicle Width 102

Time of Day 12:30 PM

Observers Robyn

Event No.	Encroachment Type (Edge of Pavement, Centerline)	DMI		Time		Maximum Amount of Encroachment (No. of Tire Widths)	Ave Spd	V
		Begin	End	Begin	End			
1	E	14.749	14.780	2.46	5.08	1	45	1
2	E	16.579	16.610	2.94	5.76	2	40	2

Figure 26. Encroachment data reduction form.



OPPOSING/PASSING VEHICLE DATA FORM

Location US 71B
Run No. 16
Date 12/4/88
Beginning/Ending Mileposts 0.00 - 19.60
Cassette No. V-008
Vehicle Type: Double ___ Semi ✓ Car ___ Pickup ___
Trailer Length 48 Width 102
Total Opposing Volume 109
Cassette Time 20:04
Weather CLEAR
Time of Day 9:45 AM
Miles Followed 19.60

Event No.	Vehicle Description	Veh. Type	Maneuver			Spd	DMI Value	Lane Placement				
			Opposing	Truck Passing	Truck Being Passed			Truck		Opposing/ Pass Veh		
								E	C	E	C	P
1	WHITE SEDAN	C	✓			48	6.468	N	1.75	N	2.50	3
2	SILVER PICKUP	C	✓			57	7.376	Y	3.85	N	2.25	3

Figure 27. Lateral placement data reduction form.

REFERENCES

1. Transportation Research Board, *Twin Trailer Trucks - Effects on Highways and Highway Safety, (Special Report 211)*, Washington, DC, 1986.

2. Rand McNally & Company, *Motor Carriers' Road Atlas*, New York, NY, 1988.

3. E.L. Seguin, K.W. Crowley, P.C. Harrison, Jr., K. Perchonok, *The Effects of Truck Size on Driver Behavior*: Final Report, Publication No. FHWA/RD-81/170, Federal Highway Administration, Washington, DC, March 1982.

4. C.V. Zegeer, J.E. Hummer, and F. Hanscom, *The Operation of Larger Trucks on Roads with Restrictive Geometry*: Final Report, Publication No. FHWA/RD-86/157, Federal Highway Administration, Washington, DC, July 1986.

5. M.R. Parker, Jr., "Use of Traffic-Conflicts Technique to Assess Hazards of Transporting Oversize Loads," *Transportation Research Record 709*, Transportation Research Board, Washington, DC, 1979, pp. 30-38.

6. E. Kakaley, D. Mela, G.B. Pilkington, F.S. Daniels, T.S. Friesz, D.W. Morrison, *Safety of Wide Buses*: Summary Report, U.S. Department of Transportation (National Highway Traffic Safety Administration/Federal Highway Administration), Washington, DC, January 1973.

7. D.H. Weis and C.S. Sihilling, *Measures of the Lateral Placement of Passenger Cars and Other Vehicles in Proximity to Intercity Buses on Two-lane and Multilane Highways*: Final Report, Federal Highway Administration, Washington, DC, October 1972.

8. O.F. Gericke and M. Walton, "Effect of Truck Size and Weight on Rural Roadway Geometric Design (and Redesign) Principles and Practices," *Transportation Research Record 806*, Transportation Research Board, Washington, DC, 1981, pp. 13-21.

9. H.W. McGee and D. Morganstein, *Development of a Large Truck Safety Data Needs Study Plans*: Volume II - Technical Report, Federal Highway Administration, Washington, DC, February 1986.

10. Transportation Research Board, *Providing Access for Large Trucks, (Special Report 223)*, Washington, DC, 1989.

11. J.C. Glennon, *Matched Pair Analysis*: Consolidated Freightways v. Larson (82-1230), reported in 647 F. Supp. 1479 M.D. Pa. 1986, 1981.

12. T. Chira-Chavala and J. O'Day, *A Comparison of Accident Characteristics and Rates for Combination Vehicles with One or Two Trailers*, Publication No. UM-HSRI-81-41, University of Michigan Highway Safety Research Institute, Ann Arbor, MI, August 1981.

13. C.S. Yoo, M.L. Reiss, and H.W. McGee, *Comparison of California Accident Rates for Single and Double Tractor-Trailer Combination Trucks*, Publication No. FHWA-RD-78-94, Federal Highway Administration, Washington, DC, March 1978.

14. P.P. Jovanis, H. Chang, and I. Zabaneh, "A Comparison of Accident Rates for Two Truck Configurations," *Transportation Research Record 1249*, Transportation Research Board, Washington, DC, 1989.

15. K.L. Campbell, D.F. Blower, R.G. Gattis, and A.C. Wolfe, *Analysis of Accident Rates of Heavy-Duty Vehicles*, Publication No. DTNH22-82/3-C-07188, University of Michigan Transportation Research Institute, Ann Arbor, MI, April 1988.

16. H.S. Stein and I.S. Jones. "Crash Involvement of Large Trucks by Configuration: A Case-Control Study," *American Journal of Public Health*, Vol. 78. No. 5, May 1988, pp. 491-498.

17. V.D. Graf and K. Archuleta, *Truck Accidents by Classification*, Publication No. FHWA/CA/TE-85, California Department of Transportation - Federal Highway Administration, Sacramento, CA - Washington, DC, January 1985.

18. F. M. Council and W.L. Hall, *Large Truck Safety in North Carolina: The Identification of Problem Locations on the Designated Route System*: Phase 2 - Final Report, University of North Carolina Highway Safety Research Center, Chapel Hill, NC, October 1989.