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HE EFFECT OF TRUCK SIZE AND WEIGHT ON CCIDENT EXPERIENCE AND TRAFFIC OPERATIONS

ol. 2. Traffic Operations

July 1981
Final Report

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FOREWORD

This report documents a study concerning the effect of truck size and weight on accident experience and traffic operations. This volume describes the results of the traffic operations portion of this study in which detailed traffic flow measurements were made at 16 individual sites. The report will be of interest to researchers and policymakers interested in the safety effects of increased truck size and weight and truck safety in general.

The study is part of Project 1U, "Safety Aspects of Increased Size and Weight of Heavy Vehicles," of the Federally Coordinated Program (FCP) of Research and Development. The project manager and contract manager is Michael D. Freitas.

Copies are being distributed to each regional and division office. A limited number of copies of this report are available for official use from the Environmental Division, HRS-43, Office of Research, Federal Highway Administration, Washington, D.C. 20590. Additional copies are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

D. Solomon
for Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

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16. Abstract

This field study examined traffic operational effects associated with truck size and weight. Selected highway geometric conditions were: upgrades (short, long; slight, steep), downgrades (long, steep), curves (freeway, non-freeway), grade/curve combinations, merge areas, ramps, and urban intersections. Matched weight and operational data were gathered on nearly 6,000 trucks ranging in gross weight from approximately 20,000 to 160,000 pounds. Extensive traffic operations measures obtained via electronic roadway sensors included: flow (e.g., speed, acceleration), perturbations (e.g., speed variance, deviation from traffic speed), accident potential (e.g., closure rate, projected collision time), delay (e.g., speed delays by following vehicles) and passing behavior (e.g., relative passing speed).

Three analytical procedures determined: operational differences between truck groupings (e.g., loaded versus empty, single- versus double-trailer combination), correlations between truck characteristic and operational measures, and the predictive effect of truck weight on speed. Despite numerous operational differences associated with truck size and weight, the observed effects were weak. Typical truck grouping differences were: generally reduced speeds, higher deviations from traffic mean speeds, and higher closures with following vehicles, all exhibited by loaded and double-trailer rigs (by comparison with empties and singles, respectively). The correlative analysis demonstrated that higher gross weight was often found to be associated with lower truck speed, poor acceleration performance, and both delay and high closures with respect to following vehicles. Negligible operational effect was associated with truck length. Adverse safety effects were most pronounced on upgrades; certain safer behavior was noted for heavier trucks on downgrades. The analyses demonstrated that a maximum of only 37 percent of truck operational effects were explainable by truck size and weight.

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CHAPTER ONE

INTRODUCTION

Background

Truck size and weight regulation has been an issue of major concern to highway agencies ever since individual states began defining vehicle size and weight limits in the early 1900's. National policies were eventually developed by AASHO in the 1940's. In 1956, the Federal Aid Highway Act specified size and weight criteria for trucks using the Interstate system, and these regulations remained in effect through 1974. Then, legislation enacted in early 1975 increased the payload capabilities of trucks in an attempt to offset the economic consequences of the recently lowered speed limit.

Although the 1975 legislation increased allowable gross truck weights from 73,280 to 80,000 pounds (33.3 to 36.3 Mg), the controversy continued in light of an existing economic justification for raising gross weights as high as 120,000 pounds (54.4 Mg) (Winfrey *et al.*, 1968) What was not known, however, were the safety implications of such increases. Traffic operations is one safety area affected by increased truck sizes and weights. The effect that larger and heavier trucks have on stream flow are known to be a function of several variables: highway geometry, traffic density, truck engine horsepower, and braking capability. But at the time this study was initiated, no empirical data were available to quantitatively describe the flow-perturbing effects of increased truck size and weight.

Objective and Scope

In view of the absence of documented knowledge regarding traffic operational effects of specific increases in truck size and weight, the objective of this study was to empirically determine existing size and weight impacts on traffic flow. Based on these data, mathematical modeling was applied to examine the effects of nonexisting larger and heavier trucks on traffic flow.

The scope of this study entailed an analysis of traffic operations under geometric conditions (e.g. grades, curves) which support a determination of truck size and weight effects. Flow interactions surrounding trucks in the traffic stream were examined as a function of truck size, type, loading condition, and measured weight. A sample of nearly 6,000 trucks with matched weight data was employed.

Background Literature

A review of the literature in which documentation exists regarding size and weight effects of trucks was contained in an interim report. A capsulized summary of selected findings relative to traffic operational aspects of the problem is presented here.

Operational effects of trucks were reviewed in terms of the following parameters: length, width, height, articulation, weight, and horsepower-to-weight ratio. Documented effects of increased truck length (e.g. triple trailer combinations) were evident in the longer times required by other vehicles to complete passing maneuvers (Petersen, 1975) on two lane highways. Similarly, longer combinations on multi-lane highways were shown to occupy more than one lane for a longer period while passing other vehicles (Winfrey, 1968; Sherard, 1971). Greater off-tracking on ramps was observed for combinations with longer trailers (Western Highway Institute, 1970; Pilkington & Howell, 1973). Wider trucks affect traffic from a capacity reduction standpoint as can be inferred from Highway Capacity Manual (1965) findings that, with all other factors remaining constant, a decrease in freeway lane width when trucks are present will result in a volume reduction of 3 percent. Research is currently underway to examine lane displacement effects on other traffic which results from incremental increases in truck width from 8 to 9 feet (2.4 to 2.7 m) (Seguin *et al.*, 1976).

Truck height was shown to impact on traffic operations as an outgrowth of its effect on truck handling and stability characteristics. The Truck Trailer Manufacturer's Association (1970) found that the rollover speed of an empty semitrailer on a cloverleaf ramp with a 40 mph (64 kph) crosswind was reduced from 39 to 36 mph (63 to 58 kph) as the overall trailer height increased from 12.5 to 13.5 feet (3.8 to 4.1 m). A loaded truck's likelihood to roll over is affected by its center of gravity. In an evaluation of truck handling, Weir *et al.* (1974) found that a 1.4-ft. (0.4-m) rise in the center of gravity significantly reduced a truck's performance on horizontal curves and increased its propensity for a rollover accident.

A dearth of empirical knowledge exists regarding the effects of truck weight on traffic operations. Mathematical discussions (e.g., Carrier, 1974; Winfrey, 1968) regarding the economic implications of increased weight seem to dominate the literature with one exception. A British study (Everall, 1969) measured travel-time delay of vehicles following trucks on grades, winding rural roads, and other areas where delay could be expected to result from heavy trucks in the traffic stream. The study showed increased trip delay for trucks characterized by larger weight-to-horsepower ratios. Out of the context of actual highway traffic situations, much is known regarding truck handling characteristics (e.g., Weir *et al.*, 1974) and stopping distances (e.g. Murphy *et al.*, 1972) as affected by truck weight.

Much documented evidence exists regarding truck performance in many highway situations although the data generally do not illustrate specific effects of varied size and weight. The influence of trucks' speed and acceleration on other traffic have been studied (Williston, 1967; and others). Mathematical modeling by St. John and Kobett (1974) has examined flow effects of traffic volume, truck mix, and roadway geometry. However, these and other performance-based studies have failed to produce quantitative relationships describing size and weight effects on traffic flow in actual highway settings.

CHAPTER TWO

STUDY METHODOLOGY

Procedures employed in gathering the empirical data that form the basis of this field study are illustrated in Figure 1. First, a truck is observed to pass an instrumented section of roadway. Performance data on the truck and interacting vehicles are unobtrusively sensed by means of pavement switches and stored in a roadside device, the Traffic Evaluator System (TES). The observed truck is subsequently weighed at a nearby state weigh station, and its weight is manually recorded. Time-lapse photography is used to provide a visual record of the truck (and the exact time and date) as it passes both the instrumented roadway section and the weigh station. Using this visual record, the truck's weight data can be matched, for purposes of analysis, to performance data obtained by the TES.

This chapter presents a detailed explanation of procedures used to derive relationships describing the effect of truck characteristics on traffic flow. The following procedural steps are discussed: designation of study measures; selection of field sites; and the collection, reduction, and analysis of data.

Designation of Measures

The design of the field study necessitated the selection of two primary sets of measures. First were descriptors of truck characteristics (e.g. size and weight), to comprise independent variables. The second set involved parameters of traffic flow (e.g. speed and perturbation), designated as dependent variables. The derivation of each is discussed separately.

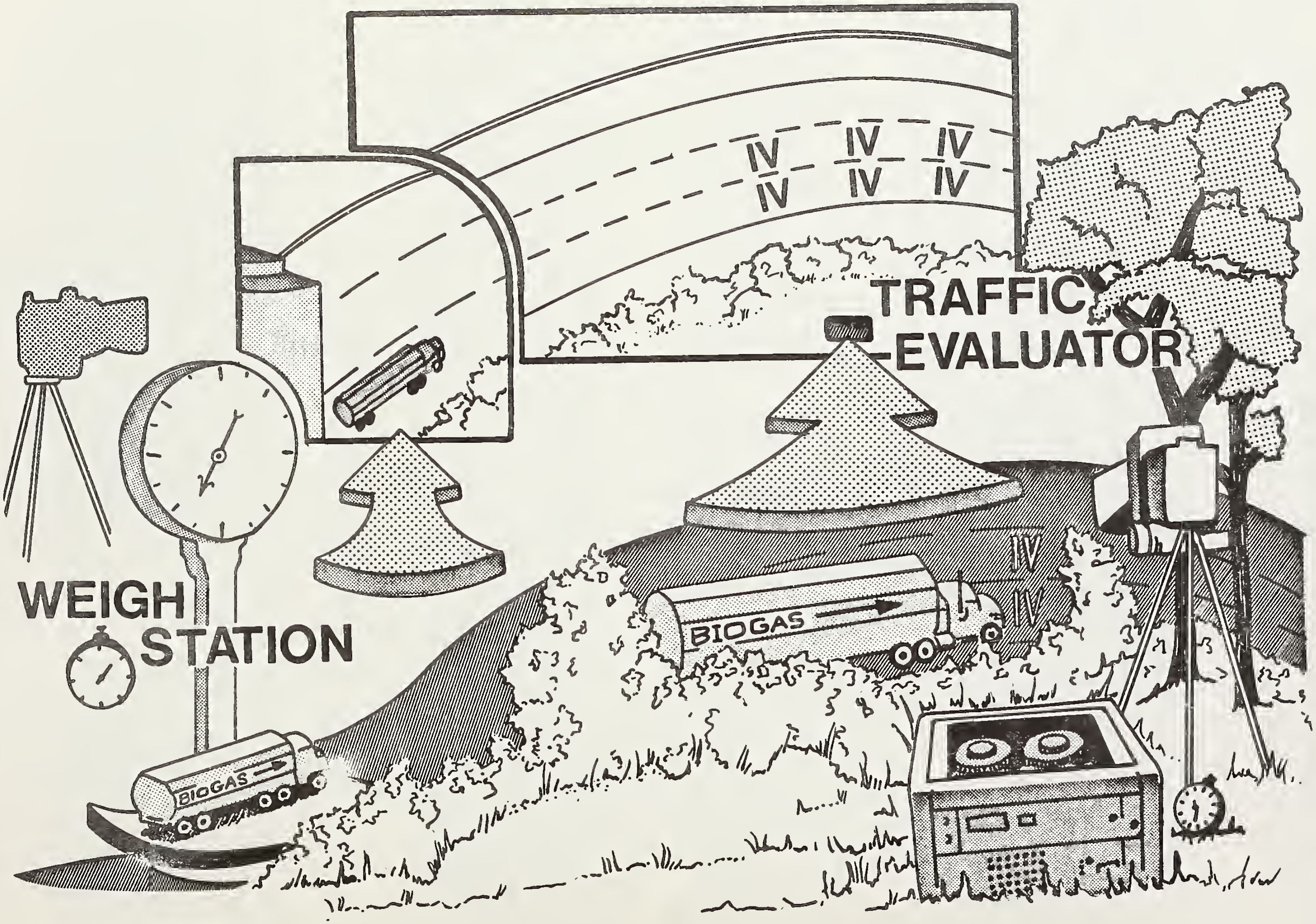


Figure 1. Characterization of field study procedures (e.g., truck weighing, measuring flow performances via roadway tapeswitches, and recording of data using time-lapse photography and the Traffic Evaluator System).

Truck Characteristics

The collection of "real world" field data to support empirical findings about the effects of truck characteristics on traffic flow placed certain restrictions on the types of measures attainable. Measurement techniques were generally limited to unobtrusive methods of gathering traffic stream behavior data, which precluded direct measurement of certain truck factors (e.g. horsepower-to-weight ratio, driver characteristics, age and condition of tractor) known to affect their performance. Practical logistical and cost constraints did not allow for concurrent interviewing of truck drivers during the collection of traffic operations data. Therefore, truck descriptive data obtainable from pavement sensors, time-lapse photography, and state-operated weigh stations were applied to develop the measures used in this study. With these data sources, truck characteristic descriptors were limited to various measures of truck weight, size, and configuration. These measures are summarized in Table 1 and described below.

Truck Weight. Data obtained in state weigh stations consisted primarily of weights taken for each axle or axle combination as trucks moved slowly across a set of scales. Certain trucks were not weighed; their drivers opted to traverse the "empty" truck lane at the station. That these trucks were really empty was generally verifiable through their "bounce response" over a speed bump in the lane, and such trucks were accorded a measure of zero payload. A sample of weights was also obtained for empty trucks representing all configurations observed at each site. Payloads could then be estimated by subtracting empty weight from measured gross weight. The weight data provided for the following measurement categories:

Table 1

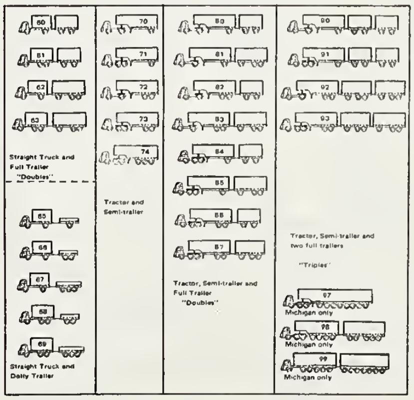
Measures of Observable Truck Characteristics

Variable	Definition
Gross weight	Gross weight of target truck.
Front axle weight	Weight of target truck's front axle.
Maximum axle weight	Weight of heaviest axle or axle pair of target truck.
Empty vs. loaded	Dichotomous variable to denote empty trucks on which no weight data was available.
Empty weight	Empty weights visually assigned for specific types.
Payload	Difference between observed gross weight and known empty weight of target truck.
Length	Total length, front of cab to rear of last trailer.
Wide load	Code to denote trucks carrying wide loads.
Number of trailers	Articulation is classified into single-, double-, and triple-trailer configuration types.
Cab type	Classification of cab types into cab-over or cab-behind.

Trailer Type

- Unknown
- Not applicable: no trailer
- Fully enclosed
- Fully enclosed low-bed
- Tank
- Bulk commodity
- Pole, pipe, logging
- Platform
- Low-bed, heavy hauler
- Dump
- Auto carrier
- Pole (Dolly type)
- Dolly
- Mobile home
- Saddle mount

Truck Type



- Gross weight - sum of axle weights at scales.
- Front axle weight - this measure is included because of special interest in the problem of front tire failure, alleged to be associated with cab-over type tractors.
- Weight of heaviest axle or axle combination - this measure is of obvious importance for establishing regulatory procedures.
- Empty versus loaded - trucks were classified according to whether or not they were empty.
- Empty weight - estimated by obtaining samples of empty weights for all truck configurations in the measured population.
- Payload - estimated from the difference between empty and gross truck weights.

Truck Size. The road switch method TES provided wheelbase measurements for trucks in the traffic stream. Using matched time-lapse photography data collected at weigh stations, the overhang for each truck was graphically obtained and added to the wheelbase for a measure of overall truck length. Although truck width data were not directly obtainable, trucks known to be carrying wide loads were segregated in the data to allow for some discernment of width effects. These procedures gave two measures related to truck size:

1. Overall length - sum of wheelbase and overhang.
2. Wide load - denoted trucks hauling over-width loads.

Truck Configuration. Visually descriptive data for all trucks in the sample were readily obtained from time-lapse film. Variables of interest here were articulation type (number of trailers), cab type, and trailer type. Specific configurative measures were:

- Number of trailers - all trucks were coded as being single-, double-, or triple-trailer combinations.
- Tractor type - either cab-over or cab-behind engine of tractor.
- Trailer type - classified as one of the following: van; lowbed van; tank; bulk commodity; pole, pipe, or logging; platform or flatbed; lowbed, heavy hauler; dump; or auto carrier.
- Truck type - coded as to axle configuration for all combination types (3S2: 3-axle tractor with 2-axle semitrailer).

Traffic Flow

Given the versatility of the field data collection method used, a myriad of traffic flow measures were possible. The TES detects the presence of vehicles and measures their trajectories using electronic switches attached to the pavement. Through the manipulation of computer software associated with the TES, practically any flow measure can be determined for the instrumented section of highway. In general, the sites used in this study were instrumented with six "traps" (pairs of electronic road switches) placed at 300-ft. (91.4-m) intervals.

some measures derived from lit review

Various measures deemed to be descriptive of flow quality (e.g. smoothness), accident potential (e.g. relative following speeds/distances), delay (e.g. slowing on upgrades), and passing (e.g. relative passing speed) were derived from a literature review. A summary of applied traffic flow measures is given in Table 2; Appendix B contains a more thorough explanation of each

Table 2

Measures of Traffic Flow Characteristics

Basic Flow Descriptors

Mean Speed — Average of spot speeds taken at each switchpair location.

Mean Acceleration & Deceleration — Change in speeds over travelled time between switchpair locations.

Headways/tailways — Time and distance measures between successive vehicles in stream.

Lateral Placement — Vehicle position in lane, distance between wheel and edgeline.

Flow Perturbation

Maximum Acceleration & Deceleration — Largest value obtained within TES switch array.

Speed Variance — Speed change function as follows:

$$\text{SVAR} = \frac{1}{N} \sum_{i=1}^{N} (\text{speed}_i - \text{Mean Speed})^2$$

where N = number of speed measurements
i = specific switchpair locations.

Acceleration Variance — Acceleration change function computed the same as speed variance.

Deviations from Mean Speed — Spot speeds which are slower or faster than one standard deviation from the mean of the entire vehicle sample (correcting for time-of-day speed variation).

Queueing Variance — Change in queue length computed as variance function.

Driver Effort — Product of speed change and lateral placement change.

Rear-End Accident Potential

Critical Following Time — Headways/tailways of either 1.0 or 2.0 seconds or less.

Critical Closure Speed — Relative closing speeds for vehicles exhibiting critical following time.

Projected Time to Collision — Time required for critical closure speed to result in collision.

Flow Delay

Queue Length — Number of vehicles following truck on up-grade.

Following Vehicle Delay — Difference between average roadway speed and speed of vehicle following truck.

Following Queue Delay — Difference between average roadway speed and speed of vehicle queue behind truck.

Passing Interactions

Probability of Pass Occurrence — Proportion of truck interactions involving other vehicles where relative positioning was conducive to passing.

Relative Passing Speed — Speed difference between vehicles in passing interaction.

measure in terms of its concept, operational definition, rationale for use, and appropriate background reference material. Each measure was obtained from field data for "target" trucks on which weight data had been gathered. The measures took into account not only the performance of the truck itself, but also the traffic flow dynamics in the stream around it.

As seen in Table 2, selected flow measures fall into several categories. Basic flow descriptors generally comprise traditional traffic engineering measures of operational characteristics: speed, acceleration, deceleration, headway, tailway, and lateral placement. From these basic flow parameters, more sophisticated and definitive measures of stream flow dynamics were developed to describe various aspects of safety-related traffic behaviors.

The first of these categories, flow perturbation, was used to describe smoothness or stability of traffic flow over a finite highway section. Variance observed in a variety of basic flow measures (speed, acceleration, queuing) was taken as a measure of stream stability. The maximum acceleration or deceleration, observed in a number of spot measurements within a highway section, was also used as an index of flow disturbance. Deviation from the mean traffic speed has been used as a measure in a number of evaluative studies (e.g. Kolsrud, 1972; Hanscom and Berger, 1974). A documented example of such usage is a measure of effectiveness defined to be the proportion of vehicles exhibiting a speed of at least 5 mph (8 kph) below the sample mean (Kolsrud, 1972). An adaptation of that procedure applied in this study, which allowed for sensitivity to normal speed variation in the stream, was to examine the proportion of vehicles traveling at speeds at least one standard deviation below the mean. Similarly, the proportion of vehicles traveling at speeds one standard deviation or more above the mean was of particular interest in cases of heavy trucks on downgrades. Another flow-stability measurement concept was derived from work by Greenshields (1965). His measure of "driver effort," taken to be the product of speed changes and lateral placement changes, was also deemed a valid flow perturbance measure in this study.

The second category of derived flow-quality measures served to estimate the potential for rear-end accidents, based on measured flow characteristics. Such measures were available in instances of closely-following vehicle pairs in which a target truck was either the leading or the following vehicle. Critically short headways and tailways were defined as being 1.0 second and 2.0 seconds or less. The 1.0-second measure was of primary interest; 2.0 seconds or less was designated in order to insure the availability of an adequate sample at all sites. Another measure of rear-end accident potential was the relative closing speed associated with short headways and tailways, as observed in the above cases. Given that two vehicles following at short distances showed a decreasing inter-vehicle gap, another measure was defined as the projected time to collision for the vehicle pair. That is, assuming that no speed or path changes were made following the measurement, this value is the amount of time elapsed when the vehicles collide. This measure proved to be a highly sensitive descriptor of traffic flow safety, as became startlingly apparent at one point during the data collection effort. A serious rear-end accident did occur, involving one of our target trucks, and the actual time to collision was nearly identical to our calculated value.

Another category of measures was vehicular delay caused by trucks. The focus of this measures group was the effect on other vehicles in the traffic flow, rather than the flow characteristics of trucks themselves. Each of three measures dealt with vehicles following trucks in upgrade and other restricted flow situations.

The first was a count of the number of vehicles (queue length) behind the target truck. The other two measures compared the speeds of vehicles following trucks with the normal speeds of nonrestricted vehicles for the particular site and time of day. Such speed differences were obtained for both single vehicles and vehicle queues behind target trucks. These measures described delay in terms of speed reduction which can be converted to travel-time delay, if necessary, by calculating from assumed trip lengths. However, such assumptions could hardly increase either the validity or the sensitivity of the delay measures.

The final category of flow measures pertained to passing behaviors involving target trucks. The passing interaction (either truck passing or truck being passed) was defined on the basis of relative roadway positioning of the truck and the interacting vehicle. The probability of a passing occurrence for a specific truck sample was then assessed by measuring the proportion of the sample that met the positioning criterion. A separate measure in the category of passing interactions was the relative speed between the two vehicles involved.

Site Selection

It was important that a complete representation of the traffic conditions necessary for describing the flow effects of truck size and weight be obtained. To this end, two general selection strategies were brought to bear. First, selected sites included both freeway and primary routes, located in both rural and urban areas. This approach permitted representativeness over a wide variety of traffic situations. Secondly, specific conditions of traffic volume and roadway geometry were designated. Of particular importance was the quantification of roadway geometrics in accordance with prescribed design standards, in order to permit parceling of size and weight effects across specific highway classifications (e.g. freeway, primary secondary). A third consideration, not directly related to examining flow effects but important in determining the overall safety impact of truck size and weight, was that each site be located within a roadway section used in the accident study reported in Volume 2.

Selection Criteria

The systematic determination of truck size and weight effects on traffic flow required careful selection of study sites in terms of the following criteria: traffic volume, truck characteristics, weight data sources, and roadway geometrics.

Traffic Volume. While no specific level of ADT could be established as a selection criterion, due to the varied nature of traffic characteristics between sites (e.g. higher volume in urban than rural areas), sufficient traffic volume was required to insure that frequent interactions occurred between trucks and other vehicles in the stream. The necessity for vehicle interactions arises from the obvious fact that an isolated truck exhibits no effect on the traffic stream, regardless of its own flow dynamics. Moreover, the requirement that a sizeable number of flow interactions involving trucks be observed in a given time period was a prerequisite for a cost-effective data collection procedure yielding a statistically valid sample.

Truck Characteristics. In addition to the requirement for trucks to be present in sufficient numbers to provide an adequate sample of flow interactions, it was necessary to have a wide representation of truck sizes and weights at each site. Therefore, one selection criterion was that the traffic stream contain both empty and fully loaded trucks and, ideally, partially loaded trucks, in order to provide a uniform distribution of gross weights. Due to its high allowable gross weight limit (164,000 pounds [74.4 Mg]), Michigan was designated as a candidate study site. Moreover, geographic regions characterized by greatly varying truck sizes and types (e.g. single-, double-, and triple-trailer combinations) were sought. The occurrence of triple-trailer combinations in certain western states made them desirable candidate sites, for instance.

Truck Weight Sources. A critical aspect of this study was the acquisition of truck weight data. The most desirable method would have been to unobtrusively gather weights on all trucks passing each site. This preference led us to consider using the truck weigh-in-motion device currently in operation at certain highway stations in Texas and Florida. However, a number of problems were found to be associated with their use. First, extensive coordination and scheduling of data collection activity with local highway agencies would be necessary, since they require that the scales be manned by local personnel. Second, due to terrain characteristics in Texas and Florida, the roadway geometrics (grades, in particular) in proximity to the scales were less than ideal. Finally, little is known about the accuracy of weigh-in-motion devices when using with heavy trucks traveling at high speeds; and reliability of weight measurement was of vital importance to this study. Therefore, a decision was made to trade off the advantage of the unobtrusive method in favor of the higher weight accuracy and greater flexibility in site selection to be had with state-operated weigh stations in other areas of the country. So it became a selection criterion that a candidate site be in reasonable proximity (1 to 5 miles [1.6 to 8.0 km]) to a truck weighing station. This requirement allowed for visual matching (using time-lapse photographic comparisons) of weight measurements with operational data gathered at the site.

Roadway Geometry. A critical element in the study was the selection of sites that allowed for a parsimonious analysis of roadway geometric influences on the operational effects of trucks. It was essential to have control over those geometric elements which impacted on the performance of trucks. Many geometric factors had to be taken into account, both individually and in combination (e.g., grade and curvature). Varying levels of each factor were experimentally desirable within some site sample size constraints.

The general strategy of establishing site paradigms on the basis of Interstate versus primary system location was not strictly applied, since inherent geometric differences between these roadway classes were obfuscated by varying standards between those states where candidate sites were sought. Thus, to make a suitable distinction on the basis of general design standards, the selection criterion became "freeway" versus "nonfreeway."

Site selection criteria relating to roadway geometrics were derived, in part, from a brief review of the Highway Capacity Manual. For example, maximum and minimum values of grade length and steepness affecting the truck equivalency factor were sought. Other geometric situations known to be factors in truck handling (e.g., tight ramp curvature) were also designated as selection criteria. The following geometric situations were eventually selected for study:

Grades

- Length (long versus short)
- Percentage (steep versus slight)
- Direction (positive versus negative)

Curvature

Mainline freeway
Nonfreeway
Tight Ramp

Grade and Curve Combination

Freeway; negative grade
Nonfreeway; negative grade

Interchange

Entrance merge
Tight ramp (see Curvature)

Two-Lane Passing Situation

Narrow Lane

Urban Intersection

The first and most critical specification is grade. To factorially account for the effects of two variations on each of the three parameters of grade geometry, eight sites (2x2x2) would have to be chosen. However, for purposes of economy in data collection, two trivial cases (short downgrades, slight and steep) were eliminated as being of minimal consequence. Six grade types then remained, using as study geometrics the following conditions:

Length: Long = 1½ miles (2.4 km), short = ½ mile (0.8 km)

Percentage: Steep >4%, slight <2%)

Direction: (Positive and negative)

Surveys of Candidate Sites

The site selection criteria posed numerous constraints on the location of potential sites. For example, specific terrain features were sought in states that permitted a variety of truck types, sizes, and weights. Candidate sites were further restricted to states that maintained on-going programs of truck weighing. Moreover, because of the desirability of conducting both the accident and the traffic operations portions of DOT-FH-11-8835 at the same locations, our sites were restricted to Maryland, Pennsylvania, Michigan, Texas, Nevada, and California. Of these, only Michigan and California maintained continuously operated truck weigh stations.

Sufficient interest existed in all of the above-mentioned states for us to conduct surveys of candidate site locations within each. Over 500 candidate sites were surveyed in the following states: Michigan and California (attractive because of the state truck weighing facilities); Nevada (the presence of triple-trailer combinations); Pennsylvania (we have had extensive accident investigation effort there); and Texas (the state's use of truck weigh-in-motion scales).

The survey of each candidate site involved taking measurements of roadway geometric factors, sample traffic volume and truck mix counts, and photographing relevant roadway features, including those required for data collection instrumentation (e.g. vantage points for time-lapse cameras, etc.). Descriptive data for each candidate site were summarized in the format shown in Figure 2. Visits to each state also involved preliminary meetings with state highway and police agencies regarding cooperative efforts.

Final Selection of Sites

The final designation of study sites was based on a blending of the criteria noted above. The majority of the sites were located in Michigan and California due to the availability of weight data from state-operated weigh stations. One site, located

Site: M-7

Paradigm: Freeway Curve

Location: I-75, NB, Near Pontiac

Wt. Sta. Locn: 3 miles south

Geometrics: Δ = 37°. L = .25 mile (0.4 km)

Volume Sample: 150 trucks/hour

Comments: Slight downgrade
Curve located just beyond top of M-6 grade

Figure 2. Typical pre-selection data summary for candidate site.

in Nevada because of the presence of triples, was selected in sufficiently close proximity to a state-operated weigh station in Utah. Another site not requiring weight measurements was located in Virginia, in close proximity to BioTechnology's home office. Data collection at this site was conducted as a pretest of the data-gathering procedure. Table 3 provides an overview of selected study sites listed by geometric characteristics. It also provides an alphabetic identification useful for locating the specific site in Appendix A, where more detailed site descriptive data are presented.

Data Collection

An unobtrusive procedure was employed to measure flow characteristics of trucks and surrounding vehicles in the traffic stream. Length and weight measures were obtained for each observed truck and matched to flow data so as to permit an analysis of truck effects on traffic flow.

Sections of roadway that met the specified geometric criteria were selected in sufficiently close proximity to state weigh stations to permit simultaneous gathering of truck weight and performance data. Each roadway section was then instrumented with the Traffic Evaluator System (TES), which consists of unobtrusive electronic pavement sensors and a digital tape recorder for gathering traffic performance data on trucks passing the roadway section. Performance data were also obtained for those vehicles that interacted with each truck. Concurrently, truck weights were gathered for each truck in the nearby (within 1 to 3 miles [1.6 to 4.8 km]) weigh station. Weights obtained for each truck at the weigh station were matched with its performance data, gathered at the roadway section. This visual matching process was accomplished through the use of specially instrumented

Table 3

Summary of Data Collection Site Characteristics

TYPOLOGY		GEOMETRICS	PRIMARY MOE	SITE ID* & LOCATION
Grades	Long, steep, +	1½ mi, > 4%	Speed	H, Canejo, Cal.
	Long, steep, -	1½ mi, > 4%	Speed	J, Canejo, Cal.
	Long, slight, +	1½ mi, < 2%	Speed	C, Pontiac, Mi.
	Long, 3%, –	1½ mi, < 3%	Speed	M, Cottonwood, Cal.
	Short, steep, +	½ mi, > 4%	Speed	G, Canejo, Cal.
	Short, slight, +	½ mi, < 2%	Speed	B, Pontiac, Mi.
Curves	Mainline freeway	D = 3°	Displacement	A, Fowlersville, Mi.
	Non-freeway	D = 4°	Displacement	E, Shasta, Cal.
	Tight ramp	D = 4°	Off-tracking	L, Carson, Cal.
Grade and Curve	Freeway, -grade	G = 5% D = 3°	Speed/ Displacement	I, Canejo, Cal
	Non-freeway, -grade	G = 5% D = 4°	Speed/ Displacement	F, Placerville, Cal.
Interchange	Entrance/merge	Acceleration lane	Gap Acceptance	K, Carson, Cal.
	Tight ramp	20 mph Exit speed	Off-tracking	L, Carson, Cal.
Passing	Two-direction	1½ mi, Flat grade	Displacement Speed change	D, Eastern Nevada
Narrow Lanes	4-lane divided	10 & 11 Foot lanes	Displacement Rel. speed	Pre, Warrenton, Va.
Inter-section	Urban arterial	2 through/ 1 turn lane	Delay	Santa Barbara, Cal.

*Alphabetical site designation in Appendix A.

time-lapse photography. Each of the three data collection procedures, the TES, time-lapse photography, and truck weigh stations, is further explained in the following sections.

Traffic Evaluator System

Description. The Traffic Evaluator System (TES) was developed in 1969 by the Federal Highway Administration to facilitate the large-scale collection of traffic flow data. Major components of the TES include:

- An array of tapeswitches that transmit an electrical pulse when vehicle presence is detected (input).
- An electronic coding unit, a digital tape recorder, and an electronic clock.
- A series of computer programs that reconstruct the actions of the vehicles and prepare descriptive and inferential statistics.

The TES is a rugged, portable, battery-operated research tool that continuously monitors 60 switch contacts. While most of the contacts are normally used for the tire detector switches, the remainder can be used for manual event coding.

The operation of the TES depends on the pressure of vehicle wheels, which is sensed by tapeswitch closures. Upon activation of any switch contact, the time of initial closure and the identification number of the active switch are recorded on a seven-track computer tape. The processing of these data tapes can yield the following measures for each vehicle passing through the array: lane changes, velocity, relative speed, headway, gap, acceleration, number of axles, and wheelbase.

Wheelbase and number of axles are, of course, constant for a given vehicle traversing the tapeswitch array. However, each of the other measures is generated at a number of points along the highway, depending on the position of tapeswitches and their distance from a selected point of interest such as an interchange gore area. The data can also be aggregated to yield summary statistics such as the number of vehicles in each lane, mean speed, and mean headway.

The TES is the property of the Federal Highway Administration. Complete information on the system, including hardware, software listings, and a complete description of the use of the system to collect traffic conflicts data, is contained in *Appendices A* and *B* of *Part 2, Volume III: Traffic Engineering Evaluation of Diagrammatic Guide Signs, Diagrammatic Guide Signs for Use on Controlled Access Highways, Report No. FHWA-RD-73-25*, available from the National Technical Information Service, Springfield, Virginia 22151.

Deployment of the TES. A schematic showing the configuration of pavement tapeswitches for each roadway site is included in Appendix A (Site Descriptive Data). In general, each site was deployed with six switchpairs at 300-ft. (91.4 m) intervals. Each switchpair consisted of two parallel switches spaced four feet apart. At sites where a measure of later placement was obtained, diagonal switches were included at appropriate switchpair locations.

The number of switchpairs varied between sites. At certain locations where high traffic volumes resulted in a hazardous traffic diversion during the deployment procedure, only one switchpair was used. The distribution of these "single pair" sites was such that a full (six switchpair) array was always deployed at another site nearby in order to avoid major data gaps in any specific geographic area or roadway geometric situation. One site that required extensive flow profile data in a two-lane passing situation was deployed using an .8-mile (1.3 km) long, 11-switchpair configuration in both directions of traffic flow.

Deploying the TES in the field required considerable cooperation from local highway agencies, due to the necessity of stopping or diverting traffic. To deploy a switchpair required the complete stoppage of traffic in each lane for a period of approximately 5 minutes. This time is required for technicians to perform necessary measurements and tape applications to the pavement. Traffic control assistance was obtained from highway departments in Michigan and California and from police agencies in Virginia and Nevada so that the deployment could be carried out. Figure 3 depicts the deployment procedure.

Field Operation of the TES. Although the TES runs continuously without manual operation, manual coding of trucks and simultaneous triggering of a time-lapse camera was one facet of its operation in this study. Coding of trucks in the traffic stream facilitated the isolation of their performance data within the continuous record of data for the entire stream. Concurrent filming of the traffic stream with a time-lapse camera provided a pictorial description of the truck for the purpose of visually matching weight data. Figure 4 depicts the TES and a manual coder operating an interconnected time-lapse camera in the field.

Time-Lapse Photography

Cameras were used both at truck weigh stations and in conjunction with the TES at the roadway data collection sites as described above. Visual records of trucks obtained at both locations were matched in order to facilitate the matching of

Figure 3. Application of TES tapeswitch to pavement at Nevada site.

Figure 4. TES during manual coding operation.

Figure 5. Time-lapse camera interconnected with TES.

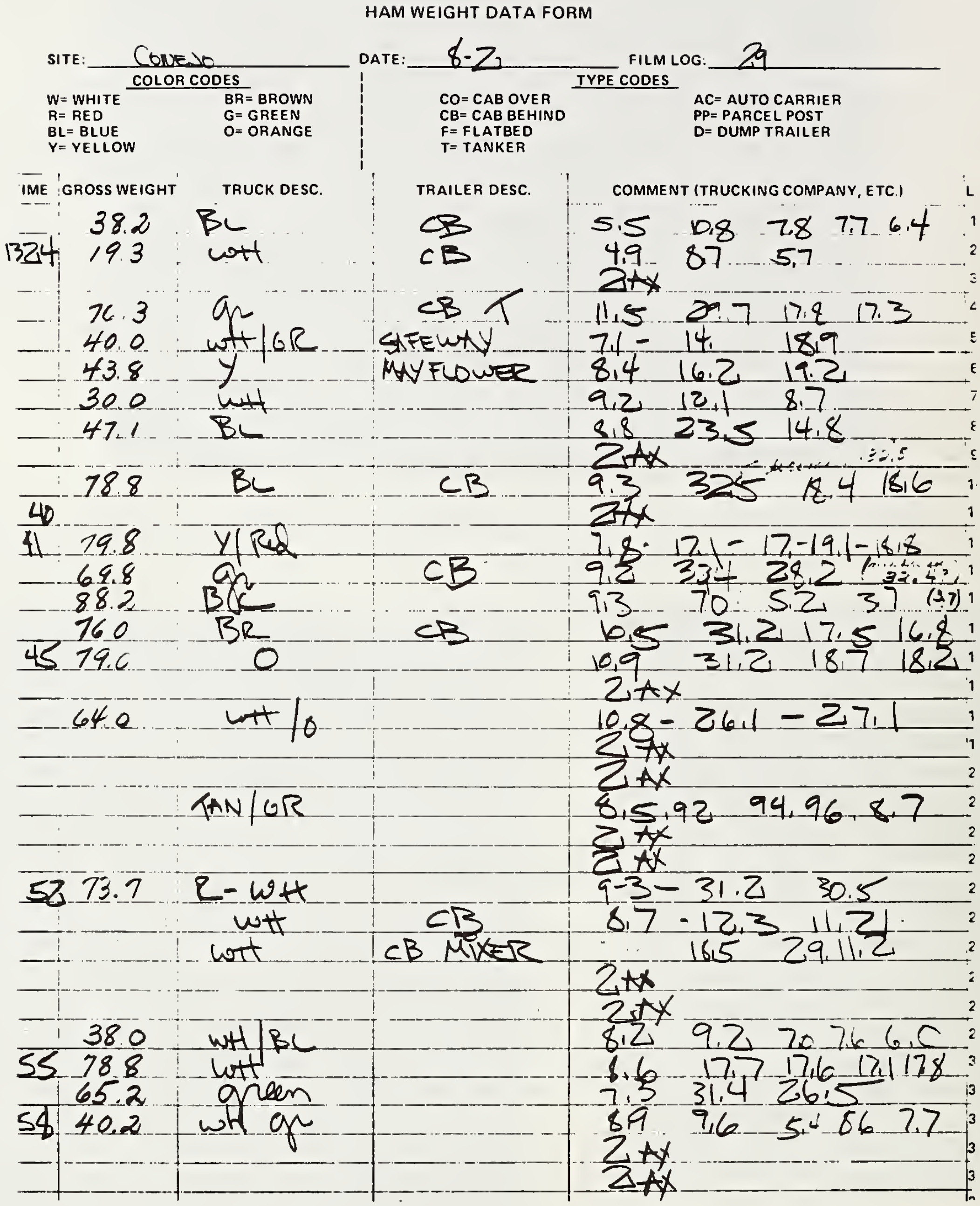
truck weight and traffic operations data. The cameras were specially instrumented (see Figure 5) with timeclocks and identification numbers which appeared in the field of view. The identification number specified the site and data collection date. A watch was used to determine exact time-of-day for the truck's passage. In view of the known distance between roadway site and weigh station, timed arrivals at each point greatly facilitated the visual matching of weight and traffic operations data for specific trucks.

Truck Weigh Stations

A data recorder at the weigh station maintained a log (see Figure 6) denoting truck weights, time-of-day, and sufficient truck descriptive information to allow weights to be matched up correctly with the time-lapse film visual records. State-operated truck weighing scales provided an accurate source of weight data for each axle combination on all loaded trucks passing the weigh station. In many instances empty trucks were allowed to pass through a separate lane at the station. That these trucks were in fact empty was confirmed by their performance over a speed bump in the lane. Operations data were matched with these trucks and their empty weights were estimated using a list of known empty weights that had been obtained for each truck type. Figure 7 depicts weight-data collection in state weigh stations.

Data Reduction

The traffic operational performance of trucks and vehicles interacting with them in the stream was directly obtained through software manipulation of TES data, with no manual reduction effort. However, associating certain data with the traffic operations information required that both of the above-mentioned sets of



HAM WEIGHT DATA FORM

SITE: CONEJO DATE: 8-21 FILM LOG: 29

COLOR CODES
W= WHITE
R= RED
BL= BLUE
Y= YELLOW
BR= BROWN
G= GREEN
O= ORANGE

TYPE CODES
CO= CAB OVER
CB= CAB BEHIND
F= FLATBED
T= TANKER
AC= AUTO CARRIER
PP= PARCEL POST
D= DUMP TRAILER

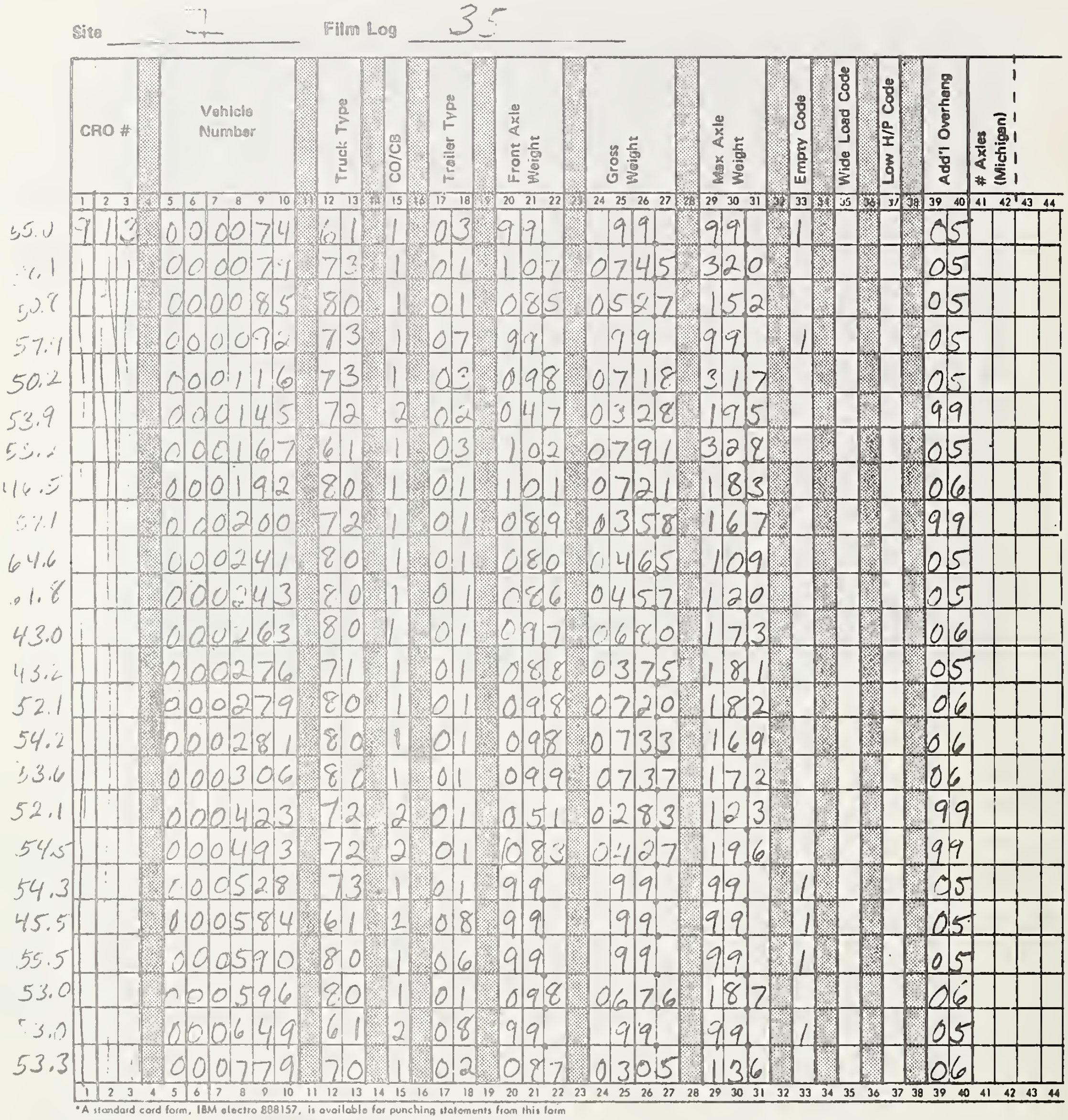
IME	GROSS WEIGHT	TRUCK DESC.	TRAILER DESC.	COMMENT (TRUCKING COMPANY, ETC.)	L
	38.2	BL	CB	5.5 10.8 7.8 7.7 6.4	1
1324	19.3	WH	CB	4.9 8.7 5.7	2
				2AX	3
	76.3	gr	CB T	11.5 29.7 17.8 17.3	4
	40.0	WH/GR	SAFEWAY	7.1 - 14. 18.9	5
	43.8	Y	MAYFLOWER	8.4 16.2 19.2	6
	30.0	WH		9.2 12.1 8.7	7
	47.1	BL		8.8 23.5 14.8	8
				2AX 32.5	9
	78.8	BL	CB	9.3 325 18.4 18.6	1
40				2AX	1
41	79.8	Y/Red		7.8 17.1 - 17.-19.1-18.8	1
	69.8	gr	CB	9.2 33.4 28.2 ([illegible] 32.4)	1
	88.2	BL		9.3 7.0 5.2 3.7 (3.7)	1
	76.0	BR	CB	10.5 31.2 17.5 16.8	1
45	79.6	O		10.9 31.2 18.7 18.2	1
				2AX	1
	64.0	WH/O		10.8 - 26.1 - 27.1	1
				2AX	1
				2AX	2
		TAN/GR		8.5, 9.2 9.4, 9.6, 8.7	2
				2AX	2
				2AX	2
53	73.7	R-WH		9.3 - 31.2 30.5	2
		WH	CB	8.7 - 12.3 11.2	2
		WH	CB MIXER	16.5 29.1 11.2	2
				2AX	2
				2AX	2
	38.0	WH/BL		8.2 9.2 7.0 7.6 6.0	2
55	78.8	WH		8.6 17.7 17.6 17.1 17.8	3
	65.2	green		7.3 31.4 26.5	3
56	40.2	WH gr		8.9 9.6 5.4 8.6 7.7	3
				2AX	3
				2AX	3

Figure 6. Example of weigh station data log. Entries are time-of-day, gross weight, truck description, trailer type, and individual axle weights.

Figure 7. Data recorder making input to weigh station data log.

time-lapse films be viewed, and that any non-TES-acquired information (truck weights, trailer types, etc.) be manually input. This step was accomplished by means of keypunched card input to the TES computerized data base. The form developed for this process is shown in Figure 8.

One punched card was prepared for each truck on which a match was made for weight and performance data. The first two entries on the card identify the truck of that type in the TES data base that served as the source of all the operational measures. The next three entries contain coded data on certain observable characteristics of the truck: the truck type, the cab type (cab over or cab behind), and the trailer type. Table 4 contains an explanation of the coded items on the card, many of which are directly compatible with the accident-study data base (see Volume III of this report). The three following entries are measures of truck weight taken from the weigh-station logs.



Site 1 Film Log 35

	CRO # (1–3)	Vehicle Number (5–10)	Truck Type (12–13)	CO/CB (15)	Trailer Type (17–18)	Front Axle Weight (20–22)	Gross Weight (24–27)	Max Axle Weight (29–31)	Empty Code (33)	Wide Load Code (35)	Low H/P Code (37)	Add'l Overhang (39–40)	# Axles (Michigan) (41–42)	(43–44)
55.0	913	000074	61	1	03	99	99	99	1			05		
56.1		000071	73	1	01	107	0745	320				05		
50.8		000085	80	1	01	085	0527	152				05		
57.1		000092	73	1	07	99	99	99	1			05		
50.2		000116	73	1	03	098	0718	317				05		
53.9		000145	72	2	02	047	0328	195				99		
55.2		000167	61	1	03	102	0791	328				05		
46.5		000192	80	1	01	101	0721	183				06		
57.1		000200	72	1	01	089	0358	167				99		
64.6		000241	80	1	01	080	0465	109				05		
61.8		000243	80	1	01	086	0457	120				05		
43.0		000263	80	1	01	097	0680	173				06		
43.2		000276	71	1	01	088	0375	181				05		
52.1		000279	80	1	01	098	0720	182				06		
54.2		000281	80	1	01	098	0733	169				06		
53.6		000306	80	1	01	099	0737	172				06		
52.1		000423	72	2	01	051	0283	123				99		
54.5		000493	72	2	01	083	0427	196				99		
54.3		000528	73	1	01	99	99	99	1			05		
45.5		000584	61	2	08	99	99	99	1			05		
55.5		000590	80	1	06	99	99	99	1			05		
53.0		000596	80	1	01	098	0676	187				06		
53.0		000649	61	2	08	99	99	99	1			05		
53.3		000779	70	1	02	087	0305	136				06		

*A standard card form, IBM electro 888157, is available for punching statements from this form

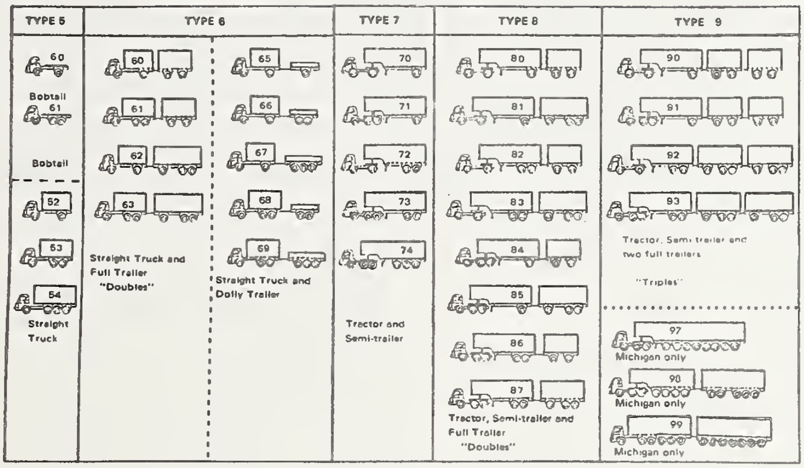
HAM (OPERATIONS) DATA CODING FORM

Figure 8. Example of manual data reduction form used to match weight and visually acquired information with TES data.

Table 4

Manually Coded Truck Characteristics Observed on Time-Lapse Film

Truck Type – Configuration coded as follows:



Trailer Type – Configuration coded as follows:

■. Unknown
00. Not applicable: no trailer
01. Fully enclosed
02. Fully enclosed low-bed
03. Tank
04. Bulk commodity
05. Pole, pipe, logging
06. Platform
07. Low-bed, heavy hauler
08. Dump
09. Auto carrier
10. Pole (Dolly type)
11. Dolly
12. Mobile home
13. Saddle mount

Cab Type

1. Cab Over
2. Cab Behind

They are: front axle weight, gross weight of the truck, and the weight of the heaviest axle combination. The next coded item was used to denote cases in which the truck had not been weighed, but was known to be empty. The next entry was used to identify trucks carrying wide loads. Certain trucks that were presumed to exhibit a low horsepower-to-weight ratio were so coded in the following entry. In order to calculate the overall length of trucks, wheelbase data obtained via the TES was added to front and rear overhang, which was graphically scaled from time-lapse film taken in weigh stations. The value for this overhang was coded in the next card entry. The final entry was used to designate the number of axles in use on certain Michigan trucks which were capable of varying axle usage depending upon load. The coded entires on the keypunched card, in combination with the TES data base, comprised the computerized data used in the analysis.

Data Analysis

An analytic approach was designed to address the traffic operational impact of specific truck characteristics across certain conditions of roadway geometrics. This approach is simplistically diagrammed in Figure 9. The x, y, and z axes represent the dependent, primary independent, and secondary independent variables, respectively. Dependent variables are measures of traffic flow, while primary independent measures were designated as truck characteristics. Relationships between these two sets of variables were examined while holding constant the secondary, or control, variables which comprise roadway geometrics. All three variable sets were discussed earlier in this chapter under the heading "Designation of Measures."

The data were treated in specific analytic steps applied at various levels. Steps refer to types of statistical procedures

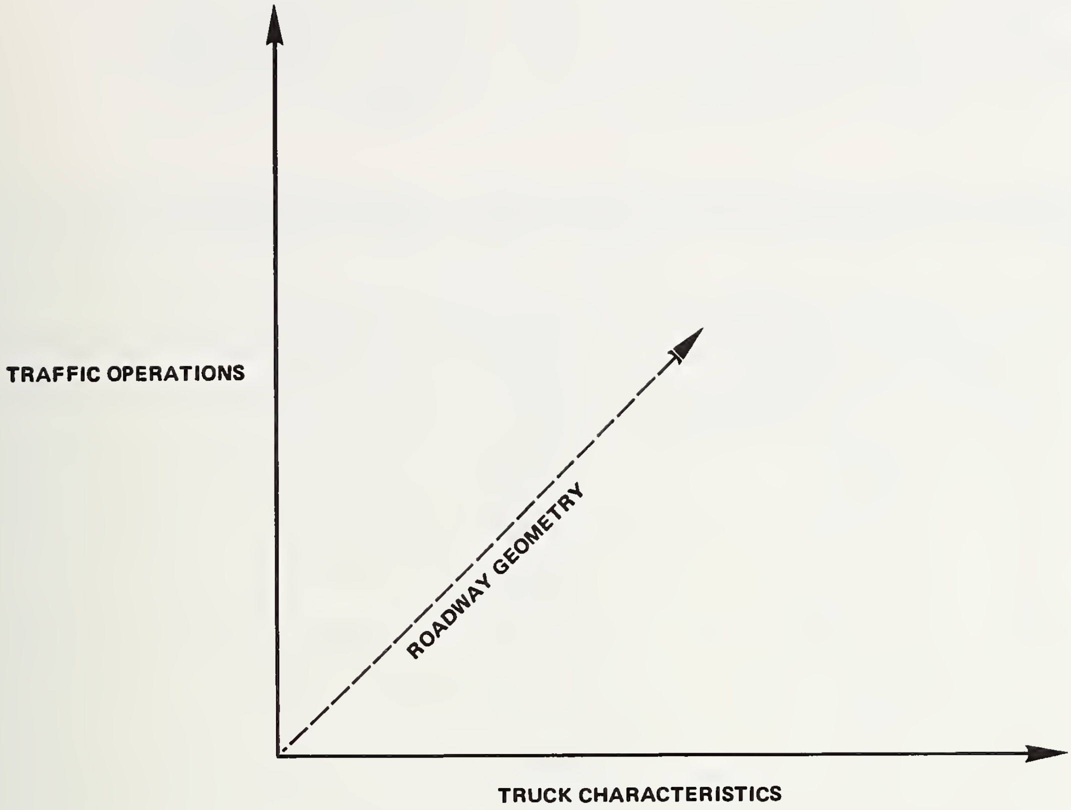


Figure 9. Diagrammatic conceptualization of analytic design.

(for example, tests of mean differences between grouped data), and levels refer to the designation of specific data sets (within or across sites) on which those procedures were brought to bear. The levels and steps are explained more fully below.

<u>Levels</u>

The three levels of analysis are:

1. Within sites
2. Across selected sites (stratified according to geometry)
3. Across all sites

The first-level analysis involved performing each statistical step separately for each site. The second level was to perform each step for specific conditions of roadway geometrics, according to the site groupings indicated below. In the third level analysis, data were collapsed across all sites.

Second-level analysis was applied to the following groupings of sites:

1.	All grades (tangent)	Sites B[*], C, G, H, I, M
2.	Upgrades (tangent)	Sites B, C, G, H
3.	Downgrades (tangent)	Sites I, M
4.	Long upgrades	Sites C, H
5.	Long downgrades	Sites J, M
6.	Short upgrades	Sites B, G
7.	Steep upgrades	Sites G, H
8.	Steep downgrades	Sites I, J
9.	Steep grades	Sites G, H, I, J
10.	Slight grades	Sites B, C
11.	Freeway sites	Sites A, B, C, G, I, J, M
12.	Nonfreeway sites	Sites D, E, F
13.	Freeway curves	Sites A, J
14.	Nonfreeway curves	Sites E, F
15.	Curves	Sites A, J, E, F
16.	Grade and curves	Sites F. J

Steps

The purpose of each step in the analysis was:

1. To examine group differences in dependent variable means. (Example: speed difference for empty versus loaded trucks.)
2. To determine correlative effects between variable sets. (Example: relationship between speed and gross weight.)

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[*] Site descriptions by alphabetical designation are found in Appendix A.

3. To predict effects for projected values of independent variables. (Example: probable impact of increased weight on speed).

The first analytic step was to determine mean differences (student *t*-test) in dependent variable measures (or traffic flow parameters) between groups of trucks. Groupings were established on the basis of independent variable measures of interest (for instance, single- versus double-trailer combinations). The grouping criteria included specified levels of independent measures, as were shown in Table 5. In all, there were 27 group comparisons. The second step consisted primarily of examining correlations between independent and dependent variables. Pearson product-moment coefficients were applied to determine the level of significance obtained in the regression. The squared value of this coefficient was useful in addressing the extent to which truck size and weight effects explained observed variations in operational measures. Finally, based on the outcome of the first two steps, the third step applied mathematical models to predict traffic flow effects for projected values of truck size and weight. Result summaries for each step in the analysis are explained in the next chapter, and a detailed discussion is presented in Chapter Four.

Table 5

Grouping Characteristics of Trucks Applied in First Analysis Step

GROUPING CRITERION	GROUP 1	GROUP 2
LOADING CONDITION	EMPTY	LOADED
CAB TYPE	CAB OVER	CAB BEHIND
TRAILER CONFIGURATION	SINGLE TRAILER	DOUBLE TRAILER
DRIVE AXLE CONFIGURATION	SINGLE AXLES	DUAL AXLES
WIDTH CONDITION	96" WIDTH	>96" WIDTH
OVERALL LENGTH	⩾ MEAN LENGTH + 1 STANDARD DEVIATION	⩽ MEAN LENGTH – 1 STANDARD DEVIATION
OVERALL LENGTH (Van Trailers Only)	SAME AS ABOVE	SAME AS ABOVE
TRAILER TYPE*	VANS	ALL TRAILER TYPES
TRAILER TYPE*	VANS	TANKERS
TRAILER TYPE*	VANS	FLATBEDS
TRAILER TYPE*	VANS	AUTO CARRIERS
TRAILER TYPE*	VANS	DUMP TRAILERS
TRAILER TYPE*	VANS	POLE/LOGGING
TRAILER TYPE*	VANS	BULK COMMODITY
HAULING CONFIGURATION*	MICHIGAN HEAVIES	CONVENTIONAL TRUCKS
HAULING CONFIGURATION*	MICHIGAN HEAVY SINGLES	CONVENTIONAL SINGLES
HAULING CONFIGURATION*	MICHIGAN HEAVY DOUBLES	CONVENTIONAL DOUBLES

* Multiple Comparisons: Loaded v. Loaded, Empty v. Empty.

CHAPTER THREE

SUMMARY OF RESULTS

Results are summarized for each of three analytic steps. The first step examined traffic operational differences between specific pairs of truck groupings (e.g. single- versus double-trailer combinations). Secondly, a correlative analysis was conducted to determine effects between truck characteristics and traffic operations variables. The third step analysis attempted mathematical modeling to predict operational effects of projected truck characteristics.

Summary of First Step Analysis

Operational effects of certain truck characteristics were determined through a series of group comparisons. Trucks were grouped according to loading conditions, length, trailer type, etc., in order to examine differences based on many measures of traffic operational performance. These measures included basic flow descriptors (e.g., closure rate, projected collision time), flow delay (e.g., speed reduction of following vehicles and queues), and passing interactions (e.g., pass probabilities, relative passing speeds). Separate group comparisons were made for the following roadway geometric conditions: upgrades (long, short, steep, slight), downgrades (long, steep, 1 mile [1.6 km] at 3 percent), curves (freeway, nonfreeway), and downgrade and curve combinations. Findings of 14 paired group comparisons based on 29 traffic operational variables for each roadway geometric condition are discussed in the next chapter.

In this chapter appear the summaries of results obtained for each geometric condition, along with a capsulized overview of the results of first-level analysis.

Table 6 summarizes selected group differences observed for certain operational variables which demonstrated insightful results pertinent to the overall objectives of the study. Truck groupings selected for this table revealed effects of weight (loaded versus empty), length (long versus short overall length), configuration (single- versus double-trailer combinations), and width (wide load versus 8-ft. [2.4 m] width.

These groupings were examined for differences on the basis of two traffic operational variables within each of five categories (flow perturbation measures, accident potential, delay, and passing interactions). The variables are:

1. Mean truck speed
2. Mean acceleration
3. Speed variance
4. Stream-speed difference (deviation of truck speed from traffic flow)
5. Critical closures (relative speed closure rates between truck and following vehicles)
6. Projected time to rear-end collision (in cases of critical closure, assuming no speed or path change)
7. Following vehicle speed
8. Following vehicle delay
9. Probability of pass occurrence
10. Relative passing speed

Observed group differences that imply a deterioration of traffic operational performance as the result of increased truck size or weight are indicated in the table. For example, the upper-left-hand cell of the table should be interpreted to mean that lower average speeds were observed on long upgrades for loaded, longer, and double-trailer combinations. In a typical case, loaded trucks averaged 7.6 mph (12.2 kph) slower than empties

Table 6

Summary of Operational Differences Between Selected Truck Groupings By Geometric Condition

		Traffic Operational Measure									
		Flow		Perturbations		Accident Potential		Delay		Passing	
		Mean Speed	Mean Acceleration	Speed Variance	Stream Speed Difference	Critical Closure	Projected Time to Collision	Following Vehicle Speed	Following Vehicle Delay	Passing Probability	Relative Passing Speed
Geometric Condition	Upgrades, long	▨ LC			▨	▨ C	▨	▨	▨	LC	▨
	short	▨ LC	▨ L	▨ L	▨	▨	▨	▨	▨		▨
	steep	▨ C	▨ LC	▨ LC	▨ C	▨	▨				▨ C
	slight	▨ C			▨	▨ C		▨	▨	L	▨
	Downgrades, long	W			▨ W	▨					
	steep	▨ WC			▨ WC	▨		▨	▨		▨ W
	3%, 1 mile										
	Curves, freeway	▨ WC			▨ WC	▨ C					▨ C
	non-freeway	▨ C									
	Grade and Curves	▨ WC			▨ WC	▨			▨		▨ C

Legend: ▨ — Loaded v. empty

L — Length (Long v. short)

C — Configuration (Double v. single trailer)

W — Width (Wide load v. standard)

(39.6 versus 46.2 mph [63.7 versus 74.3 kph]) on long grades Similar speed reductions were observed for doubles (4.3 mph [6.9 kph] slower than singles) and for longer combinations (2.8 mph [4.5 kph] slower than shorter combinations).

Operational effects of truck characteristics were seen to vary greatly across the 10 cited geometric conditions. For the upgrade condition, truck loading resulted in group differences in nearly three-fourths of the table's cells; in the cases of downgrades and curves, the impact of loading was only about one-third as great. Increased slowing due to loaded trucks on upgrades resulted in other traffic operational effects (higher speed variance, increased closure rates, and higher relative passing speeds).

The specific geometric condition where the operational consequence of truck size and weight was greatest was the short upgrade. Trucks exhibited greater deceleration and speed variance here than on long upgrades. In this situation, certain trucks began to decelerate, causing perturbative effects and speed closures among interacting traffic. In addition, following vehicles were frequently observed to be "trapped" behind slowing trucks on short upgrades, and consequently these vehicles experienced delay. They experienced less delay in the long-upgrade condition, since more time was available for vehicles to maneuver around slow trucks.

The geometric condition exhibiting the smallest operational effect of truck size and weight difference was the 3-percent, 1-mile [1.6 km] freeway downgrade. Results obtained here strongly refute the popular belief that heavier trucks tend to increase in speed on the downgrades. On the contrary, safer behavior -- in terms of slightly reduced average speeds and acceleration behavior -- was observed for certain heavy truck groupings (loaded tankers and dump-trailer combinations).

Certain truck characteristics were seen to have a greater operational effect than others. The largest effect resulted from truck loading (47 out of 100 cells in the table). As noted above, truck loading affected traffic operations most significantly at upgrade sites. For the short-upgrade condition, loading was seen to be the basis for differences in nine out of ten operational measures. Examples of loading effects at short upgrades are lower mean truck speeds (i.e., 47 mph [75.6 kph] empty; 40.5 mph [65.2 kph] loaded) and accelerations, greater speed variances and differences from mean traffic speeds (7.0 versus 3.5 mph [11.3 versus 5.6 kph]), more critical rear-end closure rates (17 versus 10 ft/second [5.2 versus 3.0 m/sec]) and projected collision times (31 versus 54 seconds), greater speed delay (46 versus 52 mph [74.0 versus 83.7 kph]) to following vehicles, and higher relative passing speeds.

The effect of truck configuration, in terms of single- versus double-trailer combinations, was much less notable (20 out of 100 cells) than the effect of loading. Loaded doubles often exhibited lower mean speeds (7 out of 10 cited geometric conditions), and this effect is interpreted to be a residual of their higher gross weight. The sample (N = 2954) average gross weight for loaded doubles was 64,100 pounds (29.1 Mg) compared to 49,700 pounds (22.6 Mg) for loaded singles. Slightly reduced average speeds (47.3 versus 50.1 mph [76.1 versus 80.6 kph]) for doubles were observed across all sites; however, loaded doubles averaged 12.8 mph (20.6 kph) slower than loaded singles in the data set describing all upgrade sites. Adverse effects of doubles were most pronounced in the steep-upgrade and the freeway-curve situations. In each, doubles were associated with higher deviations from average traffic speed, higher critical closure behavior with following vehicles, and higher relative speeds by passing vehicles than were single-trailer combinations.

The effect of overall length was examined in this analysis by designating groups of long and short trucks. The division was based on a variation of at least one standard deviation from mean length, in either direction. Relatively little adverse impact (8 out of 100 cells) was observed for length, and this effect was seen solely at upgrades. Again, these operational differences are considered to be residual effects of weight, since the gross weights were significantly higher for longer trucks in both the loaded and empty conditions. The operational effects found for longer trucks on upgrades were lower mean speeds (37.9 versus 41.5 mph [61.0 versus 66.8 kph]), degraded acceleration performance, higher speed variance, and higher relative speeds of passing vehicles.

The effect of width was determined through group differences between standard 8-ft. wide (2.4 m-wide) trucks and those carrying wide loads. No gross-weight differences existed between these two groups; therefore, observed effects were attributable solely to truck size. In contrast to the weight effects noted before, which were predominantly evident at upgrade sites, the operational impact of wide loads was observed exclusively at downgrade and curve sites. The lower mean speeds of wide loads resulted in two other operational effects: higher deviations from mean traffic speeds and higher relative speeds by passing vehicles. Drastic speed reductions (e.g., 30 mph [48.3 kph] below average traffic speed) on the part of wide loads were noted in some cases. The small size of the wide-load truck sample precluded an accurate assessment of operational effects associated with close following by other vehicles (e.g., critical closure rates).

Certain traffic operational measures were more sensitive than others to increased truck size and weight. The greatest effect was seen in mean truck-speed differences. Mean speed was impacted by some measured truck characteristics in all geometric conditions, with the single exception of the 3-percent, long downgrade. Loaded trucks exhibited lower mean speeds than empties on all geometric conditions except long downgrades. Double-trailer combinations were observed to be slower than singles in seven of the 10 cited geometric conditions.

The significance of mean truck speed as a measure of size and weight effects was seen in other applied operational measures. For example, truck groupings observed to exhibit lower mean speed were frequently found to show higher deviations from mean traffic speeds, thus creating a perturbative effect. This measure, stream-speed difference, gave differential results for various truck characteristics in 8 of the 10 geometric conditions cited in the table. Loaded trucks were observed to exhibit larger stream-speed differences in all eight cases. Another operational effect observed for trucks exhibiting lower mean speeds is that they were likely to be passed at a high speed. Higher relative passing speeds were seen for loaded (by comparison with empty) trucks in 7 of the 10 geometric conditions.

Following are summaries of the first step analysis for specific geometric conditions.

Long and Short Upgrades

Typical of the upgrade condition, lower mean speeds were observed for loaded and longer trucks. This effect was more pronounced on long grades and accentuated by increased steepness, with the lowest speeds being exhibited by loaded tankers, dump trailers, Michigan heavy-duty trucks, and double-trailer combinations. Loaded trucks demonstrated higher levels of deceleration on short grades than did empties, but this effect was not found at long-grade sites, because of the more frequent onset of crawl speeds. It was found that no headway or tailway differences had implications for increased size and weight.

Various truck-group comparisons revealed flow perturbative differences. In a few cases, trucks were observed to accelerate on long grades, but, not surprisingly, these were usually empty trucks. At short grades, loaded trucks often decelerated to an extent which caused significant variance in their speeds. Although this deceleration effect was much less pronounced at the long-grade sites, higher stream-speed differences were observed for many types of loaded trucks.

Group differences based on measures of accident potential showed that loaded trucks were more prone to higher rear closure rates and shorter projected times to collision. Trucks with lower power-to-weight ratios also tended to exhibit high rear closure rates.

Increased flow delay was found to be associated with loaded trucks. Reduced speeds and increased delay were observed both for single following vehicles and queues behind loaded trucks. Greater delay was observed for the short grade condition. Although few group differences were observed in terms of pass-occurrence probability, higher relative speeds were observed when loaded trucks were being passed on long grades.

In addition to specific truck-group differences associating traffic operational effects with truck characteristics, certain operational differences found between short and long grade-length conditions gave insights as to which roadway geometric was the more conducive to truck size and weight effects. It was found that greater operational consequences are realized at short-grade sites. Although mean truck speeds were not always shown to differ between short and long grade-length conditions, greater deceleration was consistently found for trucks at shorter grade conditions. This behavior impacted other operational measures. First, greater speed variance was observed for trucks at short-upgrade sites. Second, more critical projected times to collision resulted from interaction with following vehicles. Third, because vehicles were often "trapped" behind slowly moving trucks at short-grade sites, lower speeds were observed for following vehicles than at the long-grade sites. This resulted in greater speed delays for vehicles and queues. However, under existing conditions, traffic was generally able to maneuver around slowly moving trucks, as evidenced by relatively little truck-following behavior at the long-grade sites. The overall effect was that minimal travel-time delay accrued to the total traffic stream as the result of trucks slowing on upgrades.

Slight and Steep Upgrades

Speeds averaging from 6 to 10 mph (9.6 to 16.1 kph) lower, depending on steepness, were seen for loaded trucks in comparison with empties. Increased levels of deceleration were seen to accompany the lower speeds of loaded trucks. This slowing effect was also in evidence with longer trucks, especially double-trailer combinations on steep grades. Certain other truck components as well (i.e., tankers and dump trailers, single drive-axle tractors) were associated with pronounced slowing behavior. Truck characteristics similar to those cited above contributed to high-speed variance on steep upgrades. The extent of trucks' slowing on grades in relation to other traffic (stream-speed differences) was highly associated with weight-related features (loading condition, trailer type, etc.) and to a much lesser degree, with truck size and horsepower-to-weight ratio.

Not surprisingly, slowing of trucks on upgrades resulted in closure interactions with following vehicles and a consequent read-end accident potential. The highest closure rates were observed behind loaded trucks, double-trailer combinations, tankers, and dump trailers. Projected times to rear-end collisions, assuming no speed or path corrections, for vehicles following loaded trucks, indicated a greater likelihood of accidents on steep grades (25.4 seconds, average) than on slight grades (68.3 seconds, average). This accident measure was validated during our data collection effort when a serious accident (involving a loaded truck exhibiting a projected rear-collision time of 14 seconds) occurred on a steep upgrade.

Flow delay to other vehicles in the traffic stream also resulted from trucks slowing on upgrades. Speed delays of 7.8 mph (12.5 kph) compared to traffic flow speeds were observed for vehicles following loaded trucks on upgrades. The largest speed delays, averaging 15 mph (24.1 kph) were exhibited by vehicles and queues following heavy-duty double combinations on slight grades in Michigan; however, since vehicles were able to maneuver past the heavy-duty rigs, they were not found to disproportionately impact total stream travel-time delay. It follows that high relative passing speeds were observed for this truck type. In general, residual weight effects increased passing probability and relative passing speed.

Long Downgrades

A number of operational differences between groups of trucks were observed at the long-downgrade sites. Lower mean speeds were noted for loaded tankers, single drive-axle tractor combinations, and trucks transporting wide loads. Single drive-axle rigs followed other vehicles at shorter headways than did those with dual drive axles. Most of the flow perturbations resulted from speed reductions. Greater stream-speed differences were noted for those trucks exhibiting lower mean speeds. Of these, loaded trucks (especially tankers) were likely to exhibit speeds slower than one standard deviation below the mean. However, dual drive-axle rigs frequently drove at least one standard deviation above the mean speed.

Few differences in rear-end accident potential emerged. Loaded trucks (especially tankers) exhibited high rear-closure rates with following vehicles, yet these did not result in critically reduced times to projected collision. No flow-delay differences were found between truck groupings. Certain loaded truck types were associated with increased passing activity. A small sample of dump-trailer combinations were all passed by other vehicles, and high relative passing speeds were associated with loaded tankers and flatbeds.

Steep Downgrades

The primary operational effect of truck size and weight on steep grades resulted from slowing of heavier trucks. In addition, trucks with wide loads slowed dramatically. The perturbative effects of this slowing were large variations from mean traffic speeds. Specific truck types associated with this behavior were loaded double-trailer combinations, tankers, and flatbeds. Limited rear-end accident potential was observed. Higher rear closure rates from following vehicles were seen for loaded trucks (especially tankers), however, no adverse effect was seen for projected times to collision. The slowing of heavier trucks did result in speed reductions and flow delay to following vehicles and queues. Higher relative speeds were observed for vehicles passing loaded trucks (especially tankers) and trucks which carried wide loads.

Three-Percent, One-Mile Downgrade

Generally, no differences were noted between truck groupings for most operational measures. In fact, a few differences implied safer behavior as a consequence of larger truck size and weight (e.g., lower acceleration/deceleration with certain heavier trucks). Two group differences did appear. Larger deviations from mean traffic speeds were found to be associated with higher truck weight and lower horsepower-to-weight ratio. However, a comparison of these results with data gathered in the total study revealed that the differences were due to safer behavior on the part of some truck types (e.g., dual drive axle combinations) rather than more hazard-producing behavior on the part of others. The interpretation of these results is that no adverse effect of increased size and weight was found at the 3-percent, long-downgrade site.

Freeway Curves

Operational effects of size and weight in freeway curves came about primarily from slowing of heavier trucks. The magnitude of the speed differences was small; for instance, loaded trucks averaged 3.4 mph (5.5 kph) slower than empties. The small sample of wide-load trucks exhibited drastically reduced speeds (30 mph [48.3 kph] average); however, the limited size of the sample precluded definitive assessments of their perturbation effects. The following truck types were seen to slow down because of their weight: loaded trucks, double-trailer combinations, heavy-duty Michigan rigs, and loaded tankers and flatbeds. Perturbative effects resulted for most of the above truck types, in the form of higher mean stream-speed differences and the increased likelihood of their driving substantially below the mean traffic speed. However, negligible delay was imparted to other vehicles in the stream. Lower truck speeds did result in certain types being passed by other vehicles at higher relative speeds.

Few group differences were observed on the basis of rear-end accident potential. Loaded double-trailer combinations did exhibit higher closure rates than singles with both following and leading vehicles; their closures did not, however, result in more severe projected times to collision.

In summary, operational effects of truck size and weight on freeway curves were limited to minimal slowing of certain truck types and appeared to have marginal safety consequences.

Non-Freeway Curves

There was very little indication from the group differences that increased truck size and weight yielded any adverse operational effects in nonfreeway curve situations. Minimum slowing of loaded trucks compared to empties (51.6 mph versus 55.9 mph [83.0 versus 90.0 kph]) was insufficient to cause either delay to other vehicles or significant flow-perturbative effects. The primary perturbative effects observed for loaded trucks was high acceleration rate. Larger and heavier trucks were seen to exhibit generally safe behavior in terms of rear-end accident causative behavior. No passing interaction differences were available due to site geometrics and small sample size.

Grade and Curve Combinations

Lower speeds of about 5 mph (8.0 kph) were exhibited by certain larger and heavier truck types (loaded trucks, wide loads, and loaded double-trailer combinations, takners, and flatbeds). These lower truck speeds resulted in a perturbative effect: greater deviations from the average traffic speed. Two other measured residuals of the lower speeds were: (1) these trucks were passed at higher relative speeds, and (2) increased speed delay was experienced by both single vehicle and vehicle queues following loaded trucks.

Few rear-end accident potential differences were observed. Slightly more dangerous following behavior was associated with loaded trucks, in terms of higher front and rear closure rates, yet these did not result in more severe projected collision times. In addition, higher rear closure rates were observed with cab-over than with cab-behind tractor combinations.

Summary of Second Step Analysis

This step involved a correlative analysis of effects between certain truck characteristics (gross weight, overall length) and traffic operational variables. Detailed results of this analysis, in the form of 44x44 correlation matrices, appear in Appendix E, and a more detailed discussion of these results follows in Chapter Four.

Correlative Effects of Gross Weight

Table 7 summarizes significant correlations obtained between gross weight and traffic operational variables for three geometric conditions: upgrades, downgrades, and curves. Regression coefficients were derived for gross weight against each of twenty operational variables. Coefficients included in the table are significant at the .001 level. The number of significant correlations obtained for each geometric condition provides an indication of the relative gross weight impact across conditions.

Upgrades. Four sites of varying geometry (short, long, slight, steep) contained a sample of 2,065 observations. The primary operational effect of lower speeds exhibited by heavier trucks was generally strong (e.g., typical r=.60) on the bases of within-site data. The combined-sites correlation in the table is lower due to speed variation (and nearly equal weight

Table 7

Summary of Significant Correlation Coefficients (r) Obtained Between Gross Truck Weight and Operational Variables (α ≤ .001)

Upgrades	Downgrades	Curves
Mean Speed (-.27)	Mean Speed (-.11)	Mean Speed (-.30)
Stream Speed Difference (.45)	Proportion Slower (.16)	Stream Speed Difference (.22)
Maximum Acceleration (-.27)	Maximum Deceleration (.17)	Proportion Slower (.17)
Speed Variance (.16)	Rear Closure Rate (.20)	Rear Closure Rate (.18)
Proportion Slower (.38)	Relative Passed Speed (.20)	Relative Passing Speed (-.15)
Rear Closure Rate (.24)	Relative Passing Speed (-.34)	
Follow Vehicle Speed (-.27)		
Follow Vehicle Delay (.33)		
Follow Queue Speed (-.26)		
Follow Queue Delay (.32)		
Relative Passed Speed (.31)		

distributions) between sites, yet the relation showing speed reductions below traffic stream means for heavier trucks remained fairly strong (r=.45). The tendency for heavier trucks to travel at least one standard deviation below traffic mean speeds was demonstrated by a significant r of .38 which was also typical of within-site findings. This data set revealed weak tendencies for heavier trucks to exhibit higher speed variance (r=.16) and reduced acceleration performance (r=-.27). That heavier trucks created more traffic delay was highly evident in this analysis. Correlations between gross weight and four operational variables demonstrated that lower speeds and greater delays (relative to overall traffic flow) were experienced by both single vehicles and vehicle queues which followed heavier trucks. Two additional perturbative operational effects, increasing with gross weight, were that higher closure rates arose from interactions with following vehicles and higher relative speed differentials resulted from passing vehicles.

Downgrades. Three geometric conditions (i.e. 3-percent, long; steep; and long) are included in the sample of 1,750 observations. Although the impact of gross weight on operational performance was considerably less evident than shown for upgrade conditions, the effects were similar. That is, higher gross weights were found to be associated with: lower mean truck speeds (r=-.11), a greater probability that these speeds will be significantly below the traffic mean (r=.16), increased closure rates with following vehicles (r=.20), and higher relative passing speeds when passed by other vehicles (r=.20). An additional effect of higher weight, which was logically not observed at upgrade sites, was that heavier trucks exhibited more pronounced deceleration behaviors. Also, in cases of trucks passing other vehicles at the downgrade sites, lower relative passing speeds were evident for higher gross weights.

It should be noted that certain results suggested safer behavior (e.g., lower rear closure rates at the 3-percent site) on the part of heavier trucks. In summary, relatively few adverse operational effects of gross weight were observed at the downgrade sites. The effect observed across sites having the greatest safety implication was more dangerous closure rates from vehicles following the heavier trucks. While this result was observed for vehicles following at headways of 10 seconds, the effect was not evident for following times of 1 or 2 seconds. Additionally, the increased closure rates did not produce less safe projected times to collision.

Curves. Four sites, comprised of freeway and nonfreeway curves, yielded a sample of 1,403 observations. Based on this data set, five operational variables were found to significantly correlate with gross weight. Observed operational effects of increased weight were similar to those previously noted. That is, heavier trucks were found to be associated with lower speeds (r=-.30), higher speed differentials from stream averages (r=.22), and a slight tendency to travel slower than the traffic mean speed (r=.17). A weak effect (r=.18) was that more dangerous rear closure rates were associated with heavier trucks, however this result did not produce shorter projected collision times. A similarly slight trend (r=-.15) existed for heavier trucks to pass other vehicles at lower relative speeds. The interpretation of these results is that increased gross weight had relatively little effect, hence negligible adverse safety impact, on traffic operations at curve sites.

Correlative Effect of Overall Length

Table 8 illustrates that little effect was evident based on correlations between overall truck length and traffic operational measures. Significant findings of this analysis

Table 8

Summary of Significant Correlation Coefficient (r) Obtained Between Overall Truck Length and Operational Variables ($\alpha \leqslant .001$)

Upgrades	Downgrades	Curves
Mean Speed (-.14) Mean Acceleration (-.28) Speed Variance (.17) Maximum Deceleration (-.22)	(no significant r)	(no significant r)

were limited to upgrade sites where weak correlations (r ranged from .14 to .22) demonstrated slight tendencies for longer trucks to travel more slowly with higher variances and exhibit poorer acceleration and deceleration behaviors. These effects, though minimal in nature, are likely residuals of increased weight. This supposition, which is supported by a high positive correlation between weight and length in combination with the weak operational relationships, leads to the interpretation that overall length has a negligible effect on traffic operations.

Summary of Third Step Analysis

This step developed and applied a model to predict effects of increased weight on operational performance. A detailed discussion of results and procedures appears in Chapter Four. The model developmental attempt explored relationships between all independent (truck characteristic) and dependent (traffic operational) variables. This developmental effort initially postulated a conceptual model of applicable vehicle behavior and then examined plots and mathematical relationships for goodness of fit. Results of the developmental procedure were that, due to poor correlations between most variables, predictable relationships existed only for gross weight and truck speed at upgrade sites.

Examination of various mathematical approaches concluded that the logarithmic curves illustrated in Figure 10 comprised the best models. Solid lines in these plots indicate weight ranges over which data were collected in this study: dotted lines indicate projected speed reductions associated with increased weight.

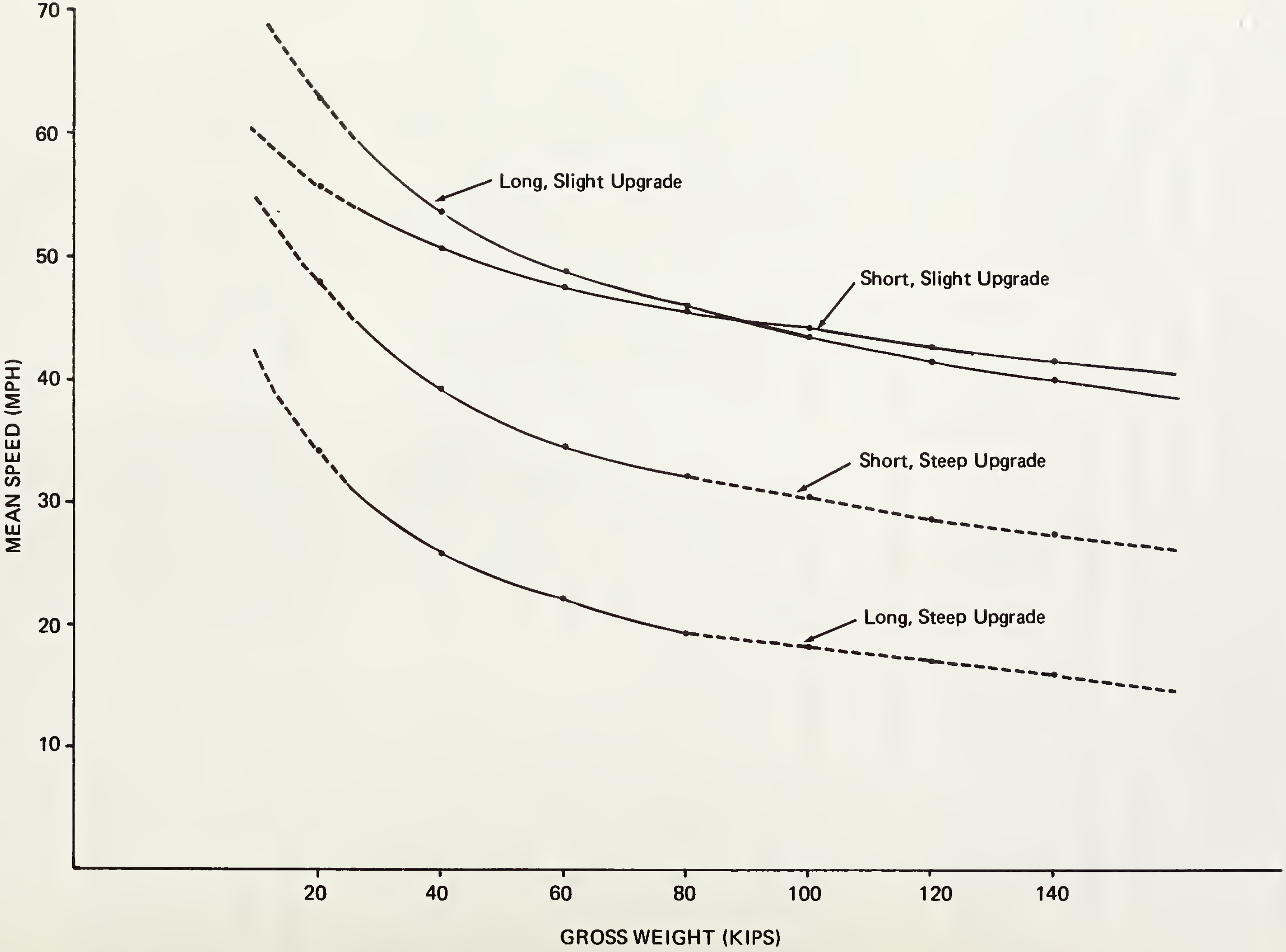

Figure 10. Model forms developed from regression analysis of speed-versus-weight relationships.

Application of the models to predict changes in truck speed as a function of increased weight can be seen in the following example. Assuming currently allowable gross weight of 67,000 pounds (30.4 Mg), and projected weights of 90,000 and 160,000 pounds (40.8 and 72.6 Mg), calculated truck speeds for each geometric condition are as follows:

	*Speed @67K	*Speed @90K	*Speed @160K
Short, slight upgrade	46.9 (75.5)	44.9 (72.2)	41.1 (66.1)
Long, slight upgrade	47.6 (76.6)	44.5 (71.6)	38.9 (62.6)
Short, steep upgrade	33.9 (54.5)	31.1 (50.0)	26.5 (42.6)
Long, steep upgrade	21.3 (34.3)	19.0 (30.6)	15.2 (24.5)

The modeled effect is that a 23 kip (10.4 Mg) increase in gross weight causes an average (across conditions) speed reduction of 2.6 mph (4.2 kph), while a 93 kip (42.2 Mg) increase results in a 6.8 mph (10.9 kph) reduction. The effect of these weight increases is most pronounced at the long, slight upgrade (3.1 mph [5.0 kph] and 8.7 mph [14.0 kph] reductions): the next most severe reduction is evident at the short, steep upgrade (i.e., 2.8 mph and 7.4 mph [4.5 and 11.9 kph]).

However, to assess the practical significance (i.e., safety implication) of the modeled effects, one must bear in mind the low r^2 values associated with the regression models. A typical obtained r^2 of .02 means that only 20 percent of the observed variance in truck speed is accounted for using the prediction model based on gross weight.

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*Speeds are noted in mph (kph).

CHAPTER FOUR

DATA ANALYSES

First Step (Group Comparison) Analysis

The first step analysis examined certain operational differences between selected groupings of trucks. These findings are summarized in tabular form for specific geometric conditions shown in Table 9. Differences between the groupings were determined on the basis of 60 variables describing traffic operational effects and truck characteristics. The Student *t*-test was used to examine significance levels of mean differences among the variables.

Over 20,000 applied *t*-tests are detailed (group means, values of the *t* statistic, significance levels, etc.) in Appendix D. This chapter provides a condensed interpretation of those voluminous test results. In cases where, using the *t*-test, differences were found to be significant and otherwise statistically meaningful (that is, the power of the test was confirmed where a strong predictive association existed between variable sets -- Hayes, 1963), that fact is indicated by an entry in the appropriate cell of the summary tables. Directionality of the difference is also shown; an "up" arrow indicates that the first group cited demonstrated a larger value of the measure than did the second. For example, in Table 9, the upper-left arrow (comparing mean speed differences for "empty" versus "loaded" trucks) indicates that empty trucks exhibited higher speeds than did loaded trucks. Shaded cells indicate differences having adverse implications for increased truck size and weight.

All Grade Sites

Table 9 gives the results of group differences obtained across all tangent grade sites. This data set is comprised of 3,140

Table 9
Observed Differences Between Truck Groupings at All Grade Sites (N=3140)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	↑ ▨					↓ ▨						↓ ▨		
	Mean Acceleration					↑ ▨									
	Headway														
	Tailway														
	Lateral Placement							↓			↕ ▨				
	Flow Pertubations														
	Maximum Acceleration														
	Maximum Deceleration												↑		
	Speed Variance	↓ ▨				↓ ▨							↑ ▨		
	Acceleration Variance														
	Stream Speed Difference	↓ ▨													
	Proportion Slower	↓ ▨	↑ ▨					↑		↑ ▨			↑ ▨		
	Proportion Faster														
	Driver Effort	↑	↑ ▨												
	Rear-End Accident Potential														
	Critical Headway														
	Critical Tailway														
	Front Closure Rate							↓							
	Rear Closure Rate	↓ ▨				↓ ▨	↑ ▨	↑ ▨		↑ ▨			↑		
	Projected Time to Collision (front)					↓					↓				
	Projected Time to Collision (Rear)									↓ ▨					
	Flow Delay														
	Queue Length														
	Following Vehicle Speed	↑ ▨						↓ ▨							
	Following Vehicle Delay	↓ ▨						↑ ▨							
	Following Queue Speed	↑ ▨						↓ ▨							
	Following Queue Delay	↓ ▨						↑ ▨							
	Passing Interactions														
	Probability of Being Passed														
	Probability of Passing	↑ ▨				↑									
	Relative Speed Being Passed	↓ ▨				↓ ▨		↑ ▨		↑ ▨			↑ ▨		
	Relative Passing Speed	↑ ▨				↑ ▨									
Truck Characteristics	**Weight**														
	Gross Weight	↓			↑		↓		↑						↑
	Front Axle Weight		↑		↑	↓	↓	↑	↑	↑	↑	↑	↑		↑
	Maximum Axle Weight				↑	↑	↓	↑	↑	↑	↑	↑	↑		↑
	Empty Weight (Estimated)	NA			↑	↓	↓	↑	↓	↑	↑	↑	↑	↑	↑
	Payload	↓			↑	↓	↓	↑	↓	↑	↑		↑	↑	↑
	Loading Condition			↑	↑										
	Size														
	Wheelbase				↑		↓		↑	↑	↑		↑		↑
	Overall Length	↑	↑		↑		↓		↑	↑	↑		↑		↑
	Wide Load	↓									↑				
	Number of Trailers				↑	↓			↑	↑	↑		↑		↑

Legend: ↑ Higher value for first group.
▨ Adverse Implication for increased size and weight.

observations across six sites, four upgrade and two downgrade, varying in length from 0.5 to 1.5 miles (0.8 to 2.4 km) and in grade steepness from 2 percent to 7 percent. The average gross weight for trucks in the sample is 48,400 pounds (22.0 Mg), and the sample contained trucks weighing up to approximately 150,000 pounds (68.0 Mg). Later sections of this chapter discuss results for more specific grade conditions.

Differences discussed here are generally those found to be significant at the .001 level, assuming the *t*-tests proved sufficiently powerful that at least one percent of the variance in the operational data could be attributed to changes in the truck groupings. In certain tests involving limited sample sizes (e.g., passing interactions, close following), sufficient statistical power was obtained at lower significance levels. In any event, the .05 level is considered the minimum significant group difference.

Basic Flow Descriptors. In Table 9, various categories of traffic operational characteristics are examined separately for differences among pairs of truck groupings. The first category, basic flow descriptors, demonstrates certain expected differences for grade-site conditions. Empty trucks are shown to exhibit higher mean speeds than loaded trucks (50.0 versus 45.4 [80.4 versus 73.0] kph), with lower mean speeds observed for loaded dump-trailer trucks, heavy duty, multiple-axle rigs unique to Michigan, and trucks characterized by tractors with single (as opposed to dual) drive axles. These lower speed effects probably resulted from the higher gross weights of the loaded truck groupings and from the lower horsepower-to-weight ratio of the single drive axle group. The lowest group mean speed, 37.6 mph (60.5 kph), was observed for loaded dump-trailer combinations, which averaged 84,700 pounds (38.4 Mg) by gross weight. The lighter weight of empty trucks apparently accounted for lower observed levels of deceleration on grades for empty single-trailer combinations, in comparison with empty doubles. Additionally, loaded dump-trailer trucks were more prone to high mean levels of deceleration on grades than were loaded van-trailer trucks. (Van trailers were used as a standard in gauging the traffic impact of other specific trailer types -- for example, tankers and flatbeds.

Flow Perturbations. The second category of traffic operations measures, flow perturbations, revealed numerous group differences. Higher maximum values of deceleration observed for dump-trailer trucks (as compared to van-trailer combinations) were consistent with the mean deceleration difference already noted between these two groups. Loaded trucks exhibited greater speed variance than empty trucks (3.1 versus 1.7 mph [5.0 versus 2.7 kph]); this effect was particularly evident for loaded double-trailer combinations (4.8 mph [7.7 kph]) and dump-trailer trucks (8.0 mph [12.9 kph]). Additionally, empty doubles were seen to exhibit higher levels of speed variance than empty singles.

A strong indicator of a vehicle's contribution to flow perturbation is its deviation from mean traffic flow speeds. All trucks in the sample averaged 5.8 mph (9.3 kph) slower than the total stream (corrected for time-of-day and volume-density effects). However, the speed difference for loaded trucks (7.4 mph [11.9 kph]) was significantly greater than that for empty trucks (2.8 mph [4.5 kph]). It was found that 55 percent of loaded trucks traveled at least one standard deviation below the mean speed, while only 29 percent of the empty trucks did so -- a significant difference. Heavy-duty, multiple-axle trucks (contained in the Michigan sample) contributed most heavily to this effect. A full 95 percent of the leaded Michigan heavy-duty doubles met the "one standard deviation below the mean speed" criterion, compared to 50 percent of the loaded conventional double-trailer trucks in our overall sample of 430 loaded double rigs on grades. Of all trailer types, the ones that most often fell into the category were loaded tankers (71%) and loaded dump trailers (79%).

The final perturbative measure, Driver Effort (DE), is the product of speed and displacement changes for specific vehicles on a section of highway. This measure showed two differences between truck groupings that carry conflicting implications for increased truck size and weight. Empty trucks exhibited higher values of DE more frequently than did loaded trucks, indicating that loads have some stabilizing effect on a truck's flow characteristics in grade situations. On the other hand, trucks with cab-over tractors (which were designed to accommodate larger loads than cab-behind tractors) were also seen to exhibit higher values of DE.

Rear-end Accident Potential. The next traffic operational category, rear-end accident potential, examines critically close following distances, associated relative speed closures, and projected times to collision -- assuming no speed or path correction from the time the closure measure is taken. Findings are as follows.

No differences in critical headway or tailway were shown; however, many closure-rate differences could be seen among various pairs of truck groupings. Empty heavy-duty Michigan trucks exhibited safer closure rates behind leading vehicles than did empty conventional-type trucks. However, closure rates of vehicles following trucks held a greater accident potential for many types of heavy trucks. A comparison of empty versus loaded trucks showed a strong tendency toward higher rear closure rates (9.4 ft/sec versus 14.6 ft/sec [2.9 m/sec versus 4.5 m/sec]) with loading. This same tendency was shown in group comparisons for both empty and loaded double-trailer combinations and the following truck types when loaded: tankers, flatbeds, dump trailers, and Michigan heavies. The apparently lower horsepower capabilities of the lighter, single drive-axle tractors resulted in higher rear closure rates than the dual drive-axle rigs exhibited.

Given closure rates and following distances, projected times to collision could be calculated and applied as measures of accident potential. In cases of trucks following other vehicles (front collision potential), loaded single-trailer combinations tended to show greater hazard with shorter projected collision times than loaded doubles. The same relationship held true for empty flatbeds and empty vans. Neither of these two results contains adverse implications for increased truck size and weight. However, loaded tankers had short projected collision times for following vehicles (rear collision times) more often than did loaded van combinations.

<u>Flow Delay</u>. The next traffic characteristic category deals with the effects of trucks on flow delay. As shown in the table, effects were found in the comparison of empty-versus-loaded truck and group differences involving Michigan heavies. Convincing evidence (power of *t*-test, sample size) demonstrated that loaded trucks impede other traffic on grades. Vehicles following loaded trucks* (*N*=105) were seen to average 51 mph [82 kph]), while those behind empty trucks (*N*=120) averaged 55 mph (88.5 kph). Statistically, an even stronger result was that these groups of vehicles differed in the speeds they could have attained (correcting for time-of-day, volume-density effects) had they not been captive behind trucks. Estimates of speed delay consisted of calculating the difference between the actual speeds of the vehicles and the mean for all traffic at the time of the observation. The result obtained was that vehicles following empty trucks were slowed by 2.8 mph (4.5 kph), on the average, compared to an average 6.9 mph (11.1 kph) reduction for vehicles following loaded trucks. A similar analysis was performed on queues of vehicles following trucks. It was shown that although the queues behind loaded

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*A headway criterion of 1.24 sec was used to identify following and queued vehicles behind trucks.

trucks were not significantly longer than those behind empty trucks, speed reductions and speed delays were nearly identical with those that occurred when single vehicles were following trucks. The delay effect was most pronounced for queues following double-trailer Michigan heavy trucks. This vehicle group experienced an average speed delay of approximately 15 mph (24.1 kph).

Passing Interactions. The final category of traffic operations variables describes passing interactions. Probabilities of passing occurrences were determined from the relative positions of interacting vehicles and trucks as they traversed instrumented sections of the roadway. For the 74 percent of the total truck sample that was observed in the right-hand lanes, no significant differences among truck groups existed in the probabilities of their being passed. However, certain differences existed in the relative speeds at which they were passed. Trucks being passed at higher speeds were more likely to be loaded than empty; more often had dual, rather than single, drive axles; and were frequently loaded Michigan heavies, tankers, and dump trailers. Of those trucks traveling in the passing lane, more empty than loaded and more single than dual drive-axle rigs were likely to be passing other vehicles. The passing speeds of these truck groupings were shown to be higher than those of other groups with which they were paired for comparison.

Summary. Numerous differences between truck groupings were revealing in terms of an operational impact on grades. Loaded trucks, as a result of their rather dramatic slowing on grades, proved more likely than empty trucks to affect other traffic by causing higher speed closure rates and increased speed delay to following vehicles. Moreover, loaded trucks were passed more frequently and at higher relative passing speeds. Similar effects were associated with certain other truck characteristics. Except that they caused less speed delay for following vehicles, double-trailer and lower horsepower combinations (single rather than dual drive axles) impacted other traffic in a nearly identical manner. Certain truck types exhibited operational differences. The most adverse effects were associated with loaded, multi-axle Michigan heavy-duty trucks tankers and dump-trailer combinations. Noteworthy examples are that (1) vehicles following heavy-duty, double-trailer combinations in Michigan averaged speed delays of approximately 15 mph (24.1 kph), and (2) three-quarters of all observed loaded tankers and dump-trailer combinations exhibited speeds at least one standard deviation below the mean for the traffic stream. Negligible effect was observed for auto carriers, pole/logging trucks, and bulk commodity vans. In general, adverse impacts on traffic flow exerted by specific truck types appeared to be a result of high gross weight or low horsepower-to-weight ratio.

Upgrades: The Effect of Steepness

Results of combined data across all upgrade sites are shown in Table 10. Because of certain inherent differences in size and site characteristics (for example, heavier trucks in Michigan and steeper grades in California), it was not possible to derive valid results for all truck-group comparisons in this data set. Only those group differences not invalidated by site inconsistencies are depicted in the table. However, simultaneous treatment of separate data sets obtained in Michigan (slight upgrades) and California (steep upgrades) eliminated confounding effects in the analysis. Results of the group comparisons for these two data sets are contained in Tables 11 and 12. Collective interpretation of the three data sets rendered findings that describe the effects of truck characteristics in steep, slight, and all upgrade situations. The effect of grade length is treated in a subsequent section of this chapter.

Table 10

Observed Differences Between Truck Groupings at All Tangent Upgrade Sites (N=2065)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑			▨ ↓	▨ ↑	▨ ↓	NA		▨ L↓	▨ L↓	↓ E	▨ L↓	—	
	Mean Acceleration				▨ ↓	▨ ↓		│		▨ L↓			▨ ↓	—	
	Headway							│						—	
	Tailway					↓		│							
	Lateral Placement	—	—	—	—	—	—	▼	—	—	—	—	—	—	—
	Flow Perturbations														
	Maximum Acceleration	▨ ↑					↓ E	│						—	▨ ↓
	Maximum Deceleration	▨ ↑	▨ ↑		▨ ↓		▨ L↓	│		▨ ↓		↓ E		—	
	Speed Variance	▨ ↓			▨ ↑			│		▨ ↑			▨ ↑	—	
	Acceleration Variance	↑						│						—	↑ E
	Stream Speed Difference	▨ ↓					▨ ↓	│	▨ L↓	▨ L↑	▨ L↑		▨ L↑	—	▨ L↑
	Proportion Slower	▨ ↓						│		▨ L↑			▨ L↑	—	
	Proportion Faster	▨ ↑						│			↑ E			—	
	Driver Effort	—	—	—	—	—	—	▼	—	—	—	—	—	—	—
	Rear-End Accident Potential														
	Critical Headway							│						—	
	Critical Tailway				↑			│						—	
	Front Closure Rate							│						—	
	Rear Closure Rate	▨ ↓			▨ ↑	▨ L↓ E		│		▨ L↑			▨ L↑	—	
	Projected Time to Collision (Front)							│			↓ E			—	
	Projected Time to Collision (Rear)	▨ ↑				▨ L↑		▼		▨ ↓				—	
	Flow Delay														
	Queue Length							│						—	
	Following Vehicle Speed	▨ ↑						│			▨ L↓			—	
	Following Vehicle Delay	▨ ↓						│						—	
	Following Queue Speed	▨ ↑						│			▨ L↓			—	
	Following Queue Delay	▨ ↓						▼						—	
	Passing Interactions														
	Probability of Being Passed					↓ E		│						—	
	Probability of Passing					▨ L↑	↑	│						—	
	Relative Speed Being Passed	▨ ↓				▨ L↓		│		▨ L↑			▨ L↑	—	
	Relative Passing Speed	▨ ↑						▼						—	
Truck Characteristics	**Weight**														
	Gross Weight	↓			↑	L↓	↓	│	↑	↑	↑		↑	—	↑
	Front Axle Weight		↓		↑		↓	│	↑	↑	↑	↑	↑	—	↑
	Maximum Axle Weight	↓	↑		↑	↑	↓	│	↑	↑	↑		↑	—	↑
	Empty Weight (Estimated)	↑			↑		↓	│	↑	↑	↓		↑	—	
	Payload	↓			↑	↓	↓	│	↑	↑	↑		↑	—	
	Loading Condition				↑			▼						—	
	Size														
	Wheelbase	↑			↑	↓	↓	│	↑	↑			↑	—	↑
	Overall Length	↑	↑		↑	↓	↓	│	↑	↑			↑	—	↑
	Wide Load		↑					▼						—	
	Number of Trailers	↑			↑	↓		NA					↑	—	

Legend:
↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Table 11

Observed Differences Between Truck Groupings at Slight Upgrade Sites (N=1023)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑		—		▨ ↑	▨ ↓	▨ L ↓	▨ L ↓	▨ L ↓	▨ L ↕ E	▨ L ↓	▨ L ↓	—	▨ L ↓
	Mean Acceleration			—										—	
	Headway			—				L ↑			↓ E		↓ E	—	
	Tailway			—							↓ E			—	
	Lateral Placement	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Flow Perturbations														
	Maximum Acceleration	▨ ↑		—			↓ E	▨ L ↓						—	▨ L ↓
	Maximum Deceleration	▨ ↓		—				↓ E	▨ L ↓				↓ E	—	
	Speed Variance			—				↑ E					↑ E	—	
	Acceleration Variance	▨ ↑		—	↑									—	
	Stream Speed Difference	▨ ↓		—	↑				▨ L ↑	▨ L ↑	▨ L ↑	▨ L ↑	▨ ↑	—	▨ ↑
	Proportion Slower	▨ ↓		—	↑				▨ ↑	▨ ↑	▨ ↑		▨ ↑	—	▨ ↑
	Proportion Faster	▨ ↑		—							↑ E			—	
	Driver Effort	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Rear-End Accident Potential														
	Critical Headway			—				↑ E						—	
	Critical Tailway			—				L ↑						—	
	Front Closure Rate			—										—	
	Rear Closure Rate	▨ ↑		—		▨ L ↑		▨ L ↑	▨ L ↑	▨ L ↑	▨ L ↑		▨ L ↑ E	—	↑
	Projected Time to Collision (Front)			—										—	
	Projected Time to Collision (Rear)			—										—	
	Flow Delay														
	Queue Length			—										—	
	Following Vehicle Speed	▨ ↑	↓	—							▨ L ↓			—	▨ L ↓
	Following Vehicle Delay	▨ ↓	↑	—									↓ E	—	▨ L ↑
	Following Queue Speed	▨ ↑	↓	—							▨ ↓			—	▨ L ↓
	Following Queue Delay	▨ ↓		—										—	▨ L ↑
	Passing Interactions														
	Probability of Being Passed			—	▨ ↑						▨ L ↑			—	
	Probability of Passing			—										—	
	Relative Speed Being Passed	▨ ↓		—				▨ ↑		▨ L ↕ E	▨ L ↑		▨ L ↑	—	
	Relative Passing Speed			—				↑						—	
Truck Characteristics	**Weight**														
	Gross Weight	↓		—	↑	↓	↓	↑	↑	↑	↑		↑	—	↑
	Front Axle Weight	↓	↓	—	↑		↓	↑	↑	↑	↑		↑	—	↑
	Maximum Axle Weight	↓		—	↑		↓	↑	↑	↑	↑		↑	—	↑
	Empty Weight (Estimated)	↓	↓	—	↑		↓	↑	↑	↑	↑	—	↑	—	—
	Payload	↓	↓	—			↓	↑	↑	↑	↑		↑	—	—
	Loading Condition	↓		—										—	
	Size														
	Wheelbase		↓	—	↑	↓	↓	↑		↑			↑	—	↑
	Overall Length		↑	—	↑	↓	↓	↑						—	↑
	Wide Load			—										—	
	Number of Trailers	↑		—	↑	↑	—		↑	↑			↑	—	↑

Legend:
↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Table 12

Observed Differences Between Truck Groupings at Steep Upgrade Sites (N=1042)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑						NA	↑ E	▨ ↕		↓ E	▨ L ↓	NA	
	Mean Acceleration	▨ ↑			▨ ↓	▨ L ↓			↑ E	▨ ↕			↑ E		
	Headway	↓													
	Tailway														
	Lateral Placement	—	—	—	—	—	—	↓	—	—	—	—	—	↓	—
	Flow Perturbations														
	Maximum Acceleration														
	Maximum Deceleration	▨ ↑							↑ E	▨ L ↕ E	↑ E		↑ E		
	Speed Variance	▨ ↓			▨ ↑	▨ L ↓	↑ E			▨ ↕	↓ E		▨ ↑		
	Acceleration Variance				↓		▨ L ↑								
	Stream Speed Difference	▨ ↓				▨ L ↓			↓ E	▨ ↕	↓ E				
	Proportion Slower	▨ ↓				▨ L ↓				▨ ↕	↓ E				
	Proportion Faster	▨ ↑													
	Driver Effort	—	—	—	—	—	—	↓	—	—	—	—	—	↓	—
	Rear-End Accident Potential														
	Critical Headway														
	Critical Tailway														
	Front Closure Rate	↑ E									↑ E				
	Rear Closure Rate	▨ ↓								↓ E	↓ E				
	Projected Time to Collision (Front)										↓ E				
	Projected Time to Collision (Rear)	▨ ↑						↓		↑ E				↓	
	Flow Delay														
	Queue Length														
	Following Vehicle Speed														
	Following Vehicle Delay														
	Following Queue Speed														
	Following Queue Delay							↓						↓	
	Passing Interactions														
	Probability of Being Passed														
	Probability of Passing														
	Relative Speed Being Passed	▨ ↓				▨ ↓				▨ L ↑	↓ E				
	Relative Passing Speed	▨ ↑						↓						↓	
Truck Characteristics	**Weight**														
	Gross Weight	↓	↑		↑	↓	—		↑	↑	↑		↑		
	Front Axle Weight	↓	↓		↑		—		↑	↑	↑	↑	↑		
	Maximum Axle Weight	↓	↑	↑	↑		—		↑	↑	↑		↑		
	Empty Weight (Estimated)				↑		↓								
	Payload	↓	↓		↑	↓				↑	↑		↑		
	Loading Condition	↑			↑			↓						↓	
	Size														
	Wheelbase	↑	↑		↑	↓	↓		↑	↑	↑		↑		
	Overall Length	↑	↑		↑	↓	↓		↑	↑	↑		↑		
	Wide Load			↑				↓						↓	
	Number of Trailers	↑	↑		↑	↓		NA	↑	↑	↑		↑	NA	↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

A sample of 2,065 observations was obtained at four upgrade sites. The two Michigan sites (*N*=1,028) were characterized by 1½ percent to 2 percent grades, with trucks ranging upward in weight to approximately 155,000 pounds (70.3 Mg). Grades at the California sites (*N*=1042) ranged from 5 percent to 7 percent with trucks weighing up to 67,500 pounds (30.6 Mg). The average weight of trucks observed at the Michigan sites was 52,200 pounds (23.7 Mg), while the average for California sites was 41,800 pounds (19.0 Mg). Findings at upgrade sites based on the various categories of traffic operational characteristics are described in the following subsections.

Basic Flow Descriptors. The mean speed for all trucks in the upgrade sample was 43.7 mph (70.3 kph). As expected, loaded trucks had significantly lower average speeds than empties. This slowing effect was more pronounced in the steep grade situation (despite lower maximum truck weights), where loaded trucks averaged 31.8 mph (51.2 kph). At the opposite extreme, empty trucks in the slight grade sample maintained an average speed of 54.9 mph (88.3 kph).

Group comparisons revealed that different truck characteristics were related to mean speed trends. The combined data for all upgrade sites demonstrated slightly reduced speeds for longer trucks, compared to shorter (37.9 versus 41.5 mph [61.0 versus 66.8 kph]); however, differences were not significant in either the steep or slight grade sets taken individually. Nevertheless, double-trailer combinations did average slower than singles in all of the upgrade situations. The largest mean speed difference between loaded doubles and singles (12.8 mph [20.6 kph]) was found in the data set describing all upgrade sites, while the lowest average speed for loaded doubles (29.6 mph [47.6 kph]) was seen in the steep grade situation. Combinations with tractors having one (rather than two) drive axles generally exhibited lower speeds, with the greatest differences being observed in the slight grade condition. Specific trailer types most often associated with lower truck speeds across all upgrade sites were tankers and dump trailers. Loaded auto carriers and heavy-duty loaded flatbeds exhibited lower speeds than comparable van-trailer combinations at the Michigan slight-grade sites.

Rate-of-slowing (deceleration) differences on upgrades were observed between many truck groupings. The mean deceleration rates of 1.32 ft/sec^2 (0.40 m/sec^2) for loaded trucks (N=220) on steep grades were statistically quite different from the average 0.95 ft/sec^2 (0.29 m/sec^2) observed for empty trucks (N=310). This result is, of course, descriptive of a short section of steep grade, prior to the onset of crawl speeds, in which minimal deceleration is expected for heavy trucks. Longer trucks averaged higher deceleration rates on upgrades. The largest deceleration performance difference was observed for loaded single-trailer combinations compared with loaded doubles (0.53 versus 1.33 ft/sec^2 [0.16 versus 0.41 m/sec^2]). The statistical validity of this finding derives from a large sample (N=579), high significance level (α=0.001), and a highly predictive association between variable sets (ω^2=0.22). All trailer types were generally seen to be associated with high levels of deceleration on upgrades when loaded, with the poorest showing accruing from tankers (-0.90 ft/sec^2 [-0.27 m/sec^2]) and dump trailers (-0.92 ft/sec^2 [-0.28 m/sec^2]).

Although few following-distance differences were evident, generally safer behavior was found to be associated with larger trucks. In a sample of trucks following other vehicles at headways of 10 seconds or less, Michigan heavy-duty rigs were observed to follow at longer distances than comparable conventional trucks. Typical of obtained results was an average following time of 5.1 sec for loaded Michigan heavy-duty, double-trailer combinations, compared to 3.2 sec for loaded conventional doubles. This finding is consistent with the longer following distances exhibited by loaded trucks on the steep California upgrades. When trucks were empty, both flatbeds and dump-trailer combinations exhibited shorter headways than comparable van combinations at the slight-upgrade sites. A likely explanation of these observed headway differences is that passing vehicles returned to the right lane farther ahead of the more slowly moving trucks after completing their pass.

Using the distances at which other vehicles followed trucks on upgrades, two group differences were found, neither of which holds any adverse implications for increased truck size and weight. Across all upgrade sites, the data showed slightly longer following times behind double-trailer combinations (4.9 sec) than behind singles (4.1 sec). A difference found for empty trucks at the slight-grade sites was that flatbeds were followed at closer distances than were vans.

Flow Perturbations. The various truck groupings showed many differences in flow perturbation, especially in terms of speed change and variance measures. Expected differences were noted in maximum acceleration and deceleration performance between empty and loaded truck groupings. Of the trucks (N=365) that showed speed increases on upgrades, loaded trucks demonstrated lower rates of acceleration (0.21 versus 0.32 ft/sec^2 [0.06 vs. 0.10 m/sec^2]). Conversely, the loaded trucks generally had larger values of deceleration. An apparent effect of higher empty weight was that empty heavy-duty Michigan trucks slowed more rapidly than empty conventional combinations. Of these, dump-trailer rigs tended to slow more than other trailer types. Other truck characteristics associated with heavy deceleration were overall length and tractor axle configuration. Slight but statistically significant deceleration differences were shown between long and short combinations (1.3 and 1.0 ft/sec^2 [0.40 vs. 0.30 m/sec^2], respectively) and single versus dual drive-axle tractors (1.1 and 0.8 ft/sec^2 [0.34 vs. 0.24 m/sec^2]).

Greater speed variance was seen to result from load condition and truck length than from other truck characteristics. Data for steep and combined upgrade sites revealed a high degree of speed variance for loaded and longer trucks; this effect was not, however, observed at the slight-grade sites. Loaded double-trailer combinations, tankers, and dump-trailer combinations were the groupings most frequently associated with higher speed variance on the steep grades. Certain differences in speed variance were also found for empty trucks. Empty tankers averaged a smaller speed variance than did empty vans on steep grades, an effect which probably resulted from their high power-to-weight ratio. That high power-to-weight ratio tended to reduce speed variance for empty trucks was also evident in the smaller variances observed for dual (compared with single) drive-axle tractor combinations.

Speed difference between trucks and other vehicles in the stream provided another important measure of flow perturbation. This measure was based on truck speed in relation to mean speed for all traffic, correcting for time-of-day and volume-density speed effects. On the average, trucks on upgrades traveled 7.7 mph (12.4 kph) below the mean traffic speed. A perturbative effect of truck weight was evident in the fact that empty trucks averaged only 3.5 mph (5.6 kph) below the mean, compared to 10 mph (16.1 kph) below for loaded trucks. Not surprisingly, a greater difference was observed for the steep grade situation (3.7 mph [6.0 kph], empty; 12.3 mph [19.8 kph], loaded); however, a significant difference also existed at slight grades (3.3 mph [5.3 kph], empty; 8.7 mph [14.0 kph], loaded). Single drive-axle tractors, with lower power-to-weight ratios than doubles, also resulted in greater stream-speed differences. Specific trailer types associated with high speed differences were: tankers in all upgrade conditions; and, at the slight-upgrade sites, flatbeds, auto carriers, dump trailers, bulk commodity carriers, and Michigan heavies. A significant finding from the data was that speed differences were more frequently associated with truck weight than with truck size. The only size-related difference was that, at the steep-grade sites, loaded double-trailer combinations averaged 14.6 mph (23.5 kph) below mean traffic speeds compared to 11.0 mph (17.7 kph) for loaded singles.

One measure of flow-perturbative effects is the proportion of vehicles found to be traveling more slowly than one standard deviation below the mean traffic speed. Results based on this measure were generally consistent with those discussed above for speed difference. That is, loaded trucks and those with the above-noted trailer types often met the low-speed criterion. The primary deviation from the results discussed above is that the single drive-axle tractor group did not exhibit a tendency to fall into the low-speed category.

A similarly derived flow perturbance measure based on speed is the proportion of vehicles traveling *faster* than one standard deviation above the mean traffic speed. As was expected, very few trucks in the upgrade situation met this criterion: 4% of the empty trucks and virtually none of the loaded. Not surprisingly, those trucks that did meet the criterion were predominantly empty flatbeds at the slight-upgrade sites.

Rear-End Accident Potential. Closure interactions between successive vehicles in a traffic stream comprise a basis for assessing accident potential. Critically close following behavior on upgrades (headways and tailways of 2.0 sec or less) occurred with little difference in frequency for the various truck groupings. Two observed differences implied a greater degree of driver caution about following specific types of large trucks too closely. First, combined data across all upgrade sites revealed slightly (yet statistically valid) longer following distances behind doubles in comparison to single-trailer combinations. This result was applicable to both empty and loaded trucks. Second, the Michigan data indicated similarly conservative following behavior behind heavy-duty, multiple-axle singles, as compared to conventional singles. Another safety-related finding with regard to the Michigan heavy-duty singles was a slightly longer average headway (1.6 versus 1.2 sec) in critically close following of other vehicles.

Although these following distance results bore no adverse safety implications for increased truck size and weight, examination of the relative closing speed for close following distances gave indications to the contrary. For 1,082 observations across all upgrade sites of trucks being followed at tailways of 10 seconds or less, the average rear closing rate for loaded trucks was 16.1 ft/sec^2 (4.9 m/sec^2) compared to 10.0 ft/sec^2 (3.0 m/sec^2) for empty trucks. The situation was more extreme for the steep-grade condition (N=482), where the average rear closure rate for all loaded trucks was 20.0 ft/sec^2 (6.1 m/sec^2). Similarly, higher rear closure rates were associated with extremely heavy trucks of various trailer types at the Michigan sites. The least prone to high rear closure rates were empty flatbeds and tankers. Double-trailer combinations were more likely than singles to be associated with high rear closure rates, yet this fact was not evident on the basis of steep-grade data alone.

Closure rate differences translated into projected time-to-collision differences for a number of group comparisons. Loaded trucks on upgrades averaged shorter projected rear-end collision times (50 versus 90 sec) than did empty trucks, and so presented a greater danger. This effect was more pronounced at steep-upgrade sites, where the average projected rear-collision time for loaded trucks was 25 sec. The time-to-collision measure was painfully validated for us during the data collection effort when a loaded truck weighing 67,400 pounds (30.6 Mg) was actually collided with just after passing our instrumentation. The truck, moving at 15 mph (24.1 kph) on a steep grade, exhibited a projected time to rear collision of 14 seconds. Almost exactly that much later, the accident (which involved a serious personal injury) occurred. Other projected time-to-collision results from the data indicated a greater likelihood of accident for loaded double-trailer combinations and tankers than for singles and van-trailer combinations.

Flow Delay. Speed observations for vehicles queued behind trucks on upgrades provided a measure of flow delay. All flow delay findings are based on data sets for combined upgrade sites and slight-grade sites. No delay measures were at the steep-grade sites, since the samples were too small to provide statistical validity. Sample sizes were small because the right lanes of these four-lane roadways were left essentially to the trucks for use as climbing lanes, and therefore no queues developed. However, nonsignificant differences obtained for the small steep-upgrade samples tended to corroborate the findings obtained in the other two data sets.

The data from all upgrade sites reveal a pronounced slowing effect for vehicles following loaded trucks. Their average following speed was 49.7 mph (80.0 kph), compared to 54.7 mph (88.0 kph) for vehicles following empty trucks. That vehicles traveling behind loaded trucks experienced substantial delays was evidenced by their speed differential: 7.8 mph (12.6 kph) less than flow speed. The flow delay was 3.0 mph (4.8 kph) for vehicles following empty trucks. Nearly identical delay differences as observed for individual vehicles were also noted for traffic queues. At the slight-grade sites, loaded flatbeds were seen to cause significantly greater speed delay (average 10.2 mph [16.4 kph]) to following vehicles than did comparable van-trailer rigs (7.4 mph [11.9 kph]); the largest delays, however, were associated with Michigan heavy-duty double combinations (15.1 mph [24.3 kph]. Comparable delay effects were seen for queued vehicles behind these trailer types.

The data have so far described increased speed delays for vehicles and queues following slow trucks. We may also calculate travel-time delay for the total stream, as in the following example. An average 11.4 mph (18.3 kph) speed reduction was observed for nine vehicles queued behind loaded Michigan heavy-duty combinations. Assuming an arbitrary one-mile distance of follow, this reduction from the mean traffic speed (57.1 mph [91.9 kph]) would result in a time delay of 15.4 sec per vehicle, or 2 min 19 sec total for the queues. Similarly, average delays for the total sample are calculated to be 2.8 and 10.2 seconds per vehicle for queues behind all empty and loaded trucks, respectively. Examination of the Michigan data (*N*=1,023 observations) revealed comparable total queue delays of 4 min 50 sec and 20 min 31 sec for all empty and loaded trucks, respectively. Yet Michigan heavy-duty rigs, while comprising 14.2 percent of the total loaded truck sample, accounted for only 11.3 percent of the total delay to queued traffic. The explanation is that although these truck types cause greater delay to individual captive vehicles, they are passed with sufficient frequency to preclude a proportionately greater delay in total traffic flow. The implication from this finding is that no cost/benefit justification exists for further restricting or reducing allowable weights of these truck types on the basis of travel time/cost criteria.

Passing Interactions. The probabilities of passing or of being passed, based on observations of relative stream positions and relative passing speed, were examined for various truck groupings. Combined data for all upgrade sites reveal a few pass-occurrence differences between single- and double-trailer combinations. For the empty combinations, about 75 percent of each type was observed in the right lane, with a somewhat larger proportion (59% versus 48%) of the doubles being passed. Although more loaded doubles than singles (20% versus 14%) appeared in the left lane, more singles (71% versus 53%) were actually passing. There was a tendency for the left-lane doubles to be passed on the right at a higher average relative speed (13.7 mph [22.0 kph] than the singles (3.0 mph [4.8 kph]). This trend in relative passing speed was evident for the entire upgrade sample: loaded trucks were passed at higher average relative speeds (15.8 mph [25.4 kph] than were empties (9.7 mph [15.6 kph]). Loaded tankers and dump trailers were consistently passed at the highest relative speed, 19.0 and 21.8 mph (30.6 and 35.1 kph), respectively. Differences were also found for trucks attempting to pass other vehicles. On the average, empty trucks passed at relative speeds of 1.5 mph [2.4 kph]; however, loaded trucks were frequently passed on their right, and at relative speeds averaging 5.3 mph (8.5 kph) over the entire upgrade sample.

Summary. Many performance differences observed between truck groups revealed operational impacts of specific truck characteristics on upgrades. Speeds averaging from 6 to 10 mph (9.7 to 16.1 kph) lower, depending on steepness, was seen for loaded trucks by comparison with empties. Higher deceleration was seen to accompany the lower speeds of loaded trucks. This slowing effect was also shown by longer trucks, especially double-trailer combinations on steep grades. Certain other truck types (tankers and dump trailers, single drive axle tractors) were also associated with pronounced slowing behavior. Comparable truck characteristics contributed to high speed variance on steep upgrades. The extent of trucks' slowing on grades in relation to other traffic (stream-speed differences) was highly associated with weight-related features (e.g., loading condition, trailer type) and, to a much lesser degree, truck size and horsepower-to-weight ratio.

Not surprisingly, the slowing of trucks on upgrades caused closure interactions with following vehicles and a consequently high rear-end accident potential. The highest closure rates were observed behind loaded trucks, double-trailer combinations, tankers, and dump-trailers. Projected times to rear-end collision, assuming no speed or path corrections, for vehicles following loaded trucks, indicated that a greater likelihood of accident existed on steep grades (25.4 sec, average) than on slight grades (68.3 sec, average). This accident measure was validated during our data collection effort when a serious accident, involving a truck and following vehicle with a projected (and actual) rear collision time of 14 seconds, occurred on a steep upgrade.

Trucks slowing on upgrades also produced flow delay to other vehicles in the traffic stream. Speed delays of 7.8 mph (12.6 kph) off traffic flow speeds were observed for vehicles following loaded trucks on upgrades. The largest speed delays, averaging 15 mph (24.1 kph), were exhibited by vehicles and queues following heavy-duty double combinations on slight grades in Michigan. But because other vehicles were able to maneuver past the heavy-duty rigs, total stream travel time did not suffer a disproportionate delay. It follows that high relative passing speeds were observed for this truck type. In general, residual weight effects increased passing probability and relative passing speed.

Upgrades: The Effect of Length

The results of truck-grouping comparisons made at grades of both short and long length appear in Tables 13 and 14, respectively. A sample of 2,065 observations was obtained at four upgrade sites. Two short-upgrade sites (N=795) had lengths of ½ mile (0.8 km) each, while the two long upgrades (N=1,270) were 1½ miles (2.4 km) in length. Data were collected in both California and Michigan, and included trucks weighing up to 155,000 pounds (70.3 Mg). The

Table 13

Observed Differences Between Truck Groupings at Short Upgrade Sites (N=795)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑			▨ ↓	▨ L↑		▨ L↓		▨ L↓			▨ L↓	—	
	Mean Acceleration	▨ ↓			▨ ↓					▨ L↓				—	
	Headway	↓									↓ E			—	
	Tailway	↓								L↓				—	
	Lateral Placement	—	—	—	—	—	—	—	—	—	—	—	—	—	
	Flow Perturbations														
	Maximum Acceleration	▨ ↑												—	
	Maximum Deceleration	▨ ↓			▨ ↑					▨ L↑				—	
	Speed Variance	▨ ↓			▨ ↑					▨ L↑	↓ E		▨ L↕ E	—	
	Acceleration Variance	↑												—	
	Stream Speed Difference	▨ ↓						▨ L↑		▨ L↑	▨ ↕		▨ L↑	—	
	Proportion Slower	▨ ↓						▨ L↑		▨ L↑	↓ E			—	
	Proportion Faster	▨ ↑												—	
	Driver Effort	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Rear-End Accident Potential														
	Critical Headway	↓												—	
	Critical Tailway													—	
	Front Closure Rate													—	
	Rear Closure Rate	▨ ↓						▨ L↑		▨ L↑	↓ E		▨ L↑	—	
	Projected Time to Collision (Front)													—	
	Projected Time to Collision (Rear)	▨ ↑									↑ E			—	
	Flow Delay														
	Queue Length												—	—	
	Following Vehicle Speed	▨ ↓											—	—	
	Following Vehicle Delay	▨ ↑											—	—	
	Following Queue Speed	▨ ↓											—	—	
	Following Queue Delay	▨ ↑											—	—	
	Passing Interactions														
	Probability of Being Passed													—	
	Probability of Passing													—	
	Relative Speed Being Passed	▨ ↓											▨ L↑	—	
	Relative Passing Speed	▨ ↑												—	
Truck Characteristics	**Weight**														
	Gross Weight	↓			↑	↓	↓	↑	↑	↑	↑		↑	—	↑
	Front Axle Weight		↓				↓	↑	↑	↑	↑	↑	↑	—	
	Maximum Axle Weight	↓			↑	↑	↓	↑	↑	↑	↑		↑	—	
	Empty Weight (Estimated)	—				↓	↓	↑	↑		↓		↑	—	
	Payload	↓			↑	↓	↓	↑	↑	↑	↑		↑	—	
	Loading Condition	↓												—	
	Size														
	Wheelbase	↑				↓	↓		↑	↑	↑		↑	—	↑
	Overall Length	↑	↑		↑	↓			↑	↑			↑	—	↑
	Wide Load													—	
	Number of Trailers					↑			↑	↑	↑		↑	—	↑

Legend: ↑ Higher value for first group.

▨ Adverse implication for increased size and weight.

Table 14

Observed Differences Between Truck Groupings at Long Upgrade Sites (N=1270)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	↑ ▨	↓ ▨		↓ ▨	L ↑ E ▨	↓ ▨	L ↓ ▨		↓ ▨			L ↓ E ▨	—	
	Mean Acceleration													—	
	Headway							↓ E					↓ E	—	
	Tailway													—	
	Lateral Placement	—	—	—	—	—	—	—	—	—	—	—	—	—	
	Flow Perturbations														
	Maximum Acceleration	↑ ▨					↓ E ▨	L ↓ ▨						—	↓ ▨
	Maximum Deceleration	↓ ▨						L ↑ ▨						—	
	Speed Variance							↑ E						—	
	Acceleration Variance	↑ ▨												—	
	Stream Speed Difference	↓ ▨					L ↓ ▨	L ↑ ▨		L ↕ E ▨	L ↕ E ▨	↑ E	L ↑ ▨	—	L ↓ ▨
	Proportion Slower	↓ ▨						L ↑ ▨		L ↕ ▨	↕ ▨			—	L ↓ ▨
	Proportion Faster	↑ ▨									↑ E			—	
	Driver Effort	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Rear-End Accident Potential														
	Critical Headway													—	
	Critical Tailway													—	
	Front Closure Rate										↑ E			—	
	Rear Closure Rate	↓ ▨				L ↑ ▨	L ↑ ▨	L ↑ ▨					L ↑ ▨	—	
	Projected Time to Collision (Front)													—	
	Projected Time to Collision (Rear)	↑ ▨												—	
	Flow Delay														
	Queue Length													—	
	Following Vehicle Speed	↑ ▨						L ↓ ▨						—	L ↓ ▨
	Following Vehicle Delay	↓ ▨						L ↑ ▨						—	L ↑ ▨
	Following Queue Speed	↑ ▨						L ↓ ▨						—	↓ ▨
	Following Queue Delay	↓ ▨						L ↑ ▨						—	↑ ▨
	Passing Interactions														
	Probability of Being Passed				L ↑ ▨	L ↓ ▨								—	
	Probability of Passing							↑ E ▨						—	
	Relative Speed Being Passed	↓ ▨				L ↓ ▨		L ↑ ▨						—	
	Relative Passing Speed	↑ ▨												—	
Truck Characteristics	**Weight**														
	Gross Weight	↓			↑	↓		↑	↑	↑	↑		↑	—	↑
	Front Axle Weight	—	↓		↑			↑	↑	↑	↑		↑	—	↑
	Maximum Axle Weight	↓	↑		↑			↑	↑	↑	↑		↑	—	↑
	Empty Weight (Estimated)	↓			↑	↑	↓	↑	↑	↑	↓	↑	↑	—	
	Payload	↓			↑	↓		↑	↑	↑	↑		↑	—	
	Loading Condition	↓			↑									—	
	Size														
	Wheelbase	↑			↑	↓	↓	↑	↑	↑	↑		↑	—	↑
	Overall Length	↑	↑			↓	↓	↑			↑		↑	—	↑
	Wide Load													—	
	Number of Trailers	↑			↑	↑			↑	↑	↑		↑	—	

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

average weights of trucks for the short- and long-grade sites are 46,000 and 47,000 pounds (20.9 and 21.5 Mg), respectively. Findings for various categories of traffic operational measures are discussed.

Basic Flow Descriptors. Mean speeds for total truck samples varied little between short- and long-upgrade conditions: 44.2 mph (71.1 kph) at the short, and 43.4 mph (69.8 kph) at the long. However, for steep-grade sites, length of grade had a significant speed-reducing effect -- from an average speed of 41.3 mph (66.5 kph) on the short grades to an average 30.7 mph (49.4 kph) on the long.

Some speed difference was found between loaded and empty trucks for each length of grade. But the length of the grade had little effect on the size of the difference: empty trucks averaged 7.4 mph (11.9 kph) higher speeds than loaded trucks in the short grade condition, while at the long-grade sites, the difference in speed was still only 7.6 mph (12.2 kph). Specific truck characteristics were demonstrated to have a bearing on speed difference between empty and loaded trucks. Across both grade-length conditions, longer trucks and double-trailer combinations were generally shown to average 2 to 3 mph (3.2 to 4.8 kph) slower than shorter rigs and single-trailer combinations. Certain truck types (loaded tankers, dump trailers, and Michigan heavies) were shown to slow more than vans at both long- and short-upgrade sites. Another speed effect, found only at the long-grade condition, was that cab-over combinations were slower than cab-behind. Although statistically significant, the effect was small. Mean speed for the cab-over rigs was 42.5 mph (68.4 kph) compared to 44.8 mph (72.1 kph) for cab-behind.

Length of upgrade was shown to have a considerable impact on mean acceleration, due apparently to the fact that trucks were more likely to enter crawl speed on the long grades. There were thus no mean acceleration differences at the long-grade sites among virtually all truck group comparisons. For the short-grade condition, however, average acceleration for empty trucks was -0.95 ft/sec^2 (-0.29 m/sec^2), compared to -1.32 ft/sec^2 (-0.40 m/sec^2) for loaded trucks. Longer trucks and loaded tankers were the most prone to low levels of mean acceleration at the short-grade sites.

No headway or tailway differences were found significant enough to have direct safety implications for truck size and weight. In some instances, lighter trucks (for example, empty flatbeds on short upgrades) followed at shorter (less safe) headways than other comparable truck types. This tendency was probably a result of their greater ability to maintain speed on upgrades. There was, however, little indication that the consequent following times were critically short (an average 3.6 sec for empty, as opposed to 4.1 sec for loaded, trucks).

Flow Perturbations. Maximum levels of acceleration and deceleration observed for trucks did often reveal differences between groupings. Of the small proportion of trucks (10%) exhibiting any degree of acceleration on the upgrades, empties showed a greater capability than loaded trucks, with the values for each being about the same at both long- and short-grade sites (averages of 0.32 ft/sec^2 [0.10 m/sec^2], empty; and 0.19 ft/sec^2 [0.06 m/sec^2], loaded). However, values for maximum deceleration were much greater at the short-grade sites (1.06 ft/sec^2 [0.32 m/sec], empty; 1.28 ft/sec^2 [0.39 m/sec^2], loaded) than on the long grades (0.33 ft/sec^2 [0.10 m/sec^2], empty; 0.18 ft/sec^2 [0.05 m/sec^2], loaded). Therefore, the greater perturbative effect of truck loading in terms of deceleration performance was realized at sites with a short, rather than a long, upgrade. Those truck characteristics most frequently associated with larger deceleration behavior were longer overall length and loaded tank trailers.

Deceleration performance differences of trucks on upgrades gave rise to differences based on another measure, speed variance. Again, the greater impact was realized at the short-grade sites. Higher speed variance was observed for loaded trucks, longer trucks, tankers, and dump-trailer combinations.

Another perturbative effect, this one more readily apparent at the longer upgrade sites, was stream-speed difference. The effect was somewhat larger than would be expected merely on the basis of lower truck speeds on the longer grade. This is to say, while the average speed across sites for loaded trucks on the long grades was only 0.8 mph (1.3 kph) slower than on the short, the trucks traveled 3.4 mph (5.5 kph) slower than the traffic on the long grades. An examination of individual data sets revealed no confounding effects, and results at specific sites were found to be consistent with the effects noted across sites.

For both grade-length conditions, loaded trucks demonstrated a larger mean stream-speed difference than empties. Specific truck types that contributed most strongly to this effect were Michigan heavies, tankers, flatbeds, and dump-trailer rigs. For the long-upgrade condition, a slight tendency existed for those combinations pulled by single (as opposed to dual) drive-axle tractors to exhibit greater stream-speed differences. Bulk commodity carriers more often exhibited high stream-speed differences (19.9 mph [32.0 kph] slower than other traffic) were observed for loaded heavy-duty double combinations in Michigan; comparably loaded van combinations at the same long-upgrade site averaged 12.8 mph (20.6 kph) slower than other traffic.

The next perturbative measure was the incidence of slowly moving trucks: those traveling at least one standard deviation below the stream mean. As seen from the tables, findings based on this measure are consistent with those noted for stream speed differences -- which is to be expected because of the similarities between these measures. In general, about 35 percent of the empty trucks met the slow-speed criterion, compared to about 70 percent of the loaded. The effect was evident for more truck types on the longer grades than on the shorter, and was most often found for loaded Michigan heavies, flatbeds, tankers, and dump-trailer combinations. Larger differences were evident in the long-upgrade Michigan data, where 95 percent of the loaded, heavy-duty combinations met the slow-speed criterion, in contrast to 69 percent for the comparable sample of loaded conventional trucks. A corresponding measure of the proportion of trucks traveling *faster* than mean traffic speeds demonstrated that while only 3 percent of the empty trucks met the criterion, virtually none of the loaded ones did.

Rear-End Accident Potential. The examination of critical following distances, closure rates, and projected collision times revealed certain differences between truck groupings. As was noted in the discussion of Basic Flow Descriptors, empty trucks at the long-grade sites frequently followed other vehicles at short headways. Based on the truck sample (N=162) found to exhibit headways of 2.0 sec or less on short upgrades, empty trucks averaged shorter headways than did loaded trucks. The difference (1.31 versus 1.45 sec), although statistically significant, cannot be interpreted as having any practical meaning, especially in view of the fact that these shorter headways did not result in higher closure rates or shorter projected collision times.

Other accident-potential findings that have safety implications were related to close following of certain trucks by other vehicles. Higher rear closure rates were found for loaded trucks; this difference was slightly more pronounced in the short upgrade condition (17.5 ft/sec [5.3 m/sec], loaded; 10.1 ft/sec [3.1 m/sec], empty). Truck types associated with higher rear closure rates at the short-grade sites were loaded Michigan heavies, tankers, and dump-trailer combinations. At the long-grade sites, differences in rear closure rate were generally associated with the above-noted truck types; however, differences were also found on the basis of trailer and drive-axle configuration. Two results seemed to implicate lower power-to-weight ratio with higher rear closure rates. First, both empty and loaded double-trailer combinations were associated with higher closures, and second, single drive-axle tractors were prone to exhibit higher closures. Among the highest observed rear closure rates in any sample was the average 21.9 ft/sec (6.7 m/sec) associated with Michigan heavy-duty combinations (compared to 11.9 ft/sec [3.6 m/sec] for the comparable sample of conventional trucks). At a long-grade site, however, these closures did not result in statistically different projected times to collision. In that regard, the only group difference was that loaded trucks averaged shorter projected rear-end collision times at both short and long upgrades than did empties. Critically shorter rear-collision times were observed at the short upgrade sites (31 sec, loaded; 54 sec, empty). Empty flatbeds, with their zest for climbing short grades, did create a somewhat safer situation in their wakes, as evidenced by significantly longer (77.0 sec) projected times to collision than for comparable van combinations (45.3 sec).

Flow Delay. A somewhat unexpected result was that greater following-vehicle and queue delays by loaded trucks were experienced in the shorter-grade condition. Following-vehicle speeds behind empty trucks did not vary for the two grade lengths. However, vehicles following loaded trucks at the short-grade sites averaged 46.4 mph (74.7 kph), while those at the long-grade sites averaged 52.1 mph (83.8 kph). A likely explanation is that the deceleration on the grades produced low truck speeds, causing following vehicles to be trapped at those speeds. By the time the trucks had traveled on the grade considerably beyond the distance defining a short grade, trapped vehicles had had an opportunity to pass and avoid further delay. Confirmation of this hypothesis was obtained by examining site-specific data and finding that a substantially smaller proportion of loaded trucks were being followed as they reached the long-grade data collection point. Thus, as in the earlier discussion of delay caused by steepness of grade, the maneuvering of traffic around slow trucks procluded substantial travel-time delay to the total traffic stream.

Nonetheless, reduced speeds behind loaded trucks on the short grades did produce greater vehicle and queue speed delays than those observed at the long-grade sites. As previously noted in this chapter, substantial delays were found to be associated with loaded Michigan heavy-duty trucks.

Passing Interactions. The probability of trucks passing or being passed, as determined by traffic stream position relative to other vehicles, differed little between either grade length condition or truck grouping. Passing occurrences referred to in the preceding discussions of delay and flow perturbations took place primarily between short- and long-grade data collection points located one mile apart. Two findings at the long-grade site demonstrated: (1) a greater likelihood of longer trucks being passed than shorter combinations (68% and 50%, respectively), and (2) that 66 percent of the double-trailer combinations were passed, compared to 53 percent of the singles. Differences in relative passing speed were observed between loaded and empty trucks. In the case of trucks being passed by other vehicles, a slightly more pronounced difference was found for the long-upgrade condition (10.1 mph [16.3 kph] empty; 16.5 mph [26.5 kph] loaded). Trucks in the left lane were frequently observed passing other vehicles at the short-upgrade sites, while more often being passed on the right at the long-grade sites. In all cases, higher relative passing speeds were associated with loaded trucks than with empty trucks. The highest such speeds (26.5 mph [42.6 kph]) were found in the sample of loaded double-trailer combinations (N=36) at the California long-grade site. High relative passing speeds (18.0 mph [29.0 kph]) were also observed for loaded Michigan heavy-duty trucks (N=37). The lower values for the Michigan site were probably the result of a lesser steepness of grade.

Summary. Typical of the upgrade condition, lower mean speeds were observed for both loaded and longer trucks. This effect was more pronounced on long grades, and accentuated by increased steepness, with lowest speeds being exhibited by loaded tankers, dump-trailers, Michigan heavy-duty trucks, and double-trailer combinations. Loaded trucks demonstrated higher levels of deceleration on short grades, but not at long-grade sites, because of the more frequent onset of crawl speeds. No headway or tailway differences were found that contained implications for increased size and weight.

Various truck group comparisons revealed flow-perturbative differences. In a few cases, trucks were observed to accelerate on long grades, but, not surprisingly, they were usually empty trucks. At short grades, loaded trucks often decelerated to an extent that caused significant variance in their speeds. Although this deceleration effect was much less pronounced at the long-grade sites, higher stream-speed differences were observed for many types of loaded trucks at those sites that on the short grades.

Group differences based on measures of accident potential showed that loaded trucks were prone to higher rear closure rates and shorter projected times tocollision than empty trucks. Trucks with apparently lower power-to-weight ratios tended to exhibit high rear closure rates.

Loaded trucks caused increased flow delay, it was found. Reduced speeds and increased delay were observed for both single following vehicles and queues behind loaded trucks. Greater delay was observed in the short-grade condition. Although few group differences were observed in terms of pass-occurrence probability, higher relative speeds were more likely to occur when loaded trucks were passed on long grades.

Besides the derivation of traffic operational effects associated with various truck characteristics, certain operational differences were also identified between short- and long-grade conditions. These differences were useful in determining which type of roadway geometric is the more vulnerable to the effects of varying truck size and weight. We found that short-grade sites reflect greater operational consequences of these truck characteristics than do the long grades. Although mean truck speeds did not differ in every case between short and long grade length conditions, increased levels of truck deceleration were consistently found at the shorter grades. This behavior impacted other operational measures. First, greater speed variance was observed for trucks at short-grade sites, resulting in, second, more critical projected times to collision with following vehicles. Third, because following vehicles were often "trapped" behind slowly moving trucks at short-grade sites, lower average speeds were observed for those vehicles than at the long-grade sites. This produced higher speed delays for both vehicles and queues. Separate consideration is given to travel-time (as opposed to speed) delay as follows. On the long grades, traffic was generally able to maneuver around slowly moving trucks, as evidenced by relatively little truck-following behavior at those sites; so that, overall, a minimal travel-time delay accrued to the total traffic stream as the result of trucks slowing on grades.

Three-Percent Long Downgrade

This geometric condition is treated separately because it occurs so frequently throughout the Interstate system. The 3-percent downgrade tangent section was one mile (1.6 km) long. For it, we obtained a sample (*N*=380) of trucks weighing up to 75,000 pounds (34.0 Mg) with an average weight of 41,780 pounds (19.0 Mg). As seen in Table 15, few differences between truck groupings were found in the data. The analysis showed, generally, a relative absence of adverse traffic operational effects due to increased truck size and weight.

Basic Flow Descriptors. That no significant difference in mean speed was found between empty and loaded trucks did refute the popular belief that heavier trucks go faster downhill in order to gain momentum for climbing the next grade. Geometric conditions at the site encouraged this scenario, since an upgrade was within sight of the data collection point. But loaded trucks, with gross weights averaging 61,000 pounds (27.7 Mg), exhibited a mean speed of 61.1 mph (98.3 kph), with only slightly higher than the 60.4 mph (97.2 kph) mean of the empty sample, with an average weight of 28,100 pounds (12.7 Mg). This result demonstrated that drivers of the loaded trucks essentially maintain their speeds to conform with normal traffic flow, and did not take advantage of the downgrade to accelerate. Similarly, somewhat conservative driving behavior was observed for heavy dump-trailer combinations (averaging 72,500 pounds [32.9 Mg]), whose mean speed on the downgrade was lower (58.3 mph [93.8 kph]) than that observed for loaded vans (61.4 mph [98.8 kph]) weighing 59,200 pounds (26.9 Mg) on the average. The implication is that drivers of the heavier trucks held their speed down for reasons of safety (for instance, to prevent runaways).

No differences between other truck groupings were available on the basis of their average acceleration or following behavior.

Table 15

Observed Differences Between Truck Groupings at Three Percent Long Grade (N=380)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed							–					L ↓		
	Mean Acceleration							–							
	Headway							–							
	Tailway							–							
	Lateral Placement	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Flow Perturbations														
	Maximum Acceleration							–		L ↓					
	Maximum Deceleration	↓						–							
	Speed Variance							–							
	Acceleration Variance							–							
	Stream Speed Difference							–							
	Proportion Slower						▨ L ↑	–					▨ L ↑		
	Proportion Faster							–							
	Driver Effort	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Rear-End Accident Potential														
	Critical Headway							–							
	Critical Tailway							–							
	Front Closure Rate							–							
	Rear Closure Rate							–							
	Projected Time to Collision (Front)							–							
	Projected Time to Collision (Rear)							–							
	Flow Delay														
	Queue Length							–							
	Following Vehicle Speed							–							
	Following Vehicle Delay							–							
	Following Queue Speed							–							
	Following Queue Delay							–							
	Passing Interactions														
	Probability of Being Passed							–							
	Probability of Passing							–							
	Relative Speed Being Passed							–							
	Relative Passing Speed						L ↓	–							
Truck Characteristics	**Weight**														
	Gross Weight	↓					↓	–		↓	↑		↑		
	Front Axle Weight		↓		↓		↓	–		↓	↑		↑		
	Maximum Axle Weight	↓			↓		↓	–		↓	↑			↑	
	Empty Weight (Estimated)	↓			↓	↓	↓	–	↓	↓	↓		↓		
	Payload	↓	↓				↓	–		↓	↑		↑		
	Loading Condition		↑		↑			–		↓					
	Size														
	Wheelbase				↑	↓	↓	–	↑		↑				
	Overall Length				↑	↓	↓	–	↑		↑		↑		
	Wide Load		↑					–			↑				
	Number of Trailers			↓		↓		–	↑	↑	↑		↑		↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Flow Perturbations. As in the case of basic flow behaviors, little evidence was found to implicate increased truck size and weight with decreased operational safety. On the contrary, two speed-change differences between groups were found that indicated safer driver behavior for heavier trucks. First, loaded tankers exhibited more conservative downhill acceleration behavior than did loaded vans. Although significantly heavier, the tankers averaged 0.16 ft/sec^2 (0.05 m/sec^2) in their maximum measured levels of acceleration, compared to 0.29 ft/sec^2 (0.09 m/sec^2) for vans. Second, empty trucks were seen to decelerate more violently than loaded trucks (mean maximum deceleration of -0.43 ft/sec^2 [-0.13 m/sec^2] versus -0.26 ft/sec^2 [-0.08 m/sec^2]).

The only operational measure demonstrating adverse size and weight effects was the proportion of certain truck groupings traveling slowly (i.e., one standard deviation below mean traffic speeds). A significantly large percentage (31% versus 8%) of single drive-axle combinations met this low-speed criterion, in comparison to the dual drive-axle rigs. Similar percentage differences also showed that loaded dump-trailer combinations were more likely than vans to travel slowly. The interpretation of group differences based on this measure must, however, take into account the fact that at this site, a smaller proportion of trucks was observed to deviate from mean traffic speed than was the norm at most sites. For example, the 8 percent of the dual drive-axle trucks falling into the "drive slowly" category here is significantly less than the 23 percent average in that category across all sites. In fact, the increased safe behavior on the part of dual drive-axle combinations at this particular site accounted for the statistical difference here, whereas the single axle truck behavior was no more or less safe than generally observed elsewhere. Therefore, the observed group difference cannot be interpreted as an absolute indication of greater hazard with increased size or weight.

Rear-End Accident Potential. No group differences were found for this class of measures. Levels of accident potential were found to be consistent with (if not lower than) those observed at most other sites. In response to a popular belief that big trucks tailgate other vehicles on downgrades, thus contributing to accident potential, particular attention was given to front closures for loaded trucks following closely behind other vehicles. Although no significant differences were found in this regard between truck groupings at the 3-percent downgrade site, the tendency was for loaded trucks and heavies to exhibit safer behavior. This was evidenced by a higher average of observed projected times to collision with leading vehicles (170 seconds for empty trucks; 192 seconds for loaded trucks).

Flow Delay. As in the case of rear end accident measures, no significant group differences were found. The previously noted slowing of loaded dump trailers did not result in delay to following vehicles, likely due to the small sample size. Furthermore, the downhill nature of the site meant that generally, minimal delays were encountered by traffic interacting with trucks.

Passing Interactions. No group differences based on this measure category were obtained at this site.

Summary. A general absence of differences between truck groupings was noted for most operational measures. In fact, a few such differences implied a pattern of safer behavior with larger truck size and weight (e.g., lower acceleration/deceleration for certain heavier trucks). Two group differences connected larger deviations from mean traffic speeds with higher truck weight and lower horsepower-to-weight ratio. However, a comparison of these particular results with data gathered in the total study revealed that the differences were due rather to safer behavior on the part of certain truck types (for example, dual drive-axle combinations) than to more hazard-producing behavior on the part of other truck types. The interpretation of these results is that no adverse effect of increased size and weight was found at the long 3-percent downgrade site.

Steep Downgrades

Two steep grades, 1/2 and 1-1/2 miles (0.8 and 2.4 km) long, and varying in slope from -5 percent to -7 percent, were used to obtain a sample of 1,370 trucks weighing up to approximately 75,000 pounds (34.0 Mg) each. Group differences depicted in Table 16 are discussed for each category of operational measures.

Basic Flow Descriptors. A difference in mean speed was observed between truck groupings, according to load condition. Loaded trucks, averaging 51.9 mph (83.5 kph), were significantly slower than empties, which averaged 56.1 mph (90.3 kph). Because loaded trucks, therefore, often traveled at speeds considerably below the traffic mean, the difference is viewed as indicative of an adverse effect of increased weight. The truck types exhibiting the lowest mean speeds were loaded tankers and flatbeds. Other truck characteristics found to be associated with reduced speed were trailer configuration and width of load. Loaded double-trailer combinations averaged 2.4 mph (3.9 kph) slower than singles, while trucks carrying wide loads were drastically slower, with an average speed of 40.3 mph (64.8 kph).

Two more observed differences, these containing no size or weight implications, were that: (1) empty dump trailers descended the steep grades more slowly than did empty vans, and (2) empty trucks averaged shorter following headways than did loaded ones.

Table 16

Observed Differences Between Truck Groupings at Steep Downgrade Sites (N=1370)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Duel Dr. Axles	Michigen Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑		▨ ↓		▨ L↑		—	▨ L↓	▨ L↓	▨ L↓		↓ E	—	
	Mean Acceleration							—						—	
	Headway	↓						—						—	
	Tailway							—						—	
	Lateral Placement							—						—	
	Flow Perturbations														
	Maximum Acceleration					L↑		—						—	
	Maximum Deceleration				↑			—						—	
	Speed Variance							—						—	
	Acceleration Varience							—						—	
	Stream Speed Difference	▨ ↓		▨ ↑		▨ L↓		—		▨ L↑	▨ L↑		↑ E	—	
	Proportion Slower	▨ ↓		▨ ↑		▨ L↓		—		▨ L↑	▨ L↑		↑ E	—	
	Proportion Faster	▨ ↑						—			▨ L↓		↓ E	—	
	Driver Effort							—						—	
	Rear-End Accident Potential														
	Criticel Headwey				↑			—				▨ L↓		—	
	Critical Tailwey							—						—	
	Front Closure Rete		↓					—		L↓				—	
	Rear Closure Rate	▨ ↓						—		▨ L↑				—	
	Projected Time to Collision (Front)	↓						—						—	
	Projected Time to Collision (Rear)							—						—	
	Flow Delay														
	Queue Length							—						—	
	Following Vehicle Speed	▨ ↑						—						—	
	Following Vehicle Delay	▨ ↓						—						—	
	Following Queue Speed	▨ ↑						—		▨ L↓				—	
	Following Queue Deley	▨ ↓						—		▨ L↑				—	
	Passing Interactions														
	Probability of Being Passed							—						—	
	Probebility of Passing	↑						—						—	
	Reletive Speed Being Passed	▨ ↓		▨ ↑				—		▨ L↑				—	
	Relative Passing Speed	↑						—						—	
Truck Characteristics	**Weight**														
	Gross Weight	↓	↑	↓	↑	↓	↓	—	↑	↑	↑			—	↑
	Front Axle Weight	↓	↓		↑	↓	↓	—		↑	↑	↑		—	
	Maximum Axle Weight	↓	↑	↓	↑		↓	—	↑	↑	↑	↑		—	
	Empty Weight (Estimated)	↑			↑	↑	↓	—						—	
	Payload	↓			↑	↓	↓	—	↑	↑				—	↑
	Loading Condition	↓	↑		↑			—			↑			—	
	Size														
	Wheelbase	↑	↑	↓	↑	↓	↓	—	↑	↑	↑		↑	—	↑
	Overall Length	↑	↑		↑	↓	↓	—	↑	↑	↑		↑	—	
	Wide Load		↑	↑		↑		—						—	
	Number of Trailers			↓	↑	↑		—	↑	↑	↑	↓		—	

Legend: ↑ Higher value for first group.

▨ Adverse implication for increased size and weight.

Flow Perturbations. A number of observed group differences resulted from the lower speeds of certain types of trucks. Loaded trucks, which exhibited a stream-speed difference of 4.6 mph (7.2 kph) below traffic speed, had a significantly larger perturbative effect than did empties, with a stream-speed difference of only 0.5 mph (0.8 kph). Flatbeds, tankers, and double-trailer combinations demonstrated particularly significant speed difference effects. Here again, wide-load trucks showed the greatest difference, traveling 15.4 mph (24.8 kph) below mean traffic speeds. All of these truck groupings demonstrated speed behaviors at least one standard deviation below the mean traffic speed.

Rear-End Accident Potential. The slowing behavior cited above resulted in increased rear closure rates for only two truck groupings: loaded trucks and tankers. However, even these closure rates did not result in critically shorter projected times to rear collision in any of the group comparisons. Additionally, loaded flatbeds were more likely than vans to follow other vehicles at critically short headways, but this behavior did not yield higher levels of other accident potential measures.

Flow Delay. Loaded trucks, in slowing more than empties on steep downgrades, did cause delays to other traffic. Single vehicles following loaded trucks (*N*=52) averaged 53.8 mph (86.5 kph) whilethose behind empties (*N*=37) averaged 56.1 mph (90.3 kph). Both speeds fell below normal traffic flow speed, but the greater delay was associated with loaded trucks. Similar speed reductions and flow delays were experienced by queues following the loaded trucks. Delay to vehicle queues was particularly evident behind loaded tankers.

Passing Interactions. The sole group difference pertaining to passing probability was that a smaller proportion of loaded than empty trucks was observed to be passing other vehicles; the loaded group also passed at lower relative speeds (3.0 mph [4.8 kph] compared to 8.0 mph [12.9 kph]). While the probabilities of their *being* passed did not differ significantly, loaded trucks were passed with higher relative speeds (8.2 mph [13.2 kph]) than were empties (3.7 mph [6.0 kph]). Very high relative passing speeds were found to be associated with loaded tankers (13.1 mph [21.0 kph]) and trucks transporting wide loads (15.4 mph [24.8 kph]).

Summary. The primary operational effect of truck size and weight on steep grades was the slowing of heavier trucks. Trucks with wide loads slowed dramatically. Perturbative effects of this slowing derived from large variations from mean traffic speeds. Specific truck types associated with this behavior were loaded double-trailer combinations, tankers, and flatbeds. Little rear-end accident potential was observed at this grade condition. Higher rear closure rates from following vehicles were seen for loaded trucks (especially tankers); however, no adverse effect was seen for projected times to collision. The slowing of heavier trucks did result in speed reductions and flow delay to following vehicles and queues. Higher relative speeds were observed for vehicles passing both loaded trucks (especially tankers) and trucks carrying wide loads.

Long Downgrades

Two long downgrades, 1 and 1-1/2 miles (1.6 and 2.4 km) in length, comprised the site pair used in this analysis. Grade steepness varied from -3 percent to -7 percent. A sample of 1,072 trucks contained individual gross weights of up to approximately 75,000 pounds (34.0 Mg). The group differences discussed below are summarized in Table 17.

Basic Flow Descriptors. While mean speeds did not vary significantly between the groups of loaded and empty trucks, there was a slight tendency for the loaded trucks to travel at lower speeds. Lower mean speeds in their respective group comparisons

Table 17

Observed Differences Between Truck Groupings at Long Downgrade Sites (N=1073)

		Truck Grouping Criterie													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed			▨ ↓			▨ L↓	–		▨ L↓			↓ E		
	Mean Acceleration							–							
	Headway						▨ ↓	–							
	Teilway							–							↓ E
	Laterel Plecement		↓		▨ ↑			–							
	Flow Perturbations														
	Meximum Acceleration					L ↑		–							
	Maximum Deceleration	↑						–							
	Speed Variance							–							
	Acceleration Variance							–							
	Streem Speed Difference	▨ ↓		▨ ↑			▨ L↑	–		▨ L↑					
	Proportion Slower	▨ ↓						–		▨ L↑					
	Proportion Faster						▨ L↓	–				↑ E			
	Driver Effort							–							
	Rear-End Accident Potential														
	Critical Headway							–							
	Critical Tailway							–							
	Front Closure Rate							–							
	Reer Closure Rate	▨ ↓						–		▨ L↑					
	Projected Time to Collision (Front)							–							
	Projected Time to Collision (Rear)							–							
	Flow Delay														
	Queue Length		–	–			–	–							–
	Following Vehicle Speed			–			–	–							–
	Following Vehicle Delay			–			–	–							–
	Following Queue Speed			–			–	–							–
	Following Queue Delay			–			–	–							–
	Passing Interactions														
	Probebility of Being Passed							–					▨ L↑		
	Probebility of Passing	↑						–							
	Relative Speed Being Passed							–		▨ L↑	▨ L↑				
	Reletive Passing Speed							–							
Truck Characteristics	**Weight**														
	Gross Weight	↓			↑	↓	↓	–	↑	↑	↑		↑	↑	↑
	Front Axle Weight		↓	↑	↑	↓	↓	–	↑	↑	↑	↑	↑		↑
	Maximum Axle Weight	↓	↑		↑	↑	↓	–	↑	↑	↑			↑	
	Empty Weight (Estimeted)	↑			↑	↓	↓	–	↓		↓				
	Payload	↓	↓		↑	↓	↓	–	↑	↑	↑		↑	↑	↑
	Loeding Condition	↓	↑		↑			–					↑		
	Size														
	Wheelbese	↑	↑		↑	↓	↓	–	↑	↑	↑		↑		↑
	Overall Length				↑	↓	↓	–	↑	↑			↑		↑
	Wide Load					↑		–	↑						
	Number of Trailers							–	↑	↑	↑		↑		

Legend: ↑ Higher velue for first group.

▨ Adverse implication for increased size and weight.

were observed for trucks carrying wide loads and for loaded tankers. Trucks carrying wide loads averaged 48.5 mph (78.0 kph), compared to 55.2 mph (88.8 kph) for those of standard 8-ft. (2.4 m) width. The average speed for loaded tankers was 50.6 mph (81.4 kph), compared to 55.4 mph (89.1 kph) for loaded vans.

The one group difference in terms of following distance was that trucks characterized by single (as opposed to dual) drive axles were more likely to follow at shorter headways. Average headways were 5.5 sec for singles and 4.4 sec for doubles. However, it is noteworthy that no effect on critically short headways (conducive to rear-end accidents) resulted from differences between these groups.

Two group differences based on lateral placement (lane positioning) contained conflicting safety implications for increased size and weight. The lateral distance between the truck's right front wheel and the right lane edge was used to assess separation from vehicles in the adjoining (left) lane. Small, but statistically valid, placement differences revealed that trucks with cab-over tractors traveled slightly closer to the right edge (1.66 versus 1.45 ft. [0.51 versus 0.44 m] -- a 2½-inch [63.5-mm] difference) than did cab-behind rigs. This safer behavior on the part of tractors designed to transport larger loads (longer trailers) is not construed to contain adverse implications for increased truck size. However, another finding gave rise to a contradictory interpretation. Longer trucks tended to travel greater distances from the right lane edge (1.82 versus 1.47 ft. [0.55 versus 0.45 m], or 4 inches [102 mm] farther away). This truck group also weighed much more (average 72,200 pounds [32.7 Mg] each) than the short trucks (average 33,500 pounds [15.2 Mg]). Despite the fact that this group of longer and heavier trucks demonstrated a slightly diminished margin of safe distance from left-lane vehicles, little real consequence seems evident from the observed difference because of the small size of the difference and because of the actual lane positioning of this truck group. Indeed, a lateral position of 2.0 ft. (0.6 m) from the edgeline would indicate that the trucks were centered in the lane. Given the mean position of 1.82 ft. (0.55 m) from the line of the long trucks, it can be seen that a safety margin still remained.

Flow Perturbations. Levels of maximum acceleration exhibited on long downgrades averaged higher (0.37 ft/sec^2 versus 0.28 ft/sec^2 [0.11 versus 0.09 m/sec^2]) for loaded single-trailer combinations than for doubles. It is noteworthy that the larger and heavier trucks (doubles averaged 62,890 pounds [28.6 Mg], compared to 50,020 pounds [22.9 Mg] for singles) exhibited safer behavior in this grade situation. Consistent findings were obtained at both long-downgrade sites. Another finding, and one with similar implications, is that higher decelerations were observed for groups of empty trucks.

Speed-difference findings, on the other hand, indicated less safe behavior for larger and heavier trucks. Lower mean speeds of loaded trucks resulted in larger deviations from normal traffic flow. While empty trucks averaged only 0.6 mph (1.0 kph) below traffic speeds, differences averaging 2.8 mph (4.5 kph) were observed for the sample of loaded trucks. Additionally, large speed differences averaging 9.2 mph (14.8 kph) below traffic speed were found in the case of trucks carrying wide loads. Moreover, large speed differences were observed for loaded tankers and trucks with single drive-axle tractors.

Another perturbative measure, driving at least one standard deviation below mean speed, provided the basis for two observed differences. Twice as large a proportion (28% versus 14%) of the loaded trucks than of the empty trucks in the sample met the slowly driving criterion. Loaded tankers were more likely to meet this criterion than were loaded vans. A similar perturbative measure based on speed, traveling one standard deviation above the mean, revealed a larger effect from loaded trucks with dual drive-axle tractors (13%) than with single drive-axle tractors (4%). One result emerging from the empty-truck sample was that more empty automobile carriers met the fast-speed criterion than did empty vans.

Rear-End Accident Potential. Very few differences were found, based on this set of measures. Slowly moving loaded tankers were seen to average high rear closure rates (16.4 ft/sec [5.0 m/sec]) with vehicles following at tailways of 10 seconds or less. Generally, higher rear closure rates were associated with loaded trucks than with empties. However, in no group comparison were differences observed for projected rear-end collision times.

Flow Delay. No differences in following delay were observed between truck groupings at the long-downgrade sites.

Passing Interactions. A few group differences were observed in terms of pass-occurrence probabilities and relative passing speeds. The sample contained a small number ($N=3$) of loaded dump-trailer trucks, all of which were passed by other vehicles. By comparison, 39 percent of the sample ($N=292$) of loaded vans were passed by other vehicles. Empty trucks were more likely to pass other vehicles than were loaded trucks, which were themselves more often passed on the right by other vehicles.

Relative passing speed differences were observed for certain truck types. Loaded tankers and flatbeds were passed by other vehicles at higher relative speeds (11.9 mph and 7.2 mph [19.1 and 11.6 kph] respectively) than were loaded vans (3.0 mph [4.8 kph]).

Summary. A number of operational differences between groups of trucks were observed at the long-downgrade sites. Lower mean speeds were noted for loaded tankers, single drive-axle tractor combinations, and trucks transporting wide loads. Single drive-axle rigs followed other vehicles at shorter headways than did those with dual drive-axles. Lateral placement differences demonstrated that trucks with cab-over tractors tracked slightly closer to the right edge of the lane, while longer trucks tracked slightly farther from the right lane line.

Most of the flow perturbation findings resulted from speed reductions. Greater stream-speed differences were noted for those trucks cited above as having exhibited lower mean speeds. Of these, loaded trucks (especially tankers) were likely to exhibit speeds slower than one standard deviation below the mean. However, dual drive-axle rigs frequently traveled at least one standard deviation above the mean speed.

Few rear-end accident potential differences emerged. Loaded trucks (especially tankers) exhibited high rear closure rates with following vehicles, yet these did not result in critically reduced projected collision times. No flow-delay differences were found between truck groupings.

Certain loaded truck types were associated with increased passing activity. A small sample of dump-trailer combinations were all passed by other vehicles, and high relative passing speeds were associated with loaded tankers and flatbeds.

All Curve Sites

Four sites comprising this data set included freeway and nonfreeway curves ranging in curvature from three to four degrees and in grade from level to 6 percent downgrade. A sample of

1,403 trucks were characterized by an average gross weight of 48,300 pounds (21.9 Mg), and included trucks weighing up to approximately 150,000 pounds (68.0 Mg). Table 18 summarizes results of the group comparisons between various categories of truck characteristics. Results are discussed for each classification of traffic operational measures.

Basic Flow Descriptors. A number of mean speed differences were observed between certain groupings. Loaded trucks averaged 53.2 mph (85.6 kph), or 3.7 mph (5.9 kph) slower than empties. This cross-sites effect is somewhat less than that observed within the data sets for some individual curve types (discussed in later sections). As was generally the case at most curve sites, lower mean speeds were also observed for wide-load trucks, double-trailer combinations, and loaded tankers and flatbeds.

Two observed group differences in following behavior demonstrated that trucks designed for larger or heavier loads were associated with shorter following distances. Shorter average tailways (4.2 sec versus 5.2 sec) were found for dual- (as opposed to single-) drive-axle tractor combinations and shorter average headways (4.6 sec versus 6.2 sec) were seen with longer combinations.

Two differences between truck groupings on the basis of lateral lane placement demonstrated that longer trucks position themselves farther from the right edgeline, thereby providing a smaller margin of separation from vehicles in the adjoining left lane. Lane-position differences were small (e.g., 4.8 inches [0.12 m] for long versus short trucks, 3.6 inches [91 mm] for cab-over versus cab-behind), and the truck group keeping the maximum distance from the right edgeline (cab-behind, with 1.97 ft [122 mm] for long versus short trucks, 3.6 inches [91 mm] for of the observed differences in lane placement are interpreted as having negative safety implications.

Table 18

Observed Differences Between Truck Groupings at All Curve Sites (N=1403)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑		▨ ↓		▨ L ↓				▨ L ↓	▨ L ↓	↑ E	↓ E		
	Mean Acceleration										↑ E				
	Headway						▨ L ↑								
	Tailway				▨ ↓										
	Lateral Placement		↓		↑										↑ E
	Flow Perturbations														
	Maximum Acceleration												↓ E		
	Maximum Deceleration				↓										
	Speed Variance														
	Acceleration Variance														
	Stream Speed Difference	▨ ↓		▨ ↑		▨ L ↓				▨ L ↑					
	Proportion Slower	▨ ↓								▨ L ↑					
	Proportion Faster											↑ E			
	Driver Effort														
	Rear-End Accident Potential														
	Critical Headway														
	Critical Tailway														
	Front Closure Rate		▨ ↑			▨ L ↓	L ↑								
	Rear Closure Rate	▨ ↓				▨ L ↓	L ↑			▨ L ↑					
	Projected Time to Collision (Front)														
	Projected Time to Collision (Rear)	▨ ↑										↑ E			
	Flow Delay														
	Queue Length														
	Following Vehicle Speed														
	Following Vehicle Delay														
	Following Queue Speed														
	Following Queue Delay														
	Passing Interactions														
	Probability of Being Passed														
	Probability of Passing					L ↑					L ↓				
	Relative Speed Being Passed	▨ ↓				▨ L ↓				▨ L ↑	▨ L ↑		↑ E		
	Relative Passing Speed														
Truck Characteristics	**Weight**														
	Gross Weight	↓	↓		↑	↓	↓	↑	↑	↑	↑	↑	↑	↑	↑
	Front Axle Weight	↓	↑	↑	↑	↓	↓	↑	↑	↑		↑	↑		↑
	Maximum Axle Weight	↓	↓		↑		↓	↑	↑	↑	↑	↑	↑	↑	↑
	Empty Weight (Estimated)		↑		↑	↓	↓	↑					↑		
	Payload	[illegible]			↑	↓	↓	↑	↑	↑	↑			↑	
	Loading Condition	↓	↓		↑										
	Size														
	Wheelbase	↑	↓		↑	↓	↓	↑	↑	↑	↑	↑	↑		↑
	Overall Length	↑	↓		↑	↓	↓		↑	↑	↑				
	Wide Load														
	Number of Trailers					↓			↑	↑	↑	↓		↑	↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Flow Perturbations. Conflicting safety implications found in this measures group included safer deceleration behavior and less safe stream-speed differences for various types of larger and heavier trucks. Longer trucks in the sample exhibited average values of maximum deceleration of 0.31 ft/sec^2 (0.09 m/sec^2), compared with the less safe 0.49 ft/sec^2 (0.15 m/sec^2) average for the shorter trucks. On the other hand, wider and heavier trucks, noted earlier to be characterized by lower mean speeds, did exhibit higher speed differences from the traffic population. Empty trucks averaged a mere 0.6 mph (1.0 kph) below traffic mean speeds, while loaded trucks exhibited stream-speed differences averaging 3.6 mph (5.8 kph). Loaded double-trailer combinations and loaded tankers exhibited the largest sustained stream-speed difference, while a very small sample (N=3) of trucks carrying wide loads averaged extremely high stream-speed differences of 26.2 mph (42.2 kph).

Loaded trucks, especially tankers, were likely to drive at least one standard deviation below mean traffic speeds. On the other hand, empty auto carriers exhibited a greater tendency than did empty vans to travel at least one standard deviation *above* mean traffic speeds.

Rear-End Accident Potential. A number of group differences based on front and rear closure rates and one difference in projected collision time tended to associate greater accident potential with increased truck size and weight. Double-trailer combinations were most often associated with high closure rates. Given following distances of 10 seconds or less, doubles exhibited both front and rear closure rates greater than those observed for singles. Average closure rates of 13 to 14 ft/sec (4.0 to 4.3 m/sec) were observed for doubles, compared with rates of 9 to 10 ft/sec (2.7 to 3.0 m/sec) for singles. Higher front closure rates were observed for cab-over tractor combinations (10.0 ft/sec [3.0 m/sec]) than for cab-behind (7.3 ft/sec [2.2 m/sec]). Two differences on the basis of rear closure rates were that loaded trucks averaged higher than empties (10.4 versus 7.1 ft/sec [3.2 versus 2.2 m/sec]), with loaded tankers averaging the highest of all (14.5 ft/sec [4.4 m/sec]). Of all the closure-rate differences noted above, only one -- that of loaded tankers -- was sufficiently severe to affect projected collision time. For the sample of trucks being followed at tailways of 10 seconds or less, average projected times to collision were more severe for loaded trucks (124 sec) than for empties (210 sec).

Two group differences within this measures group argue against the idea that increased size and weight contribute to increased rear-end accident potential. Truck combinations characterized by dual drive-axle tractors, which were larger and heavier than the single drive-axle rigs, exhibited safer front and rear closure rates. For trucks following other vehicles at headways of one second or less, average closure rates for duals was 3.3 ft/sec (1.0 m/sec), and for singles, 9.2 ft/sec (2.8 m/sec). In cases where trucks were being followed by other vehicles at tailways of 10 seconds or less, the closure rate for duals was 9.1 ft/sec (2.8 m/sec), and 12.4 ft/sec (3.8 m/sec) for singles.

Flow Delay. No differences were evident between truck groupings in terms of any flow delay measures.

Passing Interactions. Two types of group differences with conflicting size and weight safety implications demonstrated that: (1) certain larger and heavier trucks were less likely to pass other vehicles; and (2) of those trucks being passed, the slower moving larger and heavier ones were passed at higher relative speeds.

The fact that many of the slow-moving trucks discussed earlier were being passed by other vehicles at high relative speeds presents negative safety implications for increased size and weight. Trucks in this category include the groupings (all) loaded trucks, loaded double-trailer combinations, tankers, and flatbeds. Typical of the relative passing speed group differences are average values of 8.6 mph (13.8 kph) for all loaded trucks and 5.9 mph (9.5 kph) for the sample of empty trucks. High relative passing speeds were observed for loaded flatbeds (10.9 mph [17.5 kph] and loaded double-trailer combinations (11.5 mph [18.5 kph]).

Summary. Comparisons between various pairs of truck groupings, based on data collapsed across all curve sites, showed less pronounced differences than those previously reported for grade sites. The majority of the operational differences between truck groupings resulted from a general slowing effect of high truck weight.

In terms of basic flow measures, the group comparisons showed lower mean speeds for loaded trucks, wide loads, loaded double-trailer combinations, loaded tankers, and loaded flatbeds. The magnitude of the speed difference was small (for example, loaded trucks averaged only 3.7 mph [6.0 kph] slower than empties). These lower speeds imparted some perturbative effects to the traffic stream through stream-speed differences for most of those truck groupings. Loaded tankers were more likely than other truck types to be moving at speeds less than one standard deviation below mean traffic speeds.

While dual-drive axle combinations demonstrated a lower rear-end accident potential than singles, a number of other group differences tended to link increased size and weight with greater hazard. Double-trailer combinations were associated with less safe closure rates in their flow interactions with both following and leading vehicles. Higher rear closure rates were also observed for loaded trucks overall, especially for loaded tankers.

However, these closure differences led to more severe projected collision times only in the case of loaded trucks interacting with following vehicles.

In no case did the difference in flow delay measures between groups give any indication that truck size and weight differences had an impact on flow delay across curved sites. Differences on the basis of passing interactions revealed two effects with conflicting safety implications. First, safer behavior was demonstrated by certain larger and heavier truck types (i.e., double-trailer combinations and heavy flatbeds), since they were less prone to passing other vehicles than were some smaller and lighter types (i.e., single trailers and loaded vans). Second, higher relative passing speeds were generally associated with the larger or heavier truck types that exhibited lower mean speeds.

Freeway Curves

Two freeway curve sites, each having curvatures of approximately three degrees, were used in this data set. An applied sample of 1,196 trucks averaged 46,500 pounds (21.0 Mg) gross weight, and contained trucks weighing up to approximately 150,000 pounds (68.0 Mg). As seen in Table 19, a number of group differences were predominantly in the areas of basic flow and stream perturbation measures.

Basic Flow Descriptors. The mean speed of 53.4 mph (86.0 kph) for 825 loaded trucks in the sample was significantly lower than the 57.0 mph (91.7 kph) mean for the 372 empty trucks. A speed differential between loaded and empty trucks was observed separately in the data sets for each site; this consistency was found for most of the differences discussed in this section. Certain truck configurations were found to be associated with lower mean speeds. The slowest trucks in the sample were members of a very small

Table 19

Observed Differences Between Truck Groupings at All Freeway Curve Sites (N=1196)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑		▨ ↓		▨ L ↑ E		▨ L ↓		▨ L ↓	▨ L ↓	↑ E	↓ E	–	↓ E
	Mean Acceleration													–	
	Headway				▨ ↓		▨ ↑							–	
	Tailway									L ↑				–	↓ E
	Lateral Placement		↓		▨ ↑	↑								–	
	Flow Perturbations														
	Maximum Acceleration													–	
	Maximum Deceleration				↓							L ↓		–	
	Speed Variance													–	
	Acceleration Variance													–	
	Stream Speed Difference	▨ ↓		▨ ↑		▨ L ↓		▨ L ↑		▨ L ↑	▨ L ↑		↑ E	–	
	Proportion Slower	▨ ↓				▨ L ↓				▨ L ↑	▨ L ↑			–	
	Proportion Faster											↑ E		–	
	Driver Effort													–	↑
	Rear-End Accident Potential														
	Critical Headway													–	
	Critical Tailway						↑							–	
	Front Closure Rate					▨ L ↓	↑							–	
	Rear Closure Rate	▨ ↓				▨ L ↓				▨ L ↑				–	
	Projected Time to Collision (Front)									↑				–	
	Projected Time to Collision (Rear)													–	
	Flow Delay														
	Queue Length													–	
	Following Vehicle Speed													–	
	Following Vehicle Delay													–	
	Following Queue Speed													–	
	Following Queue Delay													–	
	Passing Interactions														
	Probability of Being Passed													–	
	Probability of Passing		↑			↑					L ↓			–	
	Relative Speed Being Passed	▨ ↓				▨ L ↓		▨ L ↑		▨ L ↑	▨ L ↑		▨ L ↑	–	
	Relative Passing Speed													–	
Truck Characteristics	**Weight**														
	Gross Weight				↑	↓	↓	↑	↑	↑	↑	↑	↑	–	↑
	Front Axle Weight		↑	↑	↑	↓	↓	↑	↑	↑	↑	↑	↑	–	↑
	Maximum Axle Weight		↓		↑	↑	↓	↑	↑	↑	↑	↑	↑	–	↑
	Empty Weight (Estimated)				↑		↓	↑	↑					–	
	Payload	↓			↑	↓	↓	↑	↑		↑		↑	–	
	Loading Condition		↓		↑									–	
	Size														
	Wheelbase	↑	↓		↑	↑	↓	↑	↑	↑	↑	↑	↑	–	↑
	Overall Length	↑	↓		↑	↑	↓	–	↑	↑	↑			–	
	Wide Load			↑							↑			–	
	Number of Trailers				↑				↑	↑	↑			–	↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

group (*N*=3) carrying wide loads; they averaged about 30 mph (48.3 kph). Double-trailer combinations were slower than singles in both the empty and loaded conditions. Loaded tankers and flatbeds exhibited lower mean speeds than van trailer combinations, while heavy-duty Michigan rigs were slower than conventional trucks.

A few findings related to following behavior were seen to have varied safety implications for increased size and weight. In cases of trucks following other vehicles at headways of 10 seconds or less, longer trucks were often seen to follow at closer headways (4.6 sec average) than were shorter trucks (6.5 sec average). Similar headway differences demonstrated that combinations characterized by dual drive-axle tractors followed other vehicles at shorter distances than did single drive-axle combinations. Since closer following behavior was seen to be associated with the particular truck characteristics that allow larger and heavier loads to be accommodated, the two results above are regarded as having adverse safety implications for increased truck size and weight. On the other hand, safer following behavior was associated with loaded tankers, for they were less likely to be "tailgated" than were loaded vans (average tailways were 5.5 sec and 4.3 sec, respectively).

Three observed group differences on the basis of lateral lane placement contained conflicting safety implications. Measurements of the distance of the right front wheel from the right edgeline were used to determine lane position. Favorable to increased truck size was the finding that both cab-over tractors and double-trailer combinations maintained placement closer to the edgeline than did cab-behind rigs and singles, in their respective group comparisons. Lane placements for these two types averaged 1.50 ft (0.5 m) from the edgeline, with the average difference in the group comparisons amounting to only 3½ in. (89 mm). Longer combinations, on the other hand, exhibited larger displacements than the shorter trucks, averaging 1.83 ft (0.6 m) from the edgeline compared to the 1.50 ft (0.5 m) for the shorter combinations (a 4 in [102 m] difference). Although the last of those three differences can be considered to have adverse implications due to the decreased safety margin with respect to vehicles in the adjoining lane, the fact that the longer trucks were nonetheless centered in the lane renders this result negligible in terms of safety.

Flow Perturbations. A number of group differences provided evidence of perturbative behavior resulting from the slowing associated with certain truck characteristics. The largest effect was that higher stream-speed differences were produced for those truck categories described as exhibiting low mean speeds (i.e. loaded trucks, wide loads, double-trailer combinations, heavy-duty Michigan rigs, tankers, and flatbeds). Of these, all but wide loads and Michigan rigs were inclined to exhibit speeds at least one standard deviation below the overall traffic mean speed. These results are interpreted as having negative implications for increased truck size and weight; however, certain other truck behaviors based on deceleration data demonstrated favorable results. That is, longer trucks and loaded auto carriers exhibited less violent maximum decelerations than did shorter trucks and van-trailer rigs, respectively.

Rear-End Accident Potential. Few group differences were observed in terms of critical following distances, closure rates, and projected collision times. The truck type most often associated with adverse effects was the loaded double-trailer combination, which demonstrated higher front and rear closure rates than did singles. Closure rates were approximately 15 ft/sec (4.6 m/sec) for singles, compared to 10 ft/sec (3.0 m/sec) for doubles.

The majority of the observations of high rear-end accident potential resulted from high closure rates between trucks and following vehicles (rather than the reverse). In addition to the doubles mentioned above, loaded trucks in general, and especially loaded tankers, were associated with high rear closures. The average rear closure rate observed for loaded tankers was 15.4 ft/sec (4.7 m/sec). However, loaded tankers exhibited safer behavior in terms of projected time to collision with lead vehicles. Their projected times averaged 403 seconds, compared to 147 seconds for loaded vans.

Flow Delay. No group differences were observed on the basis of flow delay measures. This result demonstrated that observed slowing by trucks was insufficient to cause delay to other vehicles in the stream.

Passing Interactions. Two types of observed group differences were related to passing. First, certain group differences demonstrated a varying likelihood of trucks passing other vehicles, and, second, certain of the trucks already described as slow were passed at higher relative speeds.

Two truck types associated with increased passing behavior were those with cab-over tractors and single-trailer combinations. Taking the sample of trucks observed in the passing lane, cab-overs were more likely to be passing other vehicles (62% passing) than were cab-behind combinations (40% passing). Similarly, 61 percent of the loaded single-trailer combinations were passing other vehicles, in contrast to 27 percent of the loaded doubles. Loaded flatbeds were less likely to pass than were loaded vans (33% versus 68%).

Frequent differences in relative passing speed were seen in comparison with the same groups of "slow" truck types. For example, loaded trucks in general (which averaged 3.6 mph [5.8 kph] slower than empties) were passed at a 2.8 mph (4.5 kph) greater relative speed. A more pronounced difference existed between loaded single and double-trailer combinations. The average relative passing speed observed for singles was 7.5 mph (12.1 kph), while doubles were passed at a 12.0 mph (19.3 kph) relative speed. Other truck types associated with higher relative passing speeds in their respective group comparisons were loaded Michigan heavy-duty rigs, tankers, flatbeds, auto carriers, and dump-trailer combinations.

Summary. Operational effects of size and weight in the freeway curve situation resulted mainly from slowing of heavier trucks. The size of the speed difference was small -- loaded trucks as a group averaged 3.4 mph (5.5 kph) slower than empties. A small sample of wide-load trucks exhibited drastically reduced speeds (an average of 30 mph [48.3 kph]), but the limited size of the sample precluded definitive results regarding their perturbation effects. The following truck types showed weight-related slowing: loaded trucks, double-trailer combinations, heavy-duty Michigan trucks, and loaded tankers and flatbeds. Perturbative effects resulted for most of these truck types, in the form of higher stream-speed differences and an increased likelihood of their driving substantially below the mean traffic speed. Even so, negligible delay was imparted to other vehicles in the stream. Lower truck speeds did, however, result in certain types being passed by other vehicles at higher relative speeds.

Few group differences were observed on the basis of rear-end accident potential. Loaded double-trailer combinations did, however, exhibit higher closure rates than singles with both following and leading vehicles. But their closures did not result in more severe projected times to collision.

In summary, the operational effects of truck size and weight on freeway curves were limited to minimal slowing of certain truck types and appear to have marginal safety consequences.

Nonfreeway Curves

Two nonfreeway curve sites, both in rural areas and with curvatures of approximately four degrees, were selected for the development of this data set. An applied sample of 205 trucks averaged 58,800 pounds (26.7 Mg) per truck and contained maximum weights up to approximately 75,000 pounds (34.0 Mg). As seen from Table 20, relatively few group differences were observed; also, sample limitations precluded observations of wide loads, Michigan heavies, and bulk commodity carriers. Site geometrics did not permit passing interactions.

Basic Flow Descriptors. Loaded trucks in the sample averaged 51.6 mph (83.0 kph), which was significantly slower than the 55.9 mph (89.9 kph) average for the empty sample. Slightly reduced mean speeds (50.2 mph [80.8 kph]) were observed for double-trailer combinations, compared to the speeds of singles (52.2 mph [84.0 kph], mean). More pronounced slowing was seen in the case of loaded tankers (45.3 mph [72.9 kph], average) which were 6 mph (9.6 kph) slower on the average than comparable van-trailer combinations. In the only nonspeed-related group difference, long average headways were observed for logging trucks (5.6 sec) compared to those recorded for comparable van-trailer combinations (2.5 sec).

Flow Perturbations. A number of group differences were observed based on levels of maximum acceleration in the curve. Various types of loaded trucks exhibited extreme acceleration behavior: the average for loaded trucks was 0.57 ft/sec^2 (0.17 m/sec^2), compared to 0.37 ft/sec^2 (0.11 m/sec^2) for empties.[1]

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[1] This effect was observed at a single nonfreeway curve site, which was also characterized by a slight downgrade.

Table 20

Observed Differences Between Truck Groupings at All Non-Freeway Curve Sites (N=205)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Meen Speed	▨ ↑		–		▨ L ↑		–		▨ L ↓					–
	Meen Acceleration			–				–							–
	Headway			–				–						↑	–
	Teilway			–				–							–
	Laterel Placement			–				–							–
	Flow Perturbations														
	Meximum Acceleration	▨ ↓		–				–	▨ L ↑		▨ L ↑			▨ L ↑	–
	Maximum Deceleration			–				–							–
	Speed Variance			–				–							–
	Acceleration Variance			–		↑ E		–						L ↓	–
	Stream Speed Difference			–				–							–
	Proportion Slower			–				–							–
	Proportion Faster			–		L ↑		–							–
	Driver Effort			–		↑ E		–							–
	Rear-End Accident Potential														
	Critical Headway			–				–							–
	Critical Tailway			–				–							–
	Front Closure Rate		▨ ↑	–				–							–
	Rear Closure Rate			–		L ↑		–			L ↓				–
	Projected Time to Collision (Front)			–				–							–
	Projected Time to Collision (Rear)			–		L ↓		–							–
	Flow Delay														
	Queue Length			–				–							–
	Following Vehicle Speed			–				–							–
	Following Vehicle Delay			–				–							–
	Following Queue Speed			–				–							–
	Following Queue Delay			–				–							–
	Passing Interactions														
	Probability of Being Passed	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Probability of Passing	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Relative Speed Being Pessed	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Relative Passing Speed	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Truck Characteristics	**Weight**														
	Gross Weight	↓		–		↓	↓	–	↑	↑	↑			↑	–
	Front Axle Weight		↑	–		↓	↓	–							–
	Meximum Axle Weight	↓	↓	–			↓	–	↑		↑			↑	–
	Empty Weight (Estimated)	↓	↓	–	↓	↑		–		↓					–
	Peyload	↓		–		↓	↓	–	↑	↑	↑			↑	–
	Loeding Condition	↓		–				–							–
	Size														
	Wheelbase	↑		–	↑	↓	↓	–	↑	↑	↑				–
	Overall Length			–	↑	↓	↓	–			↑				–
	Wide Load			–				–							–
	Number of Trailers	↑	↑	–				–		↑			↑		–

Legend:

↑ Higher value for first group.

▨ Adverse implication for increesed size and weight.

demonstrate high levels of acceleration than other loaded truck types, specifically loaded flatbeds and logging trucks. Highest mean maximum accelerations were observed for loaded flatbeds: 0.64 ft/sec^2 (0.20 m/sec^2).

A few other group differences observed for flow perturbation measures indicate safer behavior for larger or heavier trucks. Loaded pole carriers (logging trucks) averaging 74,800 pounds (33.9 Mg) each exhibited a smaller variance in their acceleration behavior than did loaded vans, which averaged 52,000 pounds (23.6 Mg). In addition, loaded double-trailer combinations were less likely (5% occurrence) than loaded singles (21% occurrence) to drive faster than one standard deviation above the mean traffic speed.

Rear-End Accident Potential. Sample restrictions precluded an analysis of rear-end accident potential measures on Michigan heavies, auto carriers, or bulk commodity carriers at nonfreeway curve sites. However, the overall sample of 85 interactions between trucks and lead vehicles and 106 interactions with following vehicles did support a general examination of rear-end accident potential measures. In all, there was only one group difference that implicated truck size and weight with adverse effects. Combinations drawn by cab-over tractors exhibited higher front closure rates (10.2 ft/sec versus 5.2 ft/sec [3.1 versus 1.6 m/sec]) than did those with cab-behind tractors. On the other hand, a small sample of loaded double-trailer combinations being followed at tailways of one second or less were associated with safer behavior than the comparable singles group. The doubles exhibited lower rear closure rates (1.0 ft/sec versus 3.1 ft/sec [0.3 versus 0.9 m/sec]) and longer projected times to collision (89 sec versus 10 sec). In addition, loaded flatbeds being followed at tailways of both 2.0 and 10.0 sec or less were associated with lower rear closure rates than the comparable group of loaded vans. In summary, the analysis of group differences based on rear-end accident potential measures in nonfreeway curve situations demonstrated more favorable than adverse implications for increased size and weight.

Flow Delay. The lack of group differences based on delay measures provided evidence that truck characteristics do not effect delay to other vehicles in nonfreeway curve situations.

Passing Interactions. Geometrics within the nonfreeway curve site grouping did not permit a sufficient sample of passing interactions to support an analysis based on these measures.

Summary. Very few group differences were available to substantiate the suggestion that increased truck size and weight yield adverse operational effects in nonfreeway curve situations. Minimal slowing (51.6 mph versus 55.9 mph [83.0 versus 89.9 kph]) of loaded trucks relative to empties was not large enough to cause either delay to other vehicles or significant flow-perturbative effects. The primary perturbative effect observed for loaded trucks was high acceleration rate. Larger and heavier trucks were seen to exhibit generally safe behavior in terms of rear-end accident-causing behavior. No differences were available in the passing interaction category because of site geometrics and lack of sufficient sample size.

Grade and Curve Combination Sites

The effect of truck size and weight for the combined conditions of curve and grade were examined at two sites, each characterized by both a downgrade and a curve. Downgrade steepness ranged from -4 percent to -6 percent, and curvatures were three and four degrees. A sample of 756 trucks was used in this data set, and truck gross weights ranged up to approximately 75,000 pounds (34.0 Mg). Group differences observed in the analysis are summarized in Table 21.

Table 21
Observed Differences Between Truck Groupings at All Grade and Curve Combination Sites (N=756)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑		▨ ↓		▨ L ↑		–		▨ L ↓	▨ L ↓				
	Mean Acceleration							–							
	Headway	↓			▨ ↓		▨ ↑	–							
	Tailway	↓						–							
	Lateral Placement		↓		↑			–							
	Flow Perturbations														
	Maximum Acceleration							–					↓ E		↓ E
	Maximum Deceleration				↓			–							
	Speed Variance					↑ E		–							
	Acceleration Variance							–							
	Stream Speed Difference	▨ ↓		▨ ↑		▨ ↓		–		▨ L ↑	▨ L ↑				
	Proportion Slower	▨ ↓						–		▨ L ↑					
	Proportion Faster							–					↑ E		
	Driver Effort							–							
	Rear-End Accident Potential														
	Critical Headway					L ↓		–							
	Critical Tailway							–							
	Front Closure Rate	▨ ↑						–							
	Rear Closure Rate	▨ ↑	▨ ↑					–							
	Projected Time to Collision (Front)							–							
	Projected Time to Collision (Rear)							–					↑ E		
	Flow Delay														
	Queue Length							–							
	Following Vehicle Speed							–							
	Following Vehicle Delay	▨ ↓						–							
	Following Queue Speed							–							
	Following Queue Delay	▨ ↓						–							
	Passing Interactions														
	Probability of Being Passed							–							
	Probability of Passing							–							
	Relative Speed Being Passed	▨ ↓				▨ L ↓		–		▨ L ↑	▨ L ↑		▨ ↑ E		
	Relative Passing Speed							–							↑ E
Truck Characteristics	**Weight**														
	Gross Weight	↓	↓		↑	↓	↓	–	↑	↑	↑			↑	
	Front Axle Weight	↓	↑		↑	↓	↓	–	↑	↑		↑			
	Maximum Axle Weight	↓	↓		↑		↓	–	↑	↑	↑			↑	
	Empty Weight (Estimated)	↑			↑		↓	–	↓						
	Payload	↓			↑	↓	↓	–	↑	↑	↑			↑	
	Loading Condition	↓	↓		↑			–							
	Size														
	Wheelbase	↑	↓		↑	↓	↓	–	↑	↑	↑		↑		
	Overall Length	↑	↓		↑	↓	↓	–	↑	↑	↑		↑		↑
	Wide Load							–			↑				
	Number of Trailers	↑	↑		↑	↓		–	↑	↑			↑		↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Basic Flow Descriptors. The primary difference found in this measures group was that larger and heavier trucks exhibited lower mean speeds. Average speed for empty trucks was 55.8 mph (89.8 kph), compared to 50.3 mph (80.9 kph) for loaded trucks. Specific types of loaded trucks exhibiting lower mean speeds in their respective group comparisons were wide loads, double-trailer combinations, tankers, and flatbeds.

Differences in following behavior demonstrated adverse effects of larger truck size, but these were somewhat offset by safer behavior on the part of heavier trucks. Less safe headways were observed, both for longer truck combinations and those with dual drive axles (which were longer than the single drive-axle combinations). Headway differences were obtained for the sample of trucks showing following times of ten seconds or less. Longer trucks followed other vehicles at shorter average headways (4.6 seconds) than did shorter combinations for which the average was 6.4 seconds. Similarly, dual drive-axle combinations averaged 4.8 sec compared to 6.0 sec for the single drive-axle group. On the other hand, safer following behavior was observed for loaded trucks. Front and rear headways averaged approximately 4 sec for loaded trucks, in contrast to 5 sec for empties.

Two differences in lateral placement yielded seemingly conflicting safety implications for size and weight. That is, while cab-over tractor combinations tracked closer to the right edgeline than cab-behinds, and thereby provided a greater margin of safety from adjoining traffic, longer combinations tracked further from the edgeline than did the shorter. A review of the data demonstrated that the largest average lateral displacement from the edgeline associated with long combinations was 1.86 ft (0.57 m). Yet if the trucks were center in the lane, the displacement would be 2.0 ft (0.61 m). Therefore, some margin of safety still remained for the large combinations, and these data are interpreted to show that no adverse effects resulted from the observed differences.

Flow Perturbation. The primary perturbative effect resulted from lower mean speeds exhibited by certain truck types mentioned above. For example, the speed difference between loaded trucks and the traffic stream was about 5 mph (8 kph) greater than that for empty trucks. This difference is nearly equivalent to the mean speed difference between the two truck groups. In their group comparisons, wide loads, loaded double-trailer combinations, tankers, and flatbeds all had the greater stream-speed differences. For these pairings, as well, the gap in stream-speed difference is consistent with the difference in mean speed between the groups. Of those truck groupings travling slower than the traffic stream, loaded trucks, and especially loaded tankers, were likely to be more than one standard deviation slower than the stream mean.

One group difference found to have positive safety implications for increased truck size was that longer combinations exhibited lower average values of maximum deceleration (0.31 ft/sec^2 [0.09 m/sec^2]) than did shorter combinations (0.49 ft/sec^2 [0.15 m/sec^2]).

Rear-End Accident Potential. A few group differences were observed on the basis of closure rates. High front and rear closure rates of approximately 14 ft/sec (4.3 m/sec) were found to be associated with loaded trucks in the sample. By comparison, empty trucks exhibited average front closure rates of 10 ft/sec (3.0 m/sec). Similarly, trucks characterized by cab-over tractors averaged 14 ft/sec (4.3 m/sec) front closure rates, which were significantly higher than the 9 ft/sec (2.7 m/sec) average for cab-behind tractor combinations. It is noteworthy, however, that none of these higher closures resulted in reduced projected times to collision.

Given a small sample (*N*=10) of trucks following other vehicles at headways of one second or less, loaded double-trailer combinations followed at safer headways (0.93 sec, average) than did the comparable group of singles (0.64 sec, average).

Flow Delay. Two observed group differences demonstrated that increased delay was experienced by both single vehicles and vehicle queues behind loaded trucks. Speed delays of 7.6 mph (12.2 kph) slower than mean traffic speeds were observed for vehicles following loaded trucks, compared to delays of 1.4 mph (2.3 kph) for vehicles following empty trucks. Similarly, average delays to queues were 4.2 mph (6.8 kph) for those behind loaded trucks and 0.8 mph (1.3 kph) behind empties.

Passing Interactions. Many of the truck types associated earlier in this section with lower mean speeds were observed to be passed by other vehicles at higher relative speeds. For example, loaded trucks were passed at an average relative speed of 8.6 mph (13.8 kph), while the relative speed of passing for empty trucks was 4.8 mph (7.7 kph). Similar differences were noted in group comparisons involving loaded doubles, tankers, and flatbeds. In addition, because of their apparently higher empty weights, empty dump trailers were also passed at higher relative speeds (8.8 mph [14.2 kph]) than the comparable group of van trailers (3.9 mph [6.3 kph]).

Summary. Lower comparative speeds, differing by about 5 mph (8 kph) from those of the other truck groupings, were exhibited by certain larger and heavier truck types (e.g., loaded trucks, wide loads, and loaded double-trailer combinations, tankers, and flatbeds). These lower truck speeds resulted in a perturbative effect -- greater deviations from the average traffic speed. Two other measured residuals of the lower speeds were: (1) these trucks were passed at higher relative speeds, and (2) increased speed delay was experienced by both single vehicles and vehicle queues following loaded trucks.

Few differences in rear-end accident potential were observed. Slightly more dangerous following behavior was associated with loaded trucks in terms of higher front and rear closure rates, yet these did not result in more severe projected collision times. Higher rear closure rates were also observed with cab-over than with cab-behind tractor combinations.

All Sites

This set of truck grouping comparisons, based on a sample of 5,008 observations, is comprised of data collected across all sites. A variety of geometric conditions were represented, including six grade sites, ranging in grade from -7 percent to +7 percent and in length from ½ to 1½ miles (0.8 to 2.4 km), and four curve sites, both freeway and nonfreeway. Table 22 summarizes the results of the analysis, discussed below for each classification of traffic operational measure.

Basic Flow Descriptors. Group differences in this measures category seemed to indicate that, while speed was affected by truck weight, acceleration performance related more closely to truck size.

The average speed for loaded trucks in the sample, 49.1 mph (79.0 kph), was significantly lower than that for empty trucks, 51.9 mph (83.5 kph). Certain types of loaded trucks were seen to drive more slowly than the sample of loaded vans, which averaged 49.7 mph (80.0 kph). These were loaded tankers (45.0 mph [72.4 kph]) and dump-trailer combinations (41.6 mph [66.9 kph]). The configuration of loaded trucks was also seen to impact on speed: double-trailer combinations averaged 2.8 mph (4.5 kph) slower than singles. One speed-related group difference observed for empty trucks was that single drive-axle rigs averaged 2.7 mph (4.3 kph) slower than those with dual drive axles.

Table 22

Observed Differences Between Truck Groupings at All Sites (N=5008)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑				▨ L ↑	↓ E			▨ L ↓			▨ L ↓		
	Mean Acceleration				▨ L ↓	▨ L ↑									
	Headway														
	Tailway														
	Lateral Placement														
	Flow Perturbations														
	Maximum Acceleration				↓										
	Maximum Deceleration					▨ L ↓	▨ L ↑								▨ L ↑
	Speed Variance														
	Acceleration Variance														
	Stream Speed Difference	▨ ↓						▨ L ↓		▨ L ↑			▨ L ↑		
	Proportion Slower	▨ ↓						▨ L ↑		▨ L ↑					
	Proportion Faster														
	Driver Effort														
	Rear-End Accident Potential														
	Critical Headway														
	Critical Tailway		↑				↓ E					▨ L ↓			
	Front Closure Rate														
	Rear Closure Rate	▨ ↓				▨ L ↓		▨ L ↑		▨ L ↑		L ↓	▨ L ↑		
	Projected Time to Collision (Front)					↓ E									
	Projected Time to Collision (Rear)				↑							↑ E			
	Flow Delay														
	Queue Length	▨ ↑												—	
	Following Vehicle Speed	▨ ↓	▨ ↑			L ↑		▨ L ↑					↑ E	—	
	Following Vehicle Delay	▨ ↑												—	
	Following Queue Speed	▨ ↓				L ↑		▨ L ↑						—	
	Following Queue Delay													—	
	Passing Interactions														
	Probability of Being Passed														
	Probability of Passing	▨ ↑			▨ ↑			↑ E							
	Relative Speed Being Passed	▨ ↓				▨ L ↓		▨ L ↑		▨ L ↑			▨ L ↑		
	Relative Passing Speed	▨ ↑													
Truck Characteristics	**Weight**														
	Gross Weight	↓	↑		↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Front Axle Weight		↓		↑	↓	↓	↑	↑	↑	↑	↑	↑		↑
	Maximum Axle Weight	↓	↑		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Empty Weight (Estimated)	↑			↑	↓	↓	↑					↑		
	Payload	↓			↑	↓	↓	↑	↑	↑	↑		↑		↑
	Loading Condition	↓	↓		↑										
	Size														
	Wheelbase	↑	↑		↑	↑	↑	↑	↑	↑	↑		↑	↑	↑
	Overall Length	↑	↑		↑	↓	↓		↑	↑	↑		↑		↑
	Wide Load	↑	↑												
	Number of Trailers	↑			↑	↓			↑	↑		↓			↑

Legend:
↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Two group differences based on mean acceleration behavior demonstrated that larger trucks have a decreased ability to maintain speed. Longer trucks in the sample (average overall length, 72.1 ft [22.0 m]) exhibited average acceleration values of -0.35 ft/sec^2 (0.11 m/sec^2), while shorter trucks (average length, 42.6 ft [13.0 m]) exhibited mean accelerations of -0.11 ft/sec^2 (-0.03 m/sec^2). Similar acceleration values were evident in the comparison of loaded double-trailer combinations (-0.29 ft/sec^2 [-0.09 m/sec^2]) with single-trailer combinations (-0.11 ft/sec^2 [-0.03 m/sec^2]). Negative values of acceleration probably resulted from the fact that geometric conditions utilized in this study were ones in which trucks are likely to experience operational difficulties. No meaningful group differences were found in the all-sites data set for measures of headway, tailway, or lateral placement.

A few differences, reflected in certain tables of Appendix C but not reported here, were deemed spurious as a result of across-sites inconsistencies in truck performance. Such instances of nonreportable group differences are established on the basis of an examination of site-specific data sets.

Flow Perturbations. The more limited ability of longer trucks to accelerate, described above, was also evidenced by observed differences in maximum accelerations. Shorter trucks averaged 0.61 ft/sec^2 (0.19 m/sec^2), compared to a significantly lower value of 0.39 ft/sec^2 (0.12 m/sec^2) for the long-trucks sample. However, maximum acceleration, being a perturbative measure, renders conflicting safety implications when contrasted with the basic flow measure of mean acceleration described previously. That is, while longer trucks demonstrated a lesser ability to maintain speed (based on the means of all measured accelerations), they also contributed a smaller perturbative effect in terms of maximum accelerations. It is worth noting, too, that neither did their maximum deceleration differences constitute an increased perturbative effect (see below).

Maximum measured values for deceleration demonstrated several group differences linking higher perturbation effects with certain truck characteristics. For those loaded double-trailer combinations in our sample that were observed to decelerate (*N*=482), the maximum observed deceleration averaged -0.82 ft/sec^2 (-0.25 m/sec^2). Yet the comparable group of loaded single-trailer combinations (*N*=1,084) showed a lower value, -0.58 ft/sec^2 (-0.18 m/sec^2) on the average. Similarly, single drive-axle tractors were found to be associated with greater maximum deceleration performance, -0.72 ft/sec^2 (-0.22 m/sec^2), compared to -0.55 ft/sec^2 (-0.17 m/sec^2) for dual drive-axle rigs. The truck type demonstrating the highest level of deceleration was the bulk commodity carrier, averaging -1.57 ft/sec^2 (-0.48 m/sec^2). Our sample of decelerative bulk commodity carriers (*N*=51) represents a very heavy subpopulation, averaging 96,700 pounds (43.9 Mg).

No group differences for the sample were observed on the basis of speed or acceleration variance.

Trucks slowing below mean traffic speeds were seen to produce a number of group differences as evidenced by two measures, stream-speed difference and proportion driving below mean speed. Because these measures are similar, observed differences in each are discussed concurrently. Truck loading condition resulted in highly pronounced differences in both measures. Loaded trucks traveled at speeds farther below mean traffic speeds than did empties (5.6 mph versus 2.1 mph (9.0 versus 3.4 kph), and they were much more likely to be at least one standard deviation below mean speed (46% of loaded sample, versus 26% of empty sample). Considerable slowing effects relative to overall stream-speed were noted in the case of loaded heavy-duty truck types in Michigan. These trucks traveled at significantly greater speed differences from the mean than did loaded conventional combinations (12.9 mph [20.8 kph] for Michigan, versus 5.2 mph [8.4 kph] for conventional). Additionally, 78 percent of the loaded heavy-duty Michigan sample met the criterion of being at least one standard deviation below the stream mean speed, compared to only 45 percent of the loaded conventional sample. Greatest speed differences below the mean were observed for loaded tankers and dump-trailer combinations.

No group differences existed for the two remaining flow-perturbation variables: proportions faster than the mean speed and driver effort (i.e., product of displacement and speed differences).

Rear-End Accident Potential. Critical following distances, closure rates and projected times to collision were compared across truck groupings. No differences were apparent involving trucks interacting with leading vehicles. The implication here is that no adverse effect due to improper following behavior by trucks could be associated with any particular truck grouping.

However, a number of differences were seen to result from interactions between trucks and following vehicles. Conflicting findings, in terms of safety implications, were noted for critical tailways. In cases of following at one second or less, combinations characterized by cab-behind tractors were followed slightly more closely than were cab-over rigs. On the other hand, loaded auto carriers were likely to be followed more closely than vans. More definitive findings, though, were evident from observed differences in rear closure rates.

Loaded trucks were generally associated with more hazardous closure rates with following vehicles. That is, for cases in which trucks were followed at tailways of 10 seconds or less, the average closure rate associated with all loaded trucks was 12.2 ft/sec (3.7 m/sec) in contrast to that of 8.6 ft/sec (2.6 m/sec) for empties. Specific types of loaded trucks were susceptible to high rear closure rates: doubles, Michigan heavies, tankers, and dump-trailer combinations. Highest rear closure rates, averaging 17.7 ft/sec (5.4 m/sec), were observed for the sample (*N*=81) of Michigan heavy-duty combinations. No group differences relating to projected collision times contained adverse implications for increased truck size and weight. In fact, for the sample of trucks followed by other vehicles at two seconds or less, longer trucks averaged safer projected collision times (96 sec) than did shorter trucks (38 sec).

Flow Delay. Slight delay to traffic in the stream was found to be associated with loaded trucks. Vehicles and queues following loaded trucks averaged approximately 2.3 mph (3.7 kph) slower than those behind empties. The speeds of the trucks themselves were reduced below normal traffic flow speeds by approximately the same margin. Additionally, vehicles behind cab-over tractor combinations experienced speed delays 1.3 mph (2.1 kph) greater than those following cab-behind combinations. Substantial delay was experienced by a small sample of vehicles following loaded heavy-duty trucks in Michigan. Delays of 14.8 mph (23.8 kph) below normal traffic speeds were noted for vehicles queued behind loaded Michigan doubles.

Passing Interactions. Certain group differences emerged on the basis of passing occurrences and relative speeds. Not surprisingly, a greater proportion of empty than loaded trucks (39% versus 28%) were observed to pass other vehicles. Also, longer trucks exhibited a greater tendency to pass. Other group differences indicated that heavier trucks were generally passed by other vehicles at higher relative speeds. Specifically, loaded trucks were passed 4.2 mph (6.8 kph) faster (12.0 versus 7.8 mph [19.3 versus 12.6 kph]) than were empty trucks. Higher relative passing speeds were also noted for loaded doubles, Michigan heavies, tankers, and dump-trailer combinations. In many cases, empty trucks were observed to pass other vehicles at an average relative passing speed of 3.5 mph (5.6 kph); by contrast, loaded trucks were passed on the right at relative speeds averaging 2.8 mph (4.5 kph).

Summary. Various operational differences were found between truck groupings based on the total sample (*N*=5,008) for this study. In general, the magnitude of differences was sufficiently small to yield minimal operational effects of size and weight.

Basic flow descriptors revealed that loaded trucks averaged 2.8 mph (4.5 kph) slower (49.1 mph [79.0 kph], empty; 51.9 mph [83.5 kph], loaded) than empties; and within the loaded sample, larger trucks demonstrated reduced accelerative capabilities. A perturbative effect observed for this group was a tendency toward more pronounced decelerative behavior. The perturbative effect of increased truck weight was evident on the basis of the slowing of certain truck types below traffic means. Loaded Michigan heavy-duty combinations demonstrated a pronounced effect of this type, averaging 12.9 mph (20.8 kph) below mean traffic speeds, in comparison to loaded conventional combinations at 5.2 mph (8.4 kph) below.

The result of rear-end accident potential measures indicated a greater hazard associated with vehicles following trucks rather than with trucks following vehicles. Critical tailways and higher rear closures were more likely to occur with loaded than with empty trucks. Highest average rear closure rates (17.7 ft/sec [5.4 m/sec]) were observed for loaded Michigan heavy-duty combinations; by contrast, the average for empty trucks in the sample was 8.6 ft/sec (2.6 m/sec]). However, average projected times to rear-end collision revealed no adverse size and weight effects. On the contrary, longer trucks demonstrated safer projected collision times.

Slightly greater speed delays (by approximately 2 mph [3.2 kph]) were noted for vehicles and queues following loaded trucks, compared to those behind empties. The highest observed delays imparted to other vehicles were average speeds of 14.8 mph (23.8 kph) below traffic means for vehicles and cueues following loaded heavy-duty combinations in Michigan. Differences in passing behavior were that loaded trucks were associated with a greater likelihood of being passed, and that this passing was characterized by higher relative speeds than was noted for empty trucks.

Second Step (Correlative) Analysis

The designated independent (truck characteristic) variables warranted a variety of analytical techniques. For example, truck characteristics readily described using a dichotomous variable set (e.g. double versus single trailer) are most amenable to a group comparison treatment; while a continuous variable set (e.g. gross weight) must be subjected to some form of correlative treatment. Therefore, while the first step analysis treated operational differences between specific groups of trucks, a more detailed examination of certain truck characteristic effects was approached via a correlational analysis of relationships between certain variables.

The correlative method utilized for this analysis applied the Pearson product-moment coefficient (r) to variable pairs. Those variables previously introduced in the group comparison tests were used to develop 44x44 correlation matrices which are contained in Appendix D. Rather than to present voluminous tables and result discussions in this text, findings presented herein will be limited to correlations between gross truck weight, overall length, and operational variables. Gross weight, while comprising only one of a number of observed weight descriptors, is emphasized in this discussion not only due to its appropriateness and direct effects on operational behavior, but also due to its regulatory relevance to study objectives. While also of regulatory interest, overall length was chosen due to the sensitivity with which we obtained the measure as well as its aptness in describing truck size. It is to be recalled that truck width was treated in the preceding discussion of group comparisons.

Although many of the obtained correlations discussed herein represent fairly weak relationships between variables (i.e. the range of r is from 0.08 to 0.62), they are nevertheless of considerable statistical significance. Discussed values of r, while dependent on sample size, are most often significant at the 0.001 level and are never weaker than the 0.01 level. The reader should bear in mind that this significance level is merely a measure of statistical power rather than a measure of the relationship between the variables. As will be indicated by the values of r, minimal associations were most frequently found to exist between truck size/weight characteristics and operational performance. The squared correlation coefficient (r^2) provides an indication of the predictive relationship between variables. For example, an r of 0.60 between truck speed and weight can be interpreted as follows: 36 percent of the observed variance in truck speed is attributable to weight effects.

Correlative effects of gross weight are discussed first, followed by a discussion of length effects.

The Effect of Weight

Upgrades. Due to the fact that most promising correlative results were obtained for upgrade site conditions, these are more thoroughly treated to the extent that certain site-specific findings are included in Table 23. Interpretations of specific correlations are separately discussed for each upgrade condition.

In the case of the short slight-grade site (N=253), significant correlations were obtained between gross weight and five operational variables. As generally demonstrated throughout the analysis, gross weight correlated more highly (r= -0.45) with mean speed than with other operational parameters. The obvious implication of this finding is that trucks with higher gross weights somewhat consistently demonstrated lower speeds. The numerical value of r would indicate that, given truck sample speed and weight characteristics observed at this site, 20% of the variance in truck speed was attributable to differences in gross weight. Gross weight was also shown (r=0.41) to affect the extent to which trucks slowed below stream speed averages. As previously pointed out in the first step analysis, greater stream differences were observed for trucks characterized by higher gross weights. Remaining correlations obtained for this site indicate that heavier trucks exhibited poorer acceleration behavior (r= -0.40) and were more likely to fall into the "drive slow" category (i.e., one standard deviation below the stream mean speed). The single correlation with a direct rear-end accident potential measure (r=.33) revealed more dangerous closure rates between heavier trucks and following vehicles.

Results in the table for the long slight-grade site depict significant correlations between gross weight and 10 operational variables. A sample of 770 observations comprised this data subset. The larger number of correlations attests to a greater effect of gross weight on truck performance at this longer site. A stronger slowing effect (r= -0.59) of gross weight on speed was obtained than for the shorter grade. Similarly, heavier trucks were also shown to exhibit greater deviations from mean traffic speeds:

Table 23

Correlation Coefficients (r) Obtained for Gross Truck Weight and Selected Operational Variables at Upgrade Sites ($\alpha = .001$)

Upgrades				
Short, Slight	Long, Slight	Short, Steep	Long, Steep	Combined Sites
Mean Speed (-.45)	Mean Speed (-.59)	Mean Speed (-.61)	Mean Speed (-.60)	Mean Speed (-.27)
Stream Speed Difference (-.41)	Stream Speed Difference (.59)	Stream Speed Difference (.54)	Stream Speed Difference (.56)	Stream Speed Difference (.45)
Maximum Acceleration (-.40)	Maximum Acceleration (-.25)	Average Acceleration (-.52)	Proportion Slower (.44)	Maximum Acceleration (-.27)
Proportion Slower (.32)	Rear Closure Rate (.34)	Speed Variance (.62)	Relative Passed Speed (.47)	Speed Variance (.16)
Rear Closure Rate (.33)	Proportion Slower (.40)	Rear Closure Rate (.38)		Proportion Slower (.38)
	Follow Vehicle Speed (-.37)	Time to Rear Collision (.-.19)		Rear Closure Rate (.24)
	Follow Vehicle Delay (.42)	Proportion Slower (.42)		Follow Vehicle Speed (-.27)
	Follow Queue Speed (-.38)	Relative Passed Speed (.47)		Follow Vehicle Delay (.33)
	Follow Queue Delay (.43)			Follow Queue Speed (-.26)
	Relative Passed Speed (.40)			Follow Queue Delay (-.32)
				Relative Passed Speed (.31)

this effect was as equally pronounced (r=0.59) as that of general slowing of heavier trucks. As was the case on the shorter grade, heavier trucks demonstrated more sluggish acceleration behavior, were likely to fall into the "drive slow" category, and were associated with higher rear closure interactions with following vehicles. Four additional significant correlations provided evidence that slowing trucks on this grade site affected the speeds of following traffic. Lower speeds were observed for single vehicles and queues (r= -0.37 and -0.38, respectively) behind trucks characterized by higher gross weights. Moreover, these vehicles and queues behind heavier trucks experienced significantly greater speed delays (i.e. reductions below stream averages). Finally, higher relative passing speed differentials were associated (r=0.40) with trucks having higher gross weights.

A sample of 542 observations provided the basis for correlational analyses at the short steep-upgrade site. As discussed in the previous group comparison analysis, a considerable perturbative effect resulted from slowing trucks at this site. A number of observed correlations between gross weight and operational measures corroborate this earlier finding. First, greater mean decelerations (r=0.52) and speed variances (r=0.62) were seen to be associated with higher gross weights. Second, that flow effects from heavier trucks involved following vehicles was evidenced by higher rear closure rates (r=0.38) and shorter projected collision times (r= -0.19) with following vehicles. The average projected observed time to rear-end collision was 43.9 seconds for a sample of 327 vehicles following trucks at headways of 10 seconds or less. Significantly shorter times were associated with heavier trucks. For a sample of 70 vehicles following at 2 seconds or less, the average projected time was 19.1 sec; however, due to the smaller sample and higher variance in times, this variable did not significantly correlate with gross weight. Similar correlational effects of higher gross weight to those observed for other upgrade conditions were lower speeds (r=0.16), higher mean stream speed differences (r=0.54), and higher relative passing speeds by other vehicles (r=0.47).

Although greater slowing of heavier trucks also occurred at the long steep-upgrade site, fewer significant correlations were evident due to the fact that stream perturbations were damped out and traffic generally avoided interacting with trucks (due to adequate number of lanes at this site). Four correlations with gross weight were based on a sample of 500 observations. Strong correlations again demonstrated greater slowing (r=0.60) and mean stream speed differences (r=0.56) on the part of heavier trucks. As in the previously discussed cases of upgrade sites, heavier trucks were more prone to fall into the "drive slow" category (r=0.44) and to be passed by other vehicles at higher speeds (r=0.47). Anecdotally, it is noteworthy that a severe rear-end accident involving a slow-moving and fully loaded truck was observed during data collection at this site, thereby attesting to the presence of rear-end collision hazard. However, no significant correlation was obtained between gross weight and projected collision time at this site. A number of factors need to be considered in assessing both the presence of the hazard and the absence of the significant correlation. Trucks at this site moved more slowly than at the previously noted shorter grade site, where collision times correlated with gross weight. Such speed reduction could present a potentially greater hazard. However, sufficient time had elapsed since the initial slowing of trucks to provide motorists (all but one!) adequate time to adjust their speed or position to avoid a rear-end collision. Therefore, a smaller sample (*N*=135) was observed to be closely following trucks, and they were following at safer closure rates.

Combined data across the four upgrade sites were examined for correlative effects to present a more general description of operational effects. Due to the large sample (*N*=2,065), lower values of r than those previously discussed were shown to be significant at the 0.001 level. A weaker correlation between gross weight and speed (r= -0.27) resulted from speed variations (for nearly equal weight distributions) between sites, yet the relation showing reductions below stream mean speeds for heavier trucks remained fairly strong (r=0.45). The uniform tendency across sites for heavier trucks to travel at least one standard deviation below traffic means was demonstrated by a significant r of 0.38 which was typical of within-site findings. This data set revealed weak across-site tendencies for heavier trucks to exhibit higher speed variance (r=0.16) and reduced acceleration performance (r= -0.27). That heavier trucks produced more speed reduction and delay to following vehicles and queues across sites was evident on the basis of correlations between gross weight and four operational variables. Two additional perturbative operational effects, increasing with gross weight, were that higher closure rates arose from interactions with following vehicles and higher relative speed differentials resulted from passing vehicles.

Downgrades. By comparison with results obtained for the upgrade conditions, relatively few operational effects of gross weight were found at downgrade sites (see Table 24). These limited findings are separately discussed for three downgrade conditions as follows: long, 3-percent; steep; and long.

The long 3-percent downgrade is of special interest due to its frequent occurrence within the Interstate System. A sample of 380 observations comprised this data set. That no significant correlation was observed here between gross weight and speed tended to refute the common belief that heavier trucks speed up

Table 24

Correlation Coefficients (r) Obtained for Gross Truck Weight and Selected Operational Variables at Downgrade Sites

Three Percent, Long	Steep	Long
Rear Closure Rate (-.23)	Mean Speed (-.41)	Proportion Slower (.13)
Time to Rear Collision (.38)	Proportion Slower (.31)	Stream Speed Difference (.16)
Probability Passed (.29)	Stream Speed Difference (.41)	Maximum Deceleration (.17)
Relative Passed Speed (.28)	Proportion Faster (-.12)	Rear Closure Rate (.19)
	Relative Passed Speed (.41)	
	Rear Closure Rate (.32)	

on downgrades. In fact, significant correlations shown in the table demonstrated certain safer behavior on the part of heavier trucks. A negative correlation with rear closure rate (r= -0.23) and a positive relation to projected rear-end collision time (r=0.38) clearly demonstrated that decreased accident potential was associated with heavier trucks at this site. This finding is that the higher the gross weight, the lower the relative speed and the longer the projected collision time from following vehicles. Two additional correlations related to passing behavior. Heavier trucks were associated with more incidences of passing which occurred at higher relative speeds.

A few more correlative effects of gross weight were observed for the steep downgrade sites (N=1,370). The primary observed operational effect was lower speeds exhibited by trucks with higher gross weights (r= -0.41). Two residual effects of the lower speeds were that heavier trucks tended to fall into the "drive slow" grouping (r=0.31), and they were also characterized by greater deviations below mean traffic speeds (r=0.41). That heavier trucks maintained controlled speeds on the steep grades was evident by a negative correlation (r= -0.12) with their incidence of meeting the "drive fast" (i.e. one standard deviation above traffic mean) criterion. An expected result due to their lower speeds, heavier trucks were passed by other vehicles at higher relative speeds. One finding, related to rear-end accident potential, was that heavier trucks experienced more dangerous relative speed closures from following vehicles.

While no direct correlation between gross weight and speed was observed at the long downgrade sites (*N*=1,073), there were slight tendencies for heavier trucks to meet the "drive slow" criterion (r=0.13) and to exhibit greater deviations below mean traffic speeds (r=0.16). Heavier trucks were slightly (r=0.17) prone to exhibit higher levels of deceleration. As was the case for the previously discussed downgrade conditions, although to a lesser extent, higher rear closure rates were shown to be associated with heavier trucks.

In summary, relatively few adverse operational effects of gross weight were observed at the downgrade sites. The operational effect observed across sites having the greatest safety implication was more dangerous closure rates from vehicles following the heavier trucks. While this closure rate result applied to vehicles following at headways of 10 seconds, the effect was not observed for following times of one or two seconds. Additionally, the increased closure rates did not result in decreased projected times to collision.

Curves. Results of the correlative analysis (see Table 25) are discussed for freeway curves, nonfreeway curves, and grade/curve combinations.

Gross weight did correlate with seven operational variables in the data set collected for freeway curves (*N*=1,198). The average truck speed for these sites was 54.6 mph (87.9 kph), with the

Table 25

Correlation Coefficients (r) Obtained for Gross Truck Weight and Selected Operational Variables at Curve Sites

Freeway	Non-Freeway	Grade and Curve
Mean Speed (-.28)	Mean Speed (-.40)	Mean Speed (-.48)
Stream Speed Difference (.32)	Speed Variance (.22)	Stream Speed Difference (.47)
Proportion Slower (.25)		Proportion Slower (.36)
Proportion Faster (-.11)		Proportion Faster (-.13)
Relative Passed Speed (.29)		Rear Closure Rate (.43)
Rear Closure Rate (.25)		Relative Passed Speed (.37)
Time to Rear Collision (.14)		

heavier trucks exhibiting lower speeds (r= -0.28). As expected, heavier trucks showed greater reductions below traffic mean speeds; and due to across-site speed difference, this correlation was slightly stronger (r=0.32) than the weight-versus-speed relationship. It follows that the heavier trucks were more likely to meet the "drive slow" criterion (r=0.25) and less likely to meet the similarly-defined "drive fast" criterion (r= -0.11). As was the case with the previously discussed geometric conditions, heavier trucks were passed by other vehicles at higher relative speeds (r=0.29). Two correlations were insightful regarding rear-end accident potential as related to gross weight. Higher closure rates from following vehicles (r=0.25), and to a lesser degree, shorter projected rear collision times (r=0.14) were found to be associated with heavier trucks. It should be noted that this last effect, although significant at the 0.01 level, is a relatively weak statistical relationship.

The data set describing nonfreeway curves (*N*=205) contained only two correlations between gross weight and operational variables. Heavier trucks exhibited lower speeds (r= -0.40) and higher speed variances (r=0.22).

Two sites containing combinations of downgrades and curves were also examined for operational effects of gross weight. The sample size for this data was 756 observations. Six observed operational effects associated with higher gross weight were as follows: lower mean speeds (r= -0.48), greater deviations below mean traffic speeds (r=0.47), greater propensity to meet "drive slow" criterion (r=0.36), lower tendency to meet "drive fast" criterion (r= -0.13), higher closure rates from following vehicles (r=0.43), and higher relative speeds by passing vehicles (r=0.37).

All Sites. Combined data representing all sites (N=5,008) was examined for correlative effects of truck weight (see Table 26). Significant correlations were found between gross weight and nine operational variables.

As generally noted, lower mean speeds were observed for heavier trucks: a diminished correlation (r= -0.14) resulted due to speed variability across sites. Stronger statistical relationships demonstrated the speed reduction of heavier trucks by relating their speeds to site specific flow rates. Larger stream speed differentials (r=0.26) and a greater tendency to meet the "drive slow" criterion (r=0.21) were associated with higher gross weight. The effect of gross weight on certain perturbative behaviors was much less pronounced. That is, higher speed variance and greater decelerations showed a very low correlation (r=0.08) to gross weight. One measure of accident potential, rear closure rate, demonstrated some increased hazard (r=0.18) to be associated with heavier trucks. A number of expected results related to passing behaviors. Heavier trucks were less likely to initiate passing (r= -0.09), and they passed at lower relative speeds (r= -0.24) than noted for lighter trucks. Finally, heavier trucks were passed by other vehicles at higher relative speeds (r=0.26).

Table 26

Correlation Coefficients (r) Obtained for Gross Truck Weight and Selected Operational Variables at all Sites ($\alpha = .001$)

Mean Speed (-.14)
Stream Speed Difference (.26)
Proportion Slower (.21)
Speed Variance (.08)
Maximum Deceleration (.08)
Rear Closure Rate (.18)
Passing Probability (-.09)
Relative Passed Speed (.26)
Relative Passing Speed (-.24)

The Effect of Length

Correlations between overall truck length and all operational variables were obtained on the same data sets applied in the preceding discussion of weight effects. By comparison, very little operational effect was found.

Upgrades. As seen from Table 27, data taken individually for four grade sites contained only one correlative effect of truck length. In the case of the long slight-grade site, less severe (r= -0.39) front closure rates were observed for longer trucks. That is, longer trucks maintained safer relative speeds with regard to leading vehicles.

Combined data across the four upgrade sites revealed four correlations between overall length and operational variables. A slight tendency (r= -0.14) for longer trucks to travel at lower speeds may be a residual effect of higher weight. This and other performance degradations found for the longer trucks were similar, though less pronounced in nature, to those previously described weight effects. Other correlative effects associated with length

Table 27

Correlation Coefficients (r) Obtained for Overall Truck Length and Selected Operational Variables at Upgrade Sites

Short, Slight†	Long, Slight	Short, Steep†	Long, Steep†	Combined Sites
	Front Closure Rate (-.39)			Mean Speed (-.14) Mean Acceleration (-.28) Speed Variance (.17) Maximum Deceleration (-.22)

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†No significant r($\alpha \leqslant .001$)

were reduced levels of acceleration (r= -0.28) and deceleration (r= -0.22) and higher speed variance (r=0.17). These lower values of r are significant, although indicative of relatively weak statistical relationships, due to the large sample (*N*=2,065) obtained by combining similar sites. The interpretation of these findings is that overall length has a minimal effect on traffic operations.

Downgrades. As in the case of upgrades, little operational effect was attributable to overall truck length (see Table 28). No significant correlations of practical consequence were obtained between length and operational variables for either the long, 3-percent downgrade or the steep-downgrade sites. Three weak findings for long downgrades were that longer trucks tended to exhibit lower speeds (r=0.10), higher speed variance (r=0.11) and lower levels of acceleration (r= -0.13).

Curves. Similarly, that little correlative effect of length on traffic operations was evident at curve sites is shown in Table 29. Lower speed variance was shown for longer trucks on freeway

Table 28

Correlation Coefficients (r) Obtained for Overall Truck Length and Selected Operational Variables at Downgrade Sites

Three percent, Long†	Steep†	Long
		Mean Speed (.10) Speed Variance (.11) Maximum Acceleration (-.13)

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†No significant r (α = .01)

Table 29

Correlation Coefficients (r) Obtained for Overall Truck Length and Selected Operational Variables at Curve Sites

Freeway	Non-freeway	Grade and Curve
Speed Variance (-.11)	Proportion Faster (-.34)	Speed Variance (-.11)

curves (r= -0.11), and this same effect was reflected in the combined data set across all curve sites. The interpretation of this finding is that safer behavior was associated with the longer trucks. A similar safety implication derives from the fact that longer trucks were less likely to meet the "drive fast" criterion (i.e. significantly exceed the mean traffic speed) on nonfreeway curves. One weak correlation was obtained between overall length and operational variables at the grade-and-curve combination sites (i.e. lower speed variance, r= -0.11). Collectively, the correlative analysis showed no detrimental operational effects of overall truck length at the curve sites.

All Sites. Combined data representing all sites (N=5,008) was examined for correlative effects of overall truck length. Only one operational variable (mean speed) was significantly correlated with length. A weak tendency (r= -0.09) was observed for longer trucks to travel at lower speeds.

Third Step (Predictive Modeling) Analysis

Having examined truck weight and length correlations to operational variables in the second step, this step explored the extent to which operational effects could be predicted on the basis of measured truck characteristics. Model developmental effort and achieved results are separately discussed.

Development of Predictive Models

After the initial partitioning of the data and generation of statistics for the subgroups of interest (e.g., various truck loading and geometric conditions), regression analysis was used in an attempt to formulate causal and predictive models of vehicle behavior. A variant of the popular BMD-02R step-wise regression program was used. This program estimates the predictive power of various parameters to affect the value of a dependent variable. After careful consideration of the candidate parameters, using both analytic and deductive techniques, a two-stage model of vehicle behavior was postulated. This model is depicted schematically in Figure 11. All measurements in the data base fall in the vehicle behavior category, i.e. they are attributes associated with the vehicle/roadway combination. Only a few may be properly characterized as control variables. Those variables used as controls are gross weight, length, maximum axle weight, and to a lesser extent, wheel base, front axle weight and payload. One factor, truck mean speed, exhibited considerable variation and a few high linear correlations with all variables. Table 30 gives values of the correlation coefficient between mean speed, loaded trucks, and several variables of both categories.

Though the model shown in Figure 11 is properly estimated by two-stage least squares (or three-stage, if the ultimate question of vehicle safety were considered), first attempts used ordinary

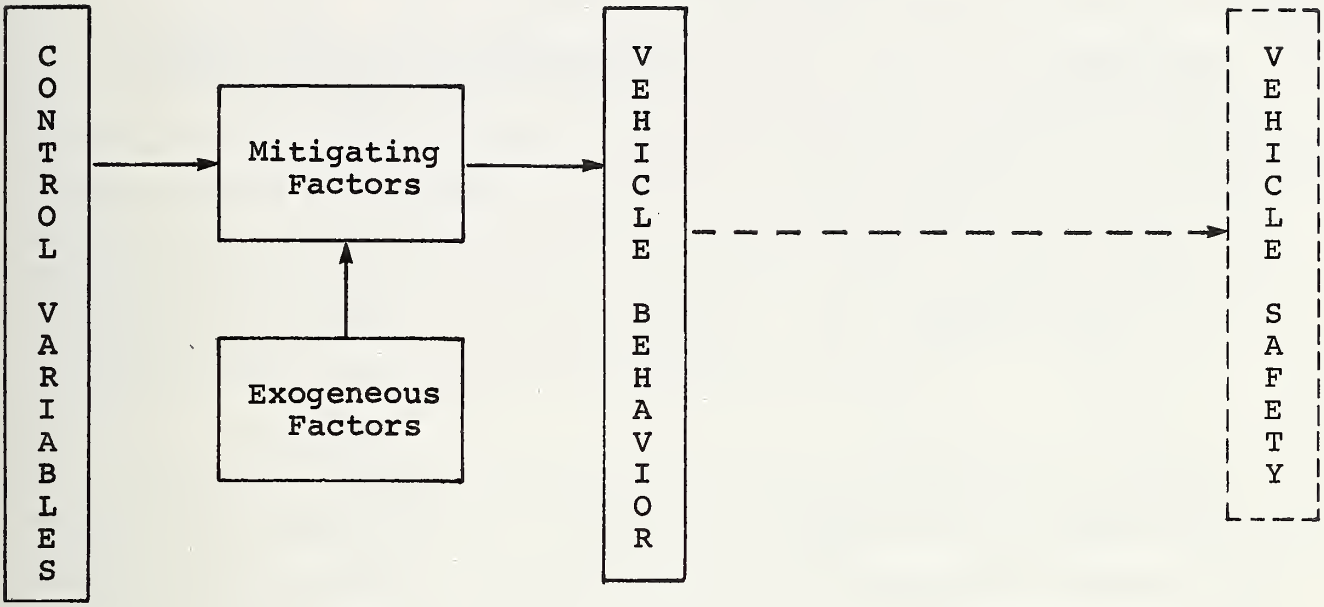


Figure 11. Model of vehicle behavior.

Table 30

Correlations Between Truck Mean Speed and Selected Variables, Loaded Trucks at the Long, Slight Upgrade

Variable	Correlation with mean speed
Gross weight	-.179
Front axle weight	-.019
Empty weight	.094
Max axle weight	-.060
Payload	-.220
Number of trailers	-.171
Relative passing speed	-.800
Passing occurrence	.309
Queue delay	-.448
Average queue speed	.729
Queue length	.222
Rear closure rate	-.478
Front closure rate	.139
Maximum acceleration	.376
Maximum deceleration	.618

least squares to estimate mean speed as a function of other independent or control variables. The initial attempts at fitting the data were very poor. Sample data for several sites were plotted by hand. This procedure highlighted the differences between loaded and nonloaded trucks, and upgrade and downgrade sites. On the basis of those sample plots, it was decided to limit investigation primarily to upgrade sites and loaded trucks. The downgrade and curve sites exhibited no pattern in mean speed compared with other variables as exemplified in the plot depicted as Figure 12. Empty trucks were primarily limited by external conditions (e.g. the speed limit) at the upgrade sites, hence no meaningful relationships to controlled variables were found.

Although the most promising results were found for upgrade sites and loaded trucks, the predictive power of a linear relationship between truck mean speed and other independent variables was disappointing. Investigations did show that independent variable significance was restricted to gross weight or one of its surrogates. When multi-variable procedures were applied, no appreciable increase in predictive power was realized. It was concluded that at any given (upgrade) site, gross weight alone of the available data affected mean speed. (Other variables or exogenous factors such as horsepower that might have explained mean speed were not available).

The poor fit of the linear model and the concave appearance of mean speed when plotted against gross weight prompted consideration of another form. The multiplicative or Cobb-Douglas form was chosen (see Appendix D). This form has an intuitive basis since one could well imagine mean speed being inversely proportional to gross weight or perhaps directly proportional to 1/ gross weight. The multiplicative form was fitted by using the linear regression program on the natural logarithms of

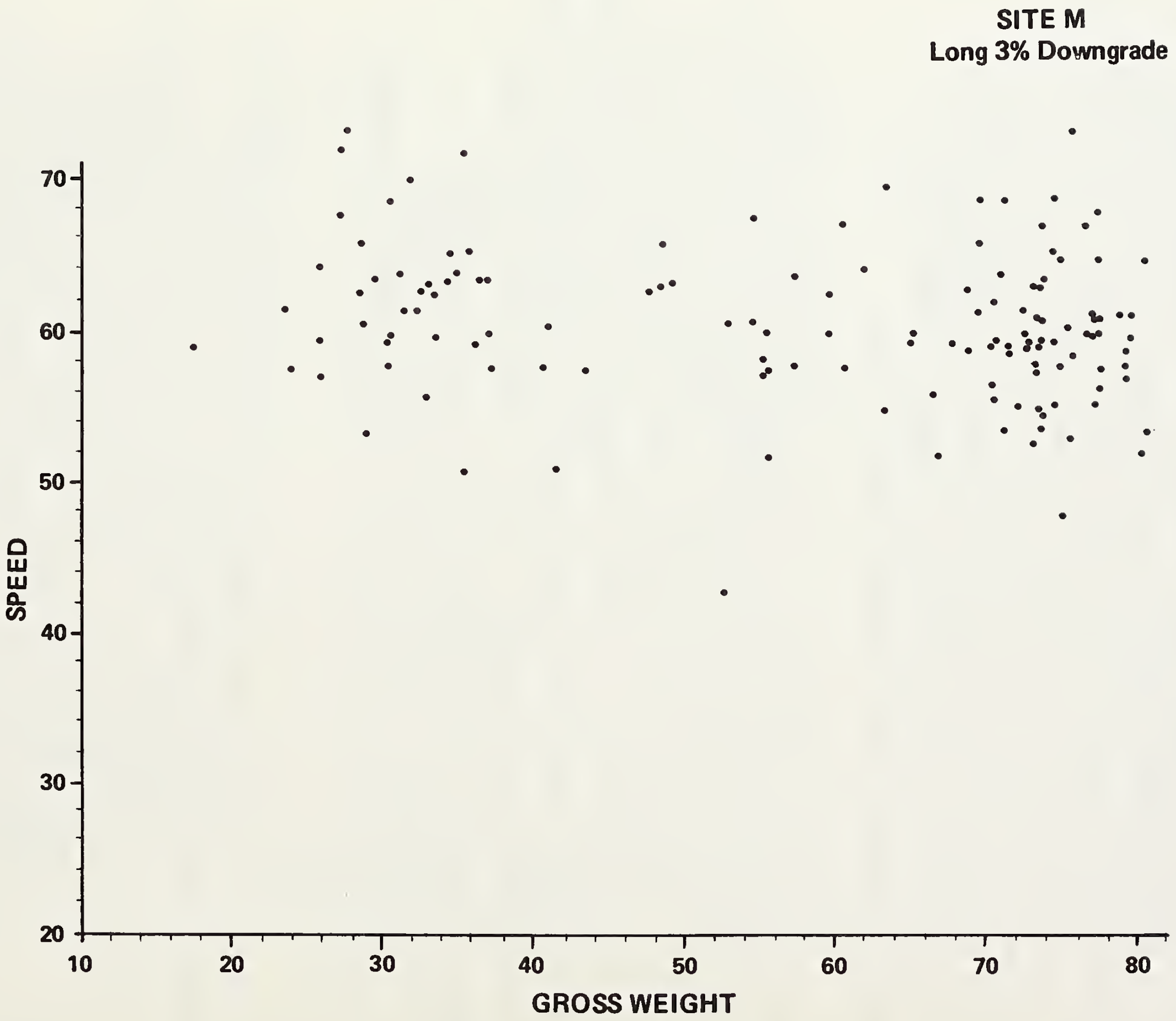


Figure 12. No correlation effect at long downgrade site.

the variables. This produced biased estimates, some better and some worse, than the linear model. The difference was not great enough to justify choosing one model over another.

Results of Modeling Effort

Models describing the effect of gross weight on speed were developed based on both linear and logarithmic curve fits. The logarithmic relationships provided slightly larger regression coefficients. Furthermore, the logarithmic form was deemed inherently superior in the respect that it can asymptotically describe a truck reaching its crawl speed. Thus, the logarithmic forms are illustrated in Figure 13. The plotted models are of the form $s=aw^b$, where s=speed, and w=gross weight. Derived values of a and b for different upgrade conditions are indicated on plots in the figure. Solid lines in these plots indicate weight ranges over which data were collected in this study: dotted lines indicate projected speed reductions associated with increased weight.

Application of the models to predict changes in truck speed as a function of increased weight can be seen in the following example. Assuming currently allowable gross weight of 67,000 pounds (30.4 Mg), and projected weights of 90,000 and 160,000 pounds (40.8 and 72.6 Mg), calculated truck speeds for each geometric condition are as follows:

	Speed @67K	Speed @90K	Speed @160K
Short, slight upgrade	46.9 (75.5)	44.9 (72.2)	41.1 (66.1)
Long, slight upgrade	47.6 (76.6)	44.5 (71.6)	38.9 (62.6)
Short, steep upgrade	33.9 (54.5)	31.1 (50.0)	26.5 (42.6)
Long, steep upgrade	21.3 (34.3)	19.0 (30.6)	15.2 (24.5)

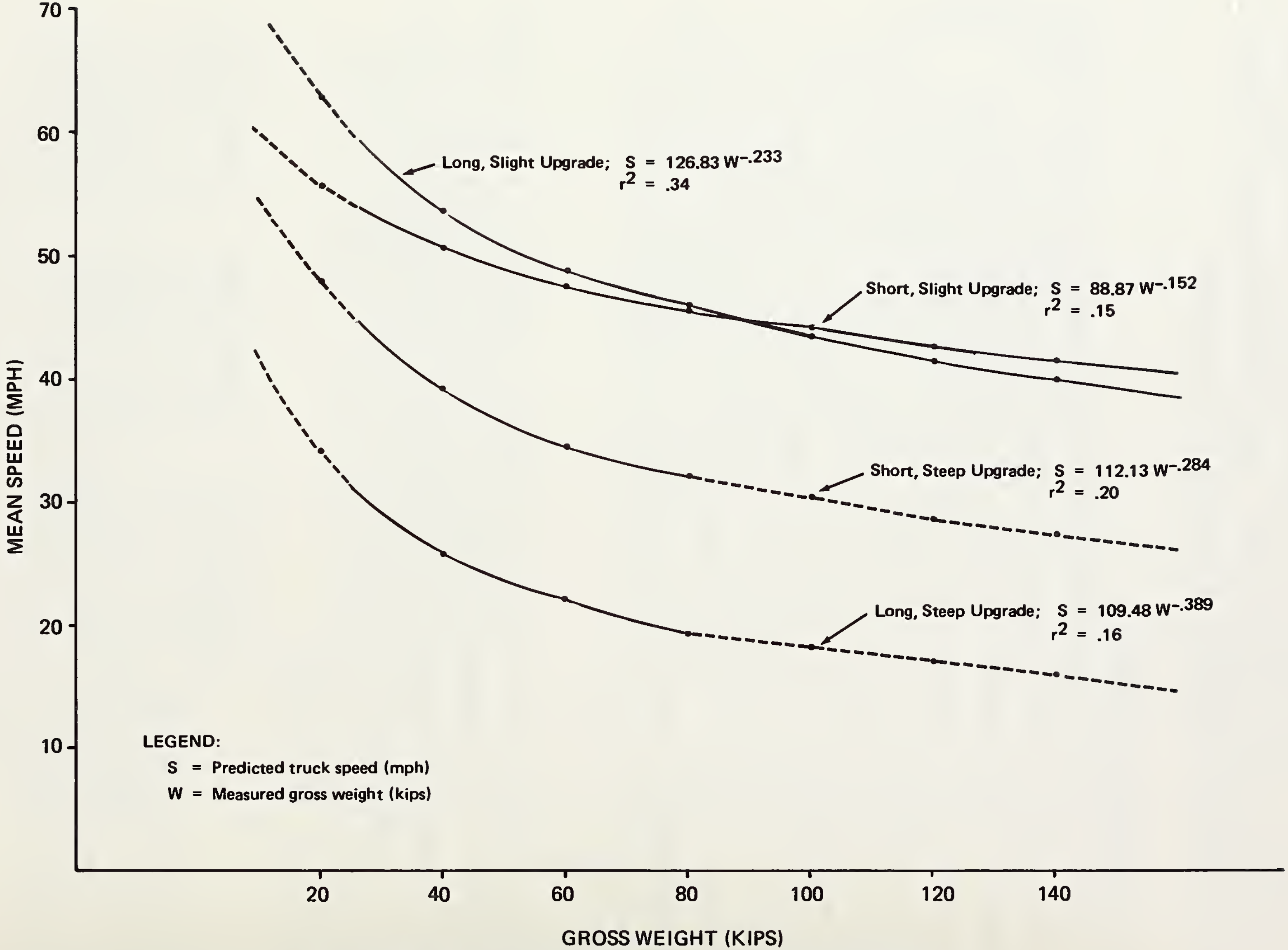


Figure 13. Models developed from regression analysis of speed-versus-weight relationships.

The modeled effect is that a 23 kip (10.4 Mg) increase in gross weight causes an average (across conditions) speed reduction of 2.6 mph (4.2 kph), while a 93 kip (42.2 Mg) increase results in a 6.8 mph (10.9 kph) reduction. The effect of these weight increases is most pronounced at the long, slight upgrade (3.1 mph and 8.7 mph [5.0 and 14.0 kph] reductions): the next most severe reduction is evident at the short, steep upgrade (2.8 mph and 7.4 mph [4.5 and 11.9 kph]).

However, to assess the practical significance (i.e., safety implication) of the modeled effects, one must bear in mind the low r values associated with the regression models. A typical obtained r of 0.20 means that only 20 percent of the observed variance in truck speed is accounted for using the prediction model based on gross weight.

To further illustrate the degree of model reliability, Figure 14 is a plot of residual speeds. A residual is the amount by which the model erred in its attempt to predict speeds of individual trucks in the data base. This residual plot points out both admirable and nefarious aspects of the predictive model. That the residuals are randomly distributed over the entire range of weights denotes that the model contains no bias with regard to specific weight categories. In fact, the residual plot for an ideal model should indeed depict "noise." On the other hand, the range of speed values is rather large. This plot clearly indicates that residuals of nearly 10 mph (16.1 kph) are not uncommon. The obvious implication in terms of the model's reliability is that it will frequently be off by a magnitude which exceeds the effect which it attempts to predict.

Thus, while a reasonably predictive relationship of speed was found based on gross weight, questionable reliability of the model indicates the obvious presence of other effects (e.g., engine horsepower differences) which impact on truck speed. This analysis suggests that a more complex model containing a wider range of variables is required to achieve precise prediction of truck operational characteristics.

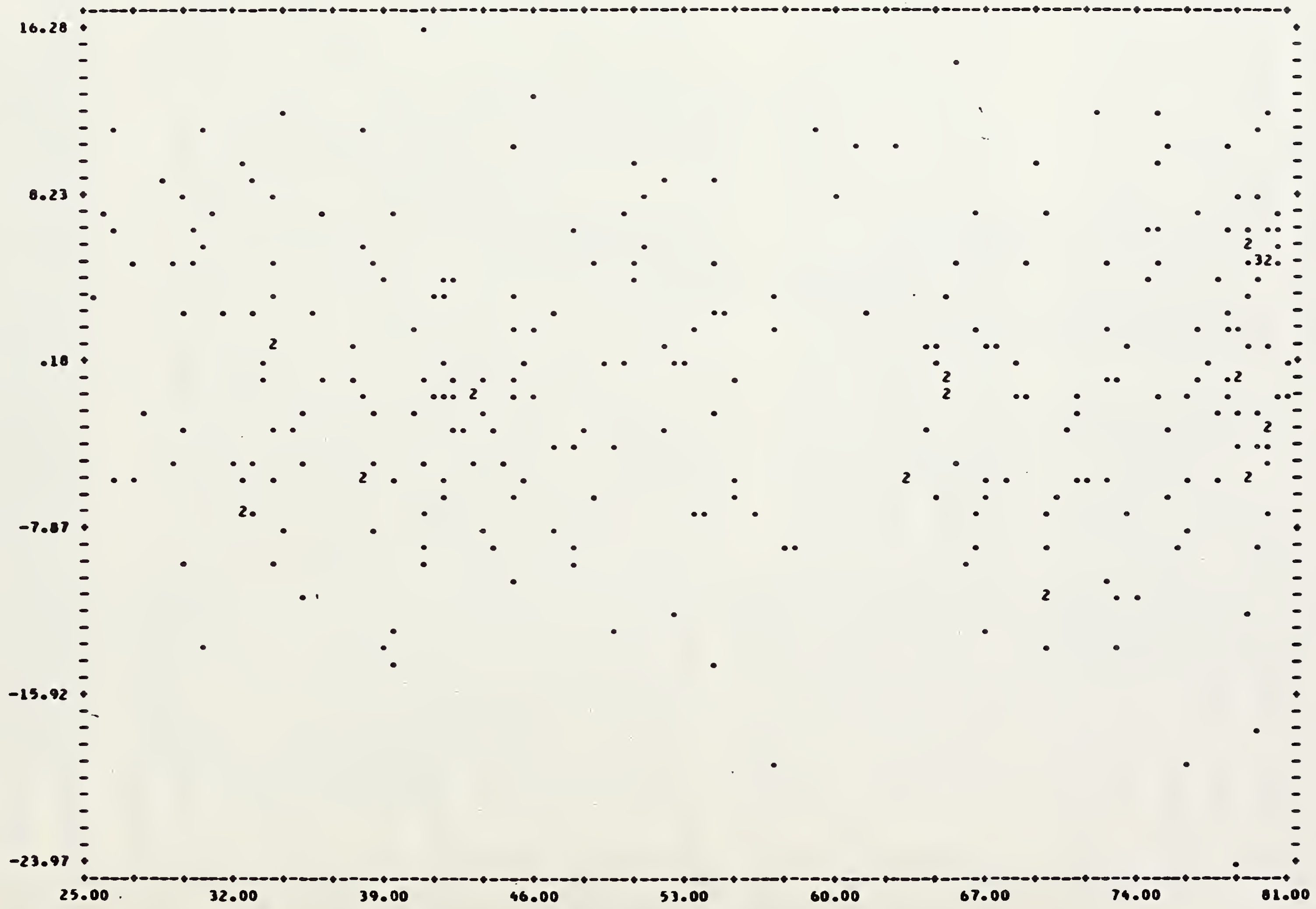


Figure 14. Computer plot of residual values of truck speed resulting from model's predictions based on gross weight.

CHAPTER FIVE

SPECIAL STUDIES: URBAN GEOMETRIC CONDITIONS

In addition to the grade and curve sites dealt with so far, certain other geometric conditions occurring in urban locations were selected for the assessment of truck size and weight effects. These included: a ramp connecting two urban freeways, a heavily traveled interchange merge point, and a signalized intersection. Each of these conditions is discussed separately.

Connector Ramp

Operational effects of truck size and weight were examined on a freeway ramp in an urban area. The ramp geometry consisted of a spiral curve characterized by a 100° change of travel direction over a roadway length of 955 feet (291.1 m). A site diagram and descriptive data appear in Appendix B. The maximum degree of curvature was approximately 20°. A sample of 96 trucks with an average gross weight of 32,900 pounds (14.9 Mg) was used in this data set. It is to be noted that the trucks in this sample are, unfortunately, somewhat lighter than those used elsewhere in the study. We surmised that heavier trucks avoided the ramp under study because of the close proximity of the weigh station (and the ready availability of alternate routes).

Results

Applied measures in this special study are the same as those used for the grade and curve situations described in Chapter Four. Table 31 summarizes results of the group comparison analysis. Few differences were found that could implicate larger and heavier trucks with adverse safety effects.

Table 31

Observed Differences Between Truck Groupings at a Freeway Ramp Site (N=96)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed	▨ ↑		—				—			↓ E			—	↓ E
	Mean Acceleration			—			↓	—					↓ E	—	
	Headway			—			↑	—						—	
	Tailway			—				—						--	
	Lateral Placement		--	—			↓ E	—						—	
	Flow Perturbations														
	Maximum Acceleration			—			↓ E	—						—	
	Maximum Deceleration			—				—						—	
	Speed Variance			—				—						—	
	Acceleration Variance			—			↓ E	—						—	
	Stream Speed Difference	▨ ↓		—				—		▨ L↑	↑ E		↓ E	—	↓ E
	Proportion Slower			—				—						—	
	Proportion Faster			—				—					↑ E	—	
	Driver Effort			—				—						—	
	Rear-End Accident Potential														
	Critical Headway			—				—						—	
	Critical Tailway			—				—						—	
	Front Closure Rate			—				—						—	↑ E
	Rear Closure Rate			—				—						—	
	Projected Time to Collision (Front)			—				—						—	
	Projected Time to Collision (Rear)			—				—						—	
	Flow Delay														
	Queue Length			—				—						—	
	Following Vehicle Speed		↑	—				—						—	
	Following Vehicle Delay			—				—						—	
	Following Queue Speed			—				—						—	
	Following Queue Delay			—				—						—	
	Passing Interactions														
	Probability of Being Passed			—				—						—	
	Probability of Passing			—				—						—	
	Relative Speed Being Passed			—				—						—	
	Relative Passing Speed			—				—						—	
Truck Characteristics	**Weight**														
	Gross Weight			—	↑	↓	↓	—		↑				—	
	Front Axle Weight			—			↓	—		↑				—	
	Maximum Axle Weight			—	↑		↓	—		↑	↑			—	
	Empty Weight (Estimated)			—	↑		↓	—						—	
	Payload			—		↓	↓	—		↑				—	
	Loading Condition			—	↑	↓		—						—	
	Size														
	Wheelbase			—	↑	↓	↓	—						—	
	Overall Length	↑		—	↑	↓	↓	—						—	↑
	Wide Load			—				—						—	
	Number of Trailers	↑		—				—						—	↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

Basic Flow Descriptors. As was found to be the case in most other geometric situations, loaded trucks exhibited lower speeds than did empties. In thise case, loaded trucks averaged 45.2 mph (72.7 kph), in comparison to 47.6 mph (76.6 kph) for empties. This result is noted in the table as an adverse effect by virtue of speed differences as with the total traffic stream. Reduced speeds for loaded trucks were found as a group difference only in the case of all loaded versus all empty trucks.

Most group differences noted in this measures category did not connote adverse effects. Trucks characterized by dual (as opposed to single) drive axles demonstrated higher values of average acceleration, which was most likely a result of their higher power-to-weight ratio. This group also demonstrated safer following behavior: average headways of 3.9 sec, compared to 1.8 sec for single drive-axle rigs.

A number of other group differences observed for empty trucks are also found in the table. The most notable is that dual drive-axle rigs tracked at a greater distance (3.0 ft versus 1.7 ft [0.9 m versus 0.5 m]) from the right edgeline than did singles. The reason for this difference is not apparent (dual axle rigs were not faster; and although they were longer, truck length was not shown to be associated with tracking differences at this site.

Flow Perturbations. A number of group differences were observed on the basis of acceleration and differential speed behavior. However, few of the differences in these categories were the effects of increased size and weight. Such effects were realized on the basis of stream-speed differences. Loaded trucks averaged 2.6 mph (4.2 kph) below the mean traffic speed, whereas empties averaged 0.9 mph (1.4 kph) slower than the stream speed. Similarly, loaded tankers exhibited a greater mean stream-speed difference than loaded vans. However, several stream-speed group differences found for certain types of empty trucks (i.e., flatbeds, dump trailers, and bulk commodity carriers) exhibited no increased size and weight effects.

Certain other behavioral differences were found for groups of empty trucks. Dual drive-axle rigs, which were seen to accelerate on the ramp, demonstrated two related perturbative effects. They exhibited higher values of maximum acceleration (0.70 versus 0.42 ft/sec^2 [0.21 versus 0.13 m/sec^2]) and acceleration variances (0.84 versus 0.14 ft/sec^2 [0.26 versus 0.04 m/sec^2]) than did single drive-axle combinations. Additionally, empty dump trailers were often traveling at a standard deviation above mean traffic speeds.

<u>Rear-End Accident Potential</u>. Neither of two group differences evident in this measures category contained adverse implications for increased size and weight. Instead the data showed that (1) in cases of critical following by other vehicles, safer behavior was associated with cab-over tractor combinations (tailways of 1.2 sec versus 0.9 sec) than with cab-behinds; and (2) empty bulk commodity carriers were likely to exhibit high front closure rates (10.6 ft/sec [3.23 m/sec]).

<u>Summary</u>. Few truck size and weight effects on traffic operations were observed in the ramp situation. Although speed differences existed between loaded and empty trucks, minimal speed variation was found between trucks and the traffic stream. Loaded trucks, for instance, averaged 2.6 mph (4.2 kph) slower than average traffic speed. This difference did not produce other perturbative effects, nor did it result in increased rear-end accident potential or delay to other traffic.

Freeway Merge

Both mainline and merging trucks traveling on an urban interchange were examined for operational effects related to their size and weight. The merge area consisted of a single-lane on-ramp and a 400-ft (121.9 m) acceleration lane. Traffic flow was also measured in the two adjacent through-lanes. A site diagram is contained in Appendix B. A sample of 387 trucks was used in this data set, with an average individual gross weight of 40,000 pounds (18.1 Mg).

Results

Table 32 summarizes results of the group comparison analysis. Measures applied in this special study are the same as those used for grade and curve situations described in Chapter Four.

Basic Flow Descriptors. Three group differences based on mean speed did not reveal adverse weight or size effects. Longer trucks (mean speed, 51.8 mph [83.3 kph]) tended to negotiate the merge area at faster speeds than did the shorter (mean speed, 49.0 mph [78.8 kph]); however, the behavior of the longer trucks is interpreted as being safer because their speed was closer to that of the traffic stream. Slight, but statistically significant, slowing was noted for loaded flatbeds -- which averaged 1.6 mph (2.6 kph) slower than loaded vans. Yet no detectable flow consequence emerged from this behavior.

Various group differences were evident on the basis of acceleration behavior. Most notably, doubles tended to slow down (average acceleration, -0.03 ft/sec^2 [-0.01 m/sec^2]), while single-trailer combinations were more likely to speed up (average acceleration, 0.31 ft/sec^2 [0.09 m/sec^2]). The heaviest deceleration behavior (average acceleration, -0.29 ft/sec^2 [-0.09 m/sec^2])

Table 32

Observed Differences Between Truck Groupings at a Freeway Merge Area (N=387)

		Truck Grouping Criteria													
		Empty vs. Loaded	Cab Over vs. Cab Behind	Wide Load vs. 96" Width	Long vs. Short Conventional	Single vs. Double Trailers	Single vs. Dual Dr. Axles	Michigan Heavies vs. Conventional	All Trailer Types vs. Vans	Tankers vs. Vans	Flatbeds vs. Vans	Auto Carriers vs. Vans	Dump Trailers vs. Vans	Pole/Logging vs. Vans	Bulk Commodity vs. Vans
Traffic Operational Characteristics	**Basic Flow Descriptions**														
	Mean Speed			—	↑			—			L ↓			—	L ↑
	Mean Acceleration			—		▨ L ↑		—				▨ L ↑	↑ E	—	▨ L ↓
	Headway			—				—						—	
	Tailway			—				—						—	
	Lateral Placement	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Flow Perturbations														
	Maximum Acceleration			—				—			▨ L ↑	↑ E		—	
	Maximum Deceleration		▨ ↑	—		▨ L ↓		—		L ↑				—	▨ L ↑
	Speed Variance			—				—			▨ L ↑	↑ E		—	
	Acceleration Variance			—				—			▨ L ↑	↑ E		—	
	Stream Speed Difference	▨ ↓		—	↓			—						—	
	Proportion Slower			—	↓			—		↓ E				—	
	Proportion Faster			—	▨ ↑	▨ L ↓		—						—	▨ ↑
	Driver Effort	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Rear-End Accident Potential														
	Critical Headway			—	▨ ↓			—						—	
	Critical Tailway		↑	—				—						—	
	Front Closure Rate			—			▨ L ↑	—						—	
	Rear Closure Rate			—		↓		—		↓ E				—	
	Projected Time to Collision (Front)			—		▨ ↓		—		↓ E				—	
	Projected Time to Collision (Rear)		↑	—				—						—	
	Flow Delay														
	Queue Length			—				—						—	
	Following Vehicle Speed			—				—						—	L ↑
	Following Vehicle Delay			—				—						—	L ↓
	Following Queue Speed			—				—						—	L ↑
	Following Queue Delay			—				—						—	L ↓
	Passing Interactions														
	Probability of Being Passed	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Probability of Passing	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Relative Speed Being Passed	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Relative Passing Speed	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Truck Characteristics	**Weight**														
	Gross Weight	—	—	↑	—	—	↓	—	↑	↑	↑	—	—	—	↑
	Front Axle Weight	—	—	↑	—	—	↓	—	↑	↑	↑	—	—	—	↑
	Maximum Axle Weight	—	↓	↑	↑	—	↓	—	↑	↑	↑	—	—	—	—
	Empty Weight (Estimated)	—	—	↑	—	↓	↓	—	—	↑		—	—	—	—
	Payload	↓		—	—	—	↓	—	—	—	↑	—	—	—	↑
	Loading Condition			—				—			↑			—	
	Size														
	Wheelbase			↑	↓	↓	↓	—	↑	↑	↑			—	
	Overall Length		↓	↑	↓	↓	↓	—	↑	↑	↑			—	
	Wide Load			—				—						—	↑
	Number of Trailers			↑				—	↑					—	↑

Legend: ↑ Higher value for first group.
▨ Adverse implication for increased size and weight.

was noted for loaded bulk commodity carriers. Loaded auto carriers exhibited the greatest accelerative behavior (an average of 1.55 ft/sec^2 [0.47 m/sec^2]).

Flow Perturbations. Differing perturbative effects were evident across various truck characteristics, as seen in the table. Considered here are those results having size and weight implications. Loaded trucks generally averaged speeds farther below traffic mean speed than did empties; yet the opposite was seen for longer trucks. Loaded auto carriers exhibited the greatest perturbative behavior, as a consequence of their extreme acceleration performance. They averaged high values of maximum acceleration (4.5 ft/sec^2 [1.4 m/sec^2]) in addition to larger variances in both speed and acceleration. Bulk commodity carriers previously noted to traverse the merging area at relatively high mean speeds, were noted to exhibit larger values of deceleration (2.3 ft/sec^2 [0.7 m/sec^2], average) and often traveled at least one standard deviation above the traffic mean speed. Quite the opposite behavior was noted for double-trailer combinations, in comparison with singles, as they demonstrated lower deceleration levels and a decreased likelihood of traveling above mean traffic speed. This group difference is consistent with the fact that the longer combinations were less likely than the shorter to travel faster than mean traffic speeds.

Certain group differences revealed safer behavior for specific truck types. Longer trucks exhibited lower stream-speed differences and a decreased likelihood of traveling drastically below mean traffic speeds than did shorter trucks.

Rear-End Accident Potential. Higher accident potential was seen to characterize longer trucks and double-trailer combinations in their respective group comparisons. Given the sample of trucks following other vehicles at two seconds or less, longer trucks demonstrated more critical following behavior (average headways of 0.93 sec) than did shorter (1.76 sec). Moreover, the total truck sample revealed less safe projected times to collision for the longer trucks. A somewhat consistent finding is that loaded double trailers demonstrated higher closure rates with lead vehicles than did singles (5.8 ft/sec versus 3.6 ft/sec [1.8 m/sec versus 1.1 m/sec]).

Flow Delay. The only group difference with an impact on flow delay measures was noted for loaded bulk commodity carriers.

Summary. Mixed results were obtained regarding truck size and weight influences on traffic operations at a merge area. Applied measures consisted of flow descriptors, flow perturbations, rear-end accident potential, and flow-delay measures. Minimal operational consequences were found.

Little effect of weight was evident. The only difference between empty and loaded trucks was that the loaded group averaged 3.4 mph (5.5 kph) lower than mean traffic speeds at the site, compared to 2.1 mph (3.4 kph) lower for empties. A notable effect of truck size was that large trucks negotiated the merge area at higher speeds, yet deviated less from traffic mean speeds than did the shorter. Another observed size effect was that loaded doubles had a greater tendency than loaded singles to decelerate.

Some adverse effect of size was evident from measures of rear-end accident potential. Longer trucks and doubles showed a slight tendency to dangerously close in on lead vehicles.

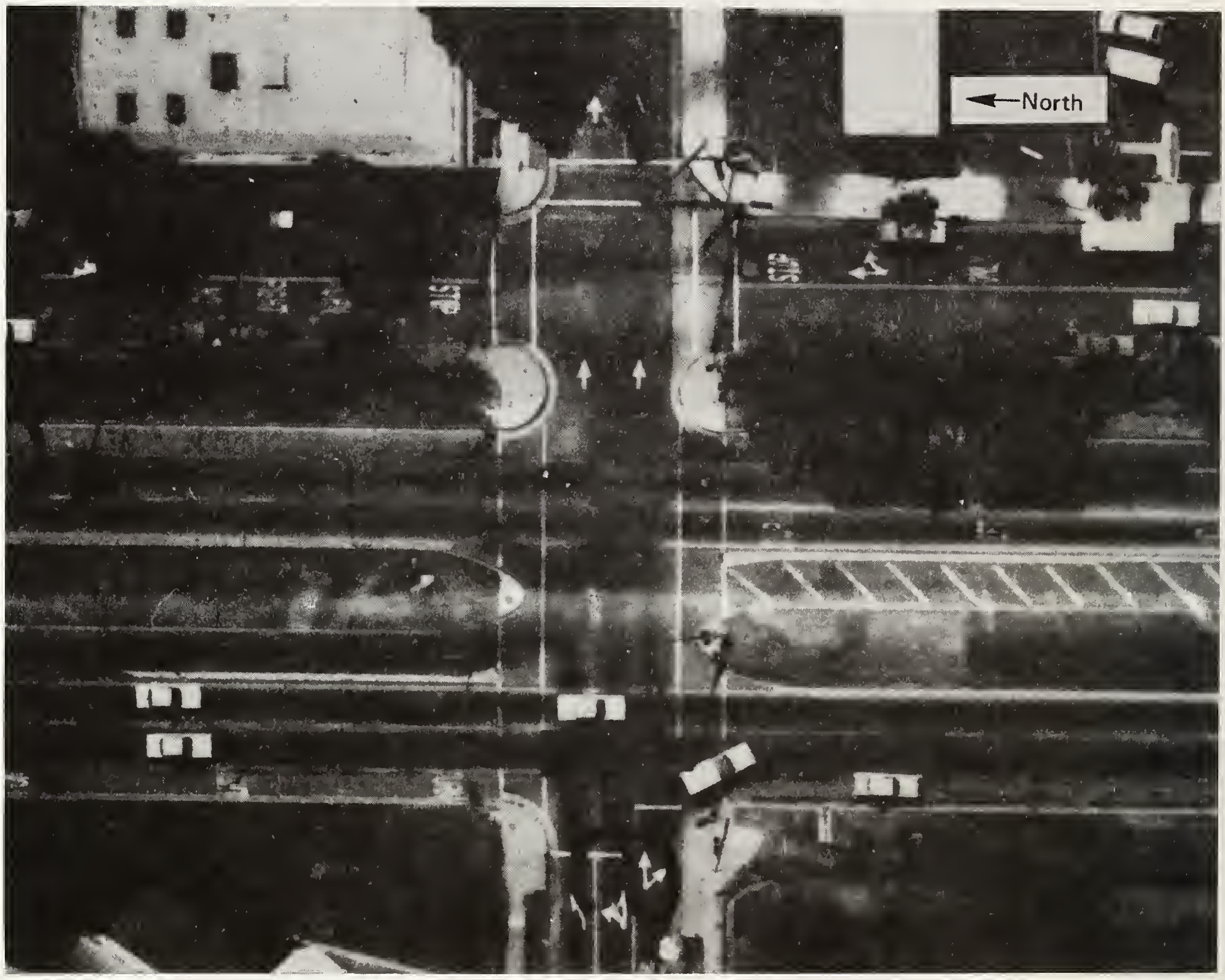
Intersection Delay

The general effects of trucks on delay at signalized intersections have been investigated elsewhere. Yurysta *et al.* (1975) examined both stopped-time and running-time delays as affected by single unit and combination commercial vehicles. However, differential delay effects imposed by varying truck combination configurations had remained undocumented. This study measured stopped-time delay of through vehicles at a signalized intersection for the purpose of determining whether or not a differential effect resulted from the presence of single- versus double-trailer combinations in the traffic stream. The studied truck sample, consisting of 5 percent of the total traffic-stream volume, was composed of single-trailer combinations ranging from approximately 43 to about 56 feet (13.1 to 17.1 m) in length and double-trailer combinations of approximately 65 feet (19.8 m) in length. Total stopped-time delay for the traffic stream was examined to determine the impact of varying percentages of singles versus doubles.

Procedure

The site of this study was the signalized intersection of U.S. 101 and Anacapa Street in Santa Barbara, California. A site photograph and relevant data appear in Figure 15. U.S. 101, the major approach leg, carries an ADT of 51,200 vehicles at this point, and constitutes a primary north-south truck route along the coast of Southern California. The intersection signal is a fixed-time, three dial, constant offset device, which was set at cycle lengths of 120 seconds and 240 seconds during our data collection periods.

Data collection and analysis procedures consisted of a slightly modified version of those recommended in Chapter 8 of



Aerial View of Site

Descriptive Data

Intersection Location	U.S. 101 and Anacapa St. Santa Barbara, California
Measured Leg	U.S. 101, Northbound
ADT	51,200
Lane Width	11.5 Feet
Signal Characteristics	Fixed time, three phase, constant offset
Cycle Lengths	120 and 240 second

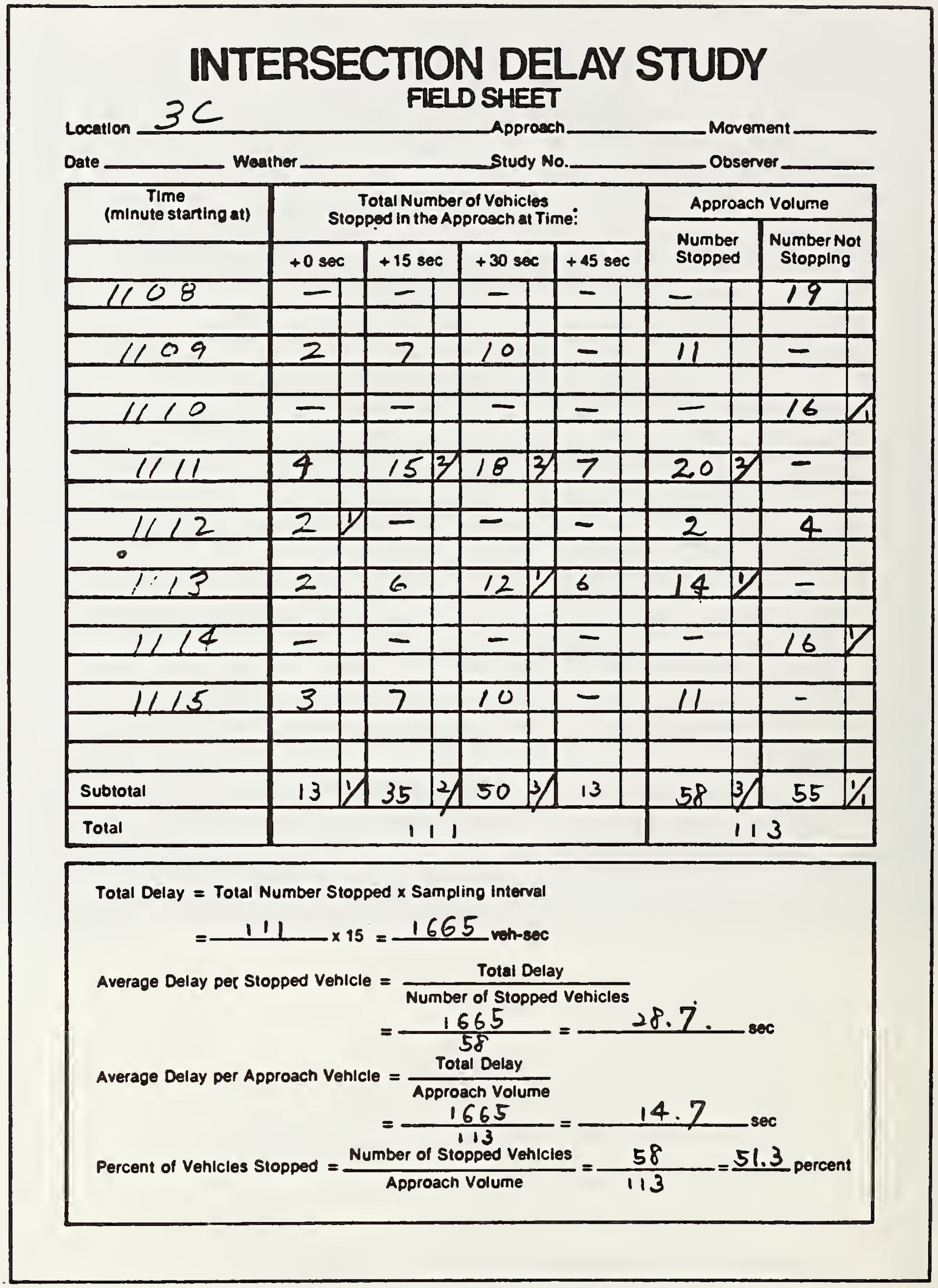
Figure 15. Description of site used for intersection delay study.

ITE's Manual of Traffic Engineering Studies (1976). The data collection procedure involved timelapse photography along with manual counts of stopped vehicles and total approach volume at 15-second intervals. But because in this case the signal's cycle length was exactly divisible into 15-second intervals, it was necessary to randomly vary start times for counting within the cycle in order to follow the ITE procedure. An example of gathered data and computation of periodic delay values appears in the field sheet illustrated in Figure 16. This example is a tailored version of ITE's recommended field sheet, amended to include the number of single and double combinations in the stream. A modified traffic volume computational procedure entailed calculating the percentages of total trucks, singles, and doubles in the stream.

Analysis and Results

Data were collected during a two-day period for a total traffic sample of 3,178 vehicles, including 121 single-trailer combinations and 23 double-trailer combinations. Twenty-seven data periods were designated for the purpose of establishing a correlational analysis procedure based on the following nine derived variables.

1. Total approach volume
2. Percent trucks
3. Percent single-trailer combinations
4. Percent double-trailer combinations
5. Signal cycle length
6. Total delay
7. Average delay per stopped vehicle
8. Average delay per approach volume
9. Percent of vehicles stopped



INTERSECTION DELAY STUDY

FIELD SHEET

Location 3C Approach ______ Movement ______

Date ______ Weather ______ Study No. ______ Observer ______

Time (minute starting at)	Total Number of Vehicles Stopped in the Approach at Time:								Approach Volume			
	+0 sec		+15 sec		+30 sec		+45 sec		Number Stopped		Number Not Stopping	
1108	—		—		—		—		—		19	
1109	2		7		10		—		11		—	
1110	—		—		—		—		—		16	1/
1111	4		15	2/	18	2/	7		20	3/	—	
1112	2	1/	—		—		—		2		4	
1113	2		6		12	1/	6		14	1/	—	
1114	—		—		—		—		—		16	1/
1115	3		7		10		—		11		-	
Subtotal	13	1/	35	2/	50	3/	13		58	3/	55	1/
Total	111								113			

Total Delay = Total Number Stopped x Sampling Interval

= 111 x 15 = 1665 veh-sec

Average Delay per Stopped Vehicle = $\frac{\text{Total Delay}}{\text{Number of Stopped Vehicles}}$

= $\frac{1665}{58}$ = 28.7. sec

Average Delay per Approach Vehicle = $\frac{\text{Total Delay}}{\text{Approach Volume}}$

= $\frac{1665}{113}$ = 14.7 sec

Percent of Vehicles Stopped = $\frac{\text{Number of Stopped Vehicles}}{\text{Approach Volume}}$ = $\frac{58}{113}$ = 51.3 percent

Form Source: Institute of Transportation Engineers

Figure 16. Example of data collection form and delay computation.

Table 33

Variable Distributions (N=27) and Correlational Matrix for Stopped Time Delay Study

Dependent Measures

Independent Measures	Mean & Std. Dev.	Total Delay (veh—sec)	Delay/ Stopped Veh. (sec)	Delay/ Appr. Veh. (sec)	Stopped Vehicles (percent)
		$\bar{X} = 750.6$ $\sigma = 450.8$	$\bar{X} = 24.4$ $\sigma = 4.8$	$\bar{X} = 6.5$ $\sigma = 4.1$	$\bar{X} = 27.1$ $\sigma = 16.3$
Approach Volume (veh)	$\bar{X} = 117.7$ $\sigma = 10.9$	–.16	.13	–.28	–.32
Total Trucks (percent)	$\bar{X} = 4.6$ $\sigma = 2.0$	.11	–.01	.17	.18
Single Combinations (percent)	$\bar{X} = 3.8$ $\sigma = 1.8$	.11	.02	.16	.15
Double Combinations (percent)	$\bar{X} = .7$ $\sigma = .7$	–.05	–.05	–.02	.02
Cycle Length (sec)	$\bar{X} = 213.7$ $\sigma = 47.3$	–.77*	–.08	–.82*	–.78*

*Indicates significant correlation ($\alpha < .01$).

Variables 1 through 5 comprise independent measures of traffic and signal-timing characteristics. Variables 6 through 9 are the computed delay measures suggested in the ITE study procedure. Table 33 summarizes distributions for each variable and contains a correlation matrix of regression coefficients obtained between independent and dependent variable pairs. The data indicate that no significant relationship existed between any of the delay measures and approach volume or truck mix measures. Only the signal cycle timing had any impact on delay. The longer cycle length used during higher volume hours is seen to reduce both total intersection delay and average approach vehicle delay at the intersection, as well as the percentage of vehicles stopped.

Interpretation of Results

Results of the analysis showed only that through-moving traffic at a level, signalized intersection did not experience increased stopped time as the result of total truck mix, percent singles, or percent doubles in the stream. Differences in other factors (street grade, increased turning movements, higher percentage of trucks, more doubles) may well have influenced the data in the other direction. Furthermore, stopped-time delay study of trucks merely reflects their capability to begin moving when the light turns green; it does not take into account possible capacity reduction or increased travel-time effects. These effects can be determined from further study with a greater variety of sites and situations. Otherwise, they can be closely estimated using existing truck length data in capacity calculations, and known performance-capability inputs to flow-simulation models.

The data did, however, prove to be sensitive to the issue of the effects of single- versus double-trailer combinations at intersections. Despite the poor significance of the relationships shown in the matrix, the directionality of the correlations does imply that doubles perform every bit as well as singles. All four delay measures correlated more highly with percent singles than with percent doubles, thereby implying that the presence of doubles is less likely to increase delay than is the presence of singles. This notion is highly credible in view of the potentially higher horsepower tractors that are used with the doubles.

CHAPTER SIX

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

To present a terse statement which captures the content of a study comprised of nearly 6,000 data observations gathered at 14 field sites and subjected to approximately 21,000 statistical tests is an awesome task. Furthermore, to translate the myriad of observed operational effects into meaningful safety implications of truck size and weight requires judicious interpretation of the statistical analyses.

This chapter first presents a summary of those findings deemed most pertinent to truck size and weight regulatory issues. The summary includes an important epilogue regarding the interpretation of these findings. Conclusions based on the observed operational impact of size and weight are then followed by recommendations for future research.

Summary of Findings

Comparison of truck groupings showed that the greatest operational differences existed between loaded and unloaded trucks. The pronounced weight difference resulted in lower speeds for loaded trucks at all tested geometric conditions except the long Interstate downgrade. Operational impacts of loading were most evident on upgrades, where typical effects were: reduced acceleration performance, greater speed deviation from traffic means, higher rear closure rates and lower projected collision times with respect to following vehicles, greater slowing and delay experienced by following vehicles, and higher relative speeds from passing vehicles. The magnitude of these differences varied greatly depending on geometric condition:

across all conditions, loaded trucks averaged only 2 mph (3.2 kph) slower than empties (51 versus 49 mph [82.1 versus 78.8 kph]); on steep upgrades, however, the difference was 8 mph (12.9 kph) (48 versus 40 mph [77.2 versus 64.4 kph]). The most extreme operational effect noted in the group comparison analysis was that 14-mph (22.5 kph)-delays were experienced by vehicle queues following loaded Michigan heavy-duty double-trailer combinations on long grades.

Operational differences noted between groupings of single- and double-trailer combinations are believed to be residual effects of the observed weight differences (i.e., average 64,100 pounds versus 49,700 pounds [29.5 Mg versus 22.5 Mg], loaded). While slightly reduced speeds were generally observed for doubles, extreme slowing (differences of up to 13 mph [20.9 kph]) was noted on certain upgrades. Operational effects were most pronounced on upgrades and freeway curves, where doubles were associated with higher deviations from average traffic speed, more hazardous closures from following vehicles, and higher relative speeds by passing vehicles.

The effect of width was examined by stratifying groups of standard 8 ft. (2.4 m)-wide trucks and those hauling wide loads. No weight difference existed between these groups; therefore, observed effects were attributed solely to truck size. Operational differences noted at downgrade and curve sites were that wide-load trucks sometimes exhibited drastic slowing behavior, e.g., as much as 30 mph (48.3 kph) below traffic mean speed. While higher relative passing speeds were logically found to be associated with the wide loads, the restricted sample size precluded a valid analysis of other interactional effects.

In order to amplify and clarify operational effects observed in the group comparisons, truck weight and length were correlated with traffic operations measures. While a number of statistically significant correlations were obtained, the coefficients indicated fairly weak relationships. Weight was found to be associated with a greater number of operational effects than was length.

Gross truck weight correlated with operational measures most frequently at upgrades. The largest obtained coefficients (e.g., r ≃.60) demonstrated that, although the primary effect of higher gross weight was lower truck speeds on upgrades, only about 35 percent of the observed speed variation could be explained by weight differences. A similarly large weight impact was associated with the extent to which heavier trucks slowed below traffic speeds. Also, but to a lesser degree, higher gross weights were noted to be associated with poorer acceleration performance, higher closures with closely following vehicles, greater relative passing speeds, and greater delay to following vehicles. Typically, variances of approximately 10 percent in these measures could be attributed to gross truck weight effects. Although more hazardous closure rates were frequently associated with heavier trucks on upgrades, shorter projected rear-end collision time correlated with gross weight only in the short steep-upgrade condition. Even so, a very weak associative relationship with weight is indicated since only 4% of the collision time differences were attributable to gross weight.

Similar, but less pronounced, correlative effects of higher weight at downgrade and curve sites were: somewhat reduced truck speeds, greater deviations from traffic mean, higher relative passing speeds and frequently higher relative passing speeds, and frequently higher relative closure rates with following vehicles. A notable exception was safer behavior of heavier trucks at the long Interstate downgrade site. Decreased rear-end accident potential was associated with heavier trucks at this site by virtue of lower closure rates and longer projected collision times with interacting vehicles. Also noteworthy is the general trend of heavier trucks to lower speeds at downgrade sites, which refutes the popular belief that these trucks speed up on downgrades in order to gain momentum.

Correlations between overall truck length and operational variables revealed a negligible effect on traffic operations. No significant correlations were evident in either downgrade or curve combined-sites data. Combined data for all upgrades demonstrated slight tendencies toward lower speeds and degraded acceleration and deceleration behaviors for longer trucks. However, this result is likely a residual effect of higher weight.

An attempt to mathematically model traffic operations on the basis of truck characteristics was nearly sabotaged by the poor correlative relations noted above. The most promising models were limited to predictions of truck speed at upgrade sites based on gross weight. Although statistically valid, the predictive power of the models was not without question. The average projected effect of an increase in gross truck weight from 67,000 to 160,000 pounds (30.4 to 72.6 Mg) was a 6.8 mph (10.9 kph) speed reduction.

Operational effects found in the group comparison and correlative analyses to be associated with certain truck characteristics are capsulized in Table 34. The selected truck factors and geometric conditions are those deemed most useful for consideration by a regulatory agency. Accordingly, designated geometric conditions are stratified with reference to Interstate System design standards. Pertinent truck factors

Table 34

Summary of Operational Effects Associated with Selected Truck Characteristics

		Reduced Truck Speed	Degraded Acceleration	Critical Rear Closures*	Delay Effects*	High Relative Passing Speed
Freeway	Upgrades	▨ C	▨	▨ C	▨	▨
Freeway	Downgrades			†		▨
Freeway	Curves	▨ C		▨		▨ C
Non-Freeway	Upgrades	▨ WC	▨ C	▨		▨ WC
Non-Freeway	Downgrades	▨ C		▨		▨
Non-Freeway	Curves*	▨ C				

Notes:

†Safer behavior associated with heavier trucks.

*Inadequate wide load sample.

LEGEND

▨ — Gross Weight
L — Overall Length (No effect)
C — Configuration: Doubles vs. Singles
W — Width: Wide Load vs. Standard

are gross weight, overall length, single- or double-trailer configuration, and wide loads. The magnitude of observed operational effects is that previously discussed in this summary. That truck length is not indicated in any of the table's cells is due to the fact that overall length did not correlate with any performance measures in the data set for which results are depicted in the table.

Epilogue

Voluminous data analyzed in this study revealed many operational effects of truck size and weight. Numerous observed effects, although statistically strong, had little practical significance. For example, while more hazardous rear closure rates were repeatedly observed for heavier trucks on upgrades, only 10 percent of the effect was explained by weight differences. Conflicting safety evidence also exists: While heavier trucks created traffic perturbances at short upgrade sites, they were associated with less rear-end accident potential on the long, 3-percent-downgrades. What the analysis demonstrated most clearly is that operational effects of trucks are most often caused by factors other than size and weight.

To illustrate this last point, consider that a correlation coefficient of at least 0.71 must exist in order to account for one-half of the variability in a regression analysis between two variables ($0.71^2=0.50$). Of the 924 coefficients between gross weight, overall length, and operational variables obtained in the correlative analysis, this condition was never met.

That causative effects other than size and weight contributed heavily to truck performance was also highly evident during the modeling attempt. The best available mathematical model, a logarithmic function to predict a truck's upgrade speed based on its gross weight, was characterized by mediocre reliability. The model's residuals (the amount by which the speed prediction was in error) equaled or exceeded the projected weight effect for nearly one-third of the estimation trials.

Several influencing factors, other than size and weight, which affected truck performance became somewhat apparent to the data collection team during the field activity phase of this project. Differences in overhauling practices and in the general operating condition of tractors from one commercial carrier to another were pointed out to us by weigh station officials. Many rigs gave visible and audible evidence of being in a state of poor repair. Finally, continuous monitoring of truckers' CB communications (a practice we conducted to insure our unobtrusiveness) indicated that some drivers were driving while fatigued or under the influence of alcohol or other drugs. It is likely that there are other such factors which may explain operational differences.

Conclusions

The applicability of these findings to a realistic assessment of the traffic operational impact of truck size and weight requires close examination. One must consider the difference between an *associative* and a *causative* effect. Although differing safety-related behaviors were often shown to be associated with varying truck size and weight characteristics, there is a glaring lack of evidence to establish *causation* between these truck factors and operational safety. Extensive analysis conclusively demonstrated that size and weight alone contributed relatively little to observed truck performance differences. Furthermore, results showed even weaker associations between measured truck characteristics and those traffic operational measures derived from the performance of interacting vehicles.

The clearest example is seen in the overwhelmingly obvious case of heavier trucks proceeding more slowly on upgrades. Despite highly significant speed differences between groups of empty and loaded trucks, in combination with significant correlations between truck speed and gross weight, the analysis pointed out that a maximum of only 37% of the observed speed variation was explained by gross weight effects. Attempts to multi-correlatively determine the combined impact of various size and weight measures on speed showed no significant improvement. This finding leads to the obvious conclusion that most of the speed effect is not dependent upon size and weight. Likely exogenous factors affecting speed derive from truck engine size and condition and various driver characteristics.

Recommendations for Future Research

That heavy trucks maintain uniform speeds across varying geometric conditions is necessary for safe operation in traffic. Safety measures applied in this study (e.g., flow perturbances, traffic delays, and rear-end accident likelihood) demonstrated no adverse effect of truck size and weight in situations where speeds were maintained. It was also shown that size and weight alone do not cause significant speed reduction.

It is obvious that the problem of operational safety associated with larger and heavier vehicles cannot be approached solely through regulation of their size and weight. The objective must be to increase the uniform operational characteristics of trucks, rather than to make them merely smaller or lighter. In view of the current finding that size and weight alone are not determining factors in truck performance, further research is necessary to examine other factors affecting traffic operational characteristics. Such information is essential for the development of regulatory procedures to effectively increase operational safety on the highway.

Attention must be given to the combined effects of factors such as size and weight, engine horsepower, engine maintenance procedures, and driver characteristics. Truck manufacturers' studies and other test-track procedures are enlightening regarding performance potential when such factors are controlled. However, information about the current status of these factors as they exist in actual highway operation is necessary for a real-world assessment of their effect on operational safety. Once determined, these factors directly affecting truck performance can be the target of effective regulatory procedures.

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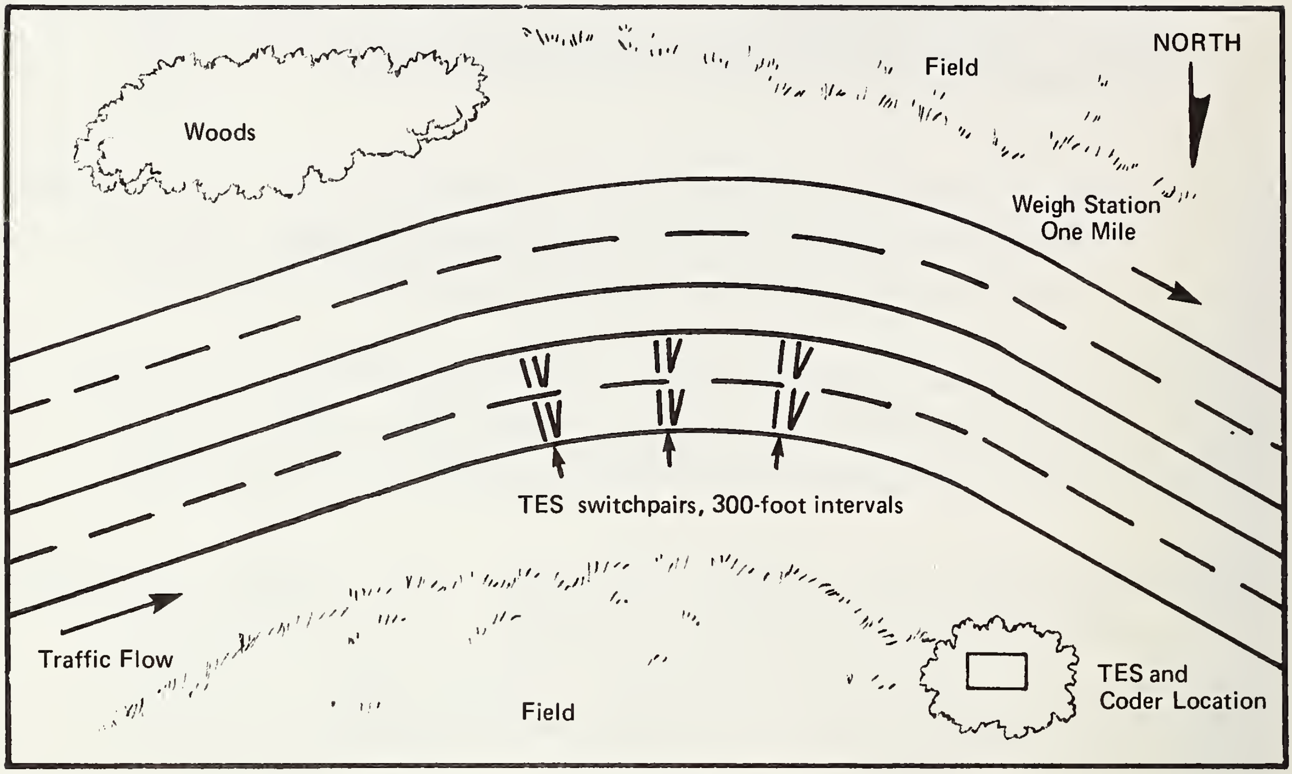
APPENDIX A

This appendix contains site descriptive data.

SITE: A: Fowlerville, Michigan



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Mainline Freeway Curve

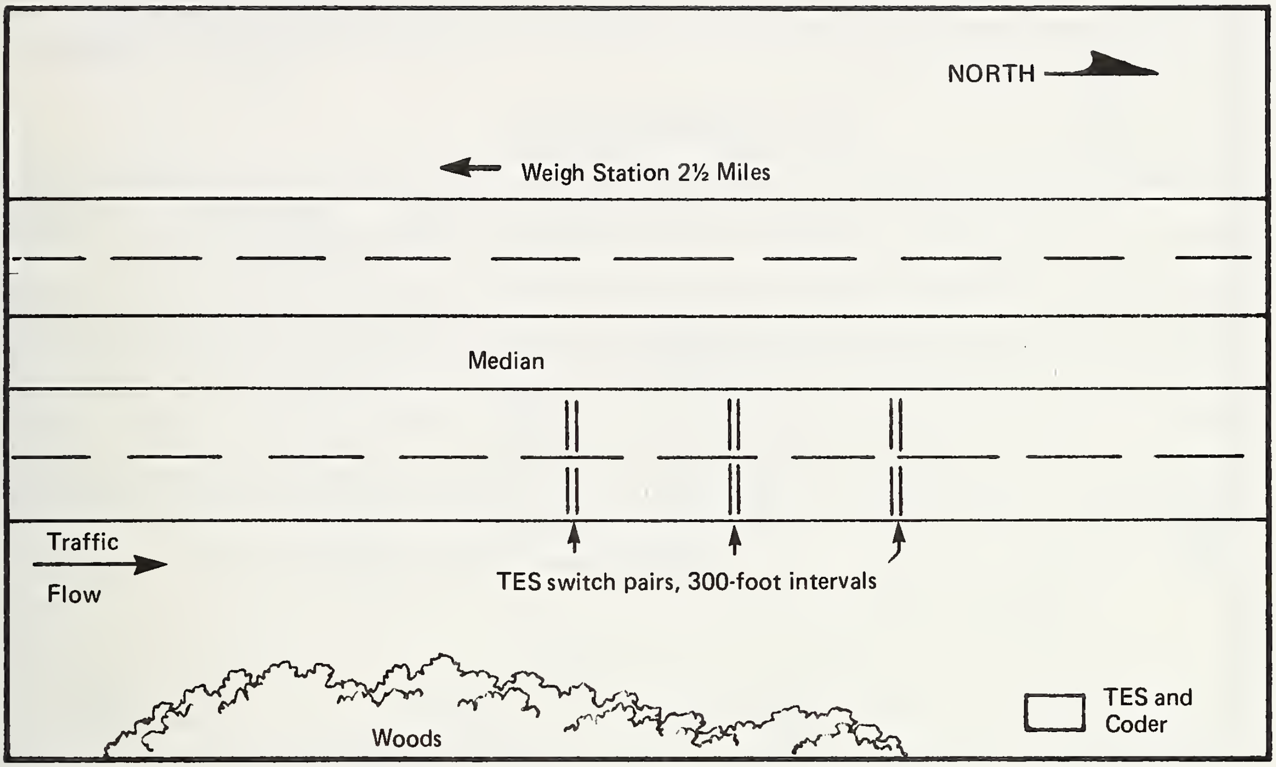
GEOMETRY:

2 Lanes, Freeway
D = 3°, Δ = 40°, L = .25 mile

LOCATION:

I-96, Westbound
2 miles East of Fowlerville

SITE: B: Pontiac, Michigan



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Grade;
Short, Slight, Positive

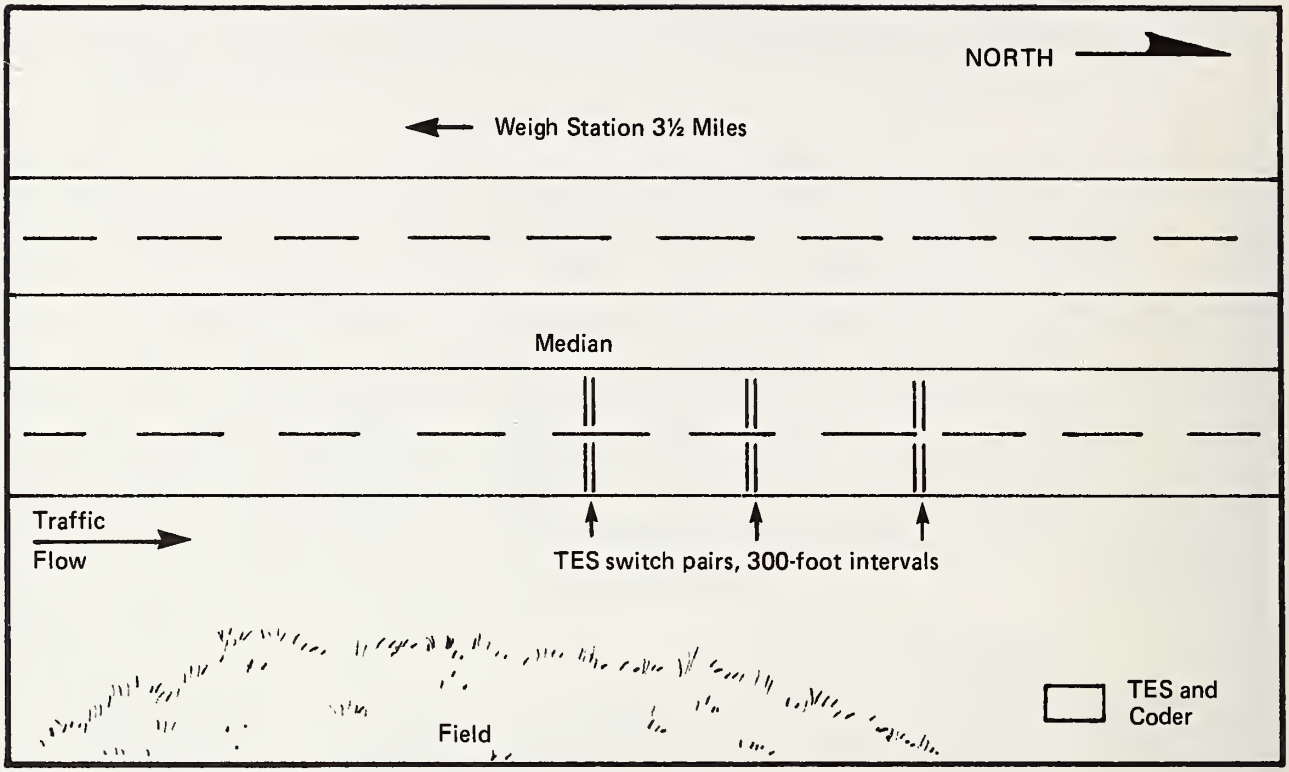
GEOMETRY:

G=1.5%, L=.6 mile

LOCATION:

I-75, Northbound
5 miles North of Pontiac

SITE: C: Pontiac, Michigan



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Grade;
Long, Slight, Positive

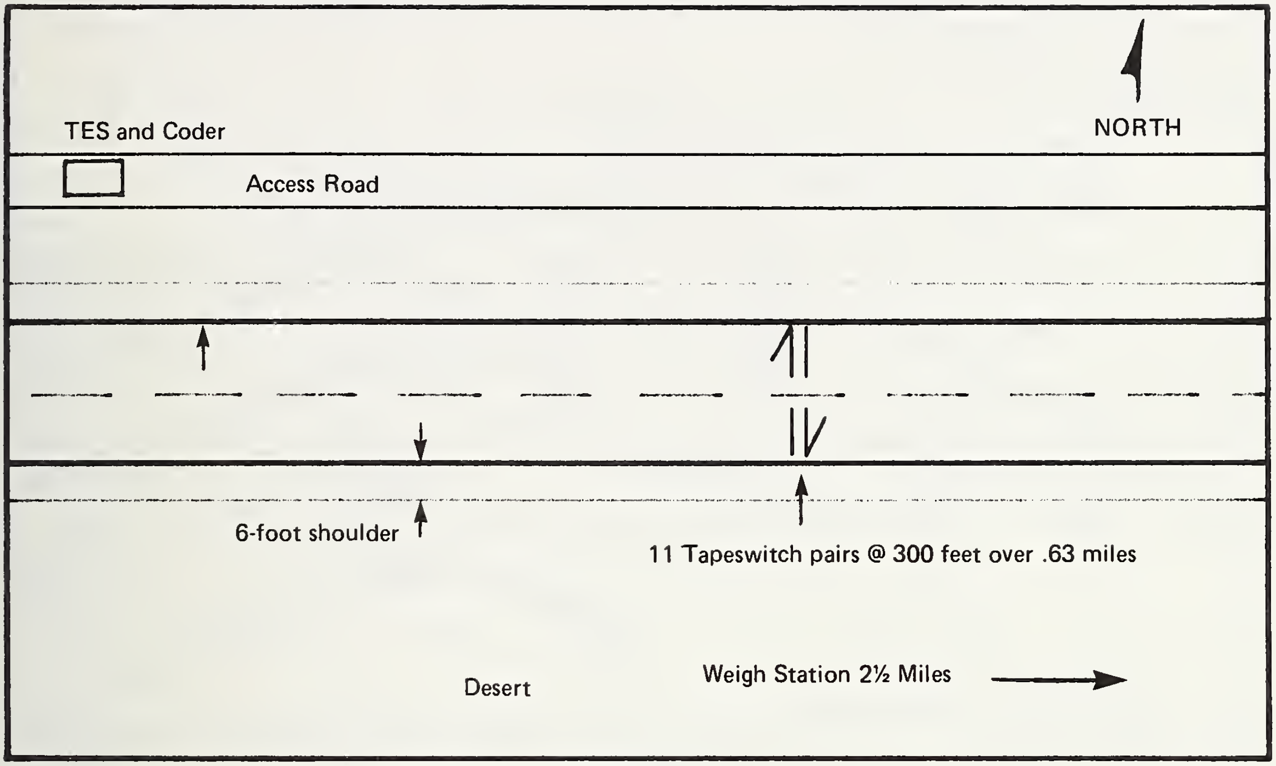
GEOMETRY:

G=1.5%, L=1.6 miles

LOCATION:

I-75, Northbound
6 miles North of Pontiac

SITE: D: Wendover, Nevada



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Passing

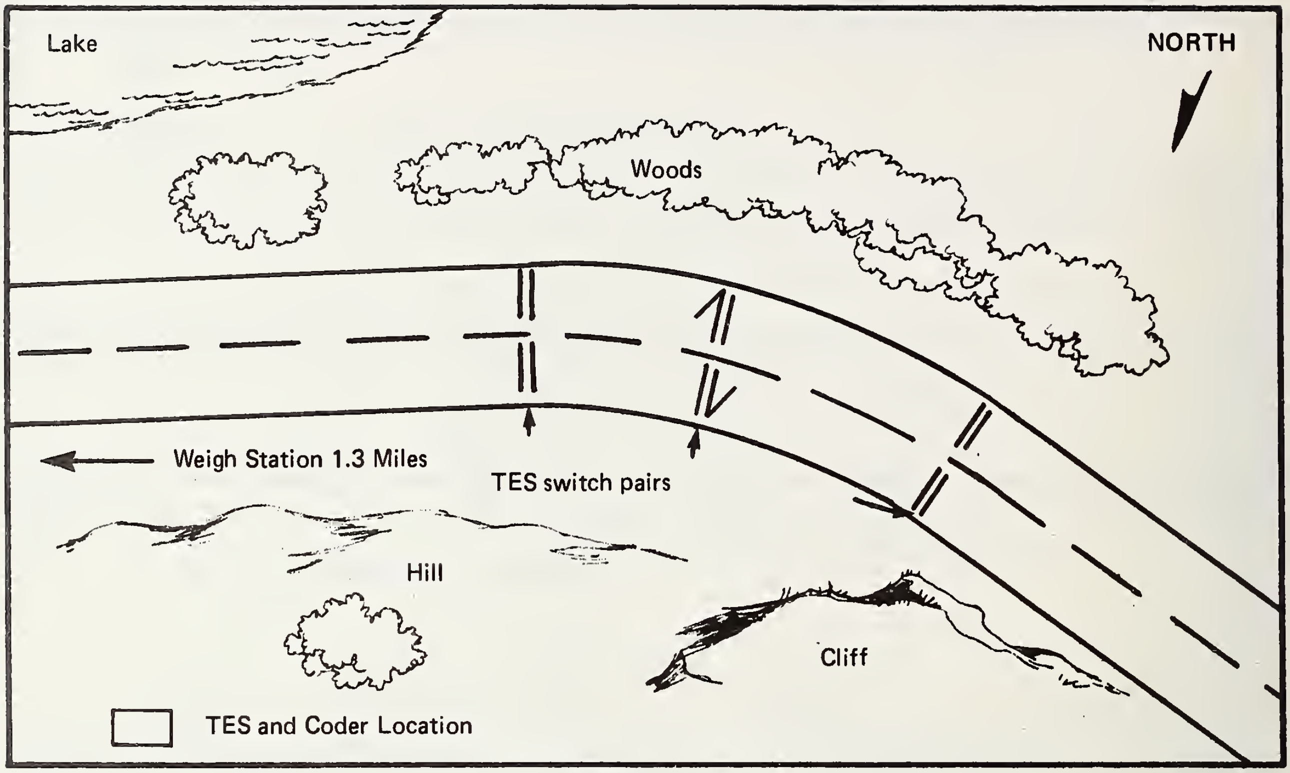
GEOMETRY:

2-Lane, Level Grade

LOCATION:

US 40, 2 miles West of Wendover

SITE: E: Shasta, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Curve, Non-Freeway

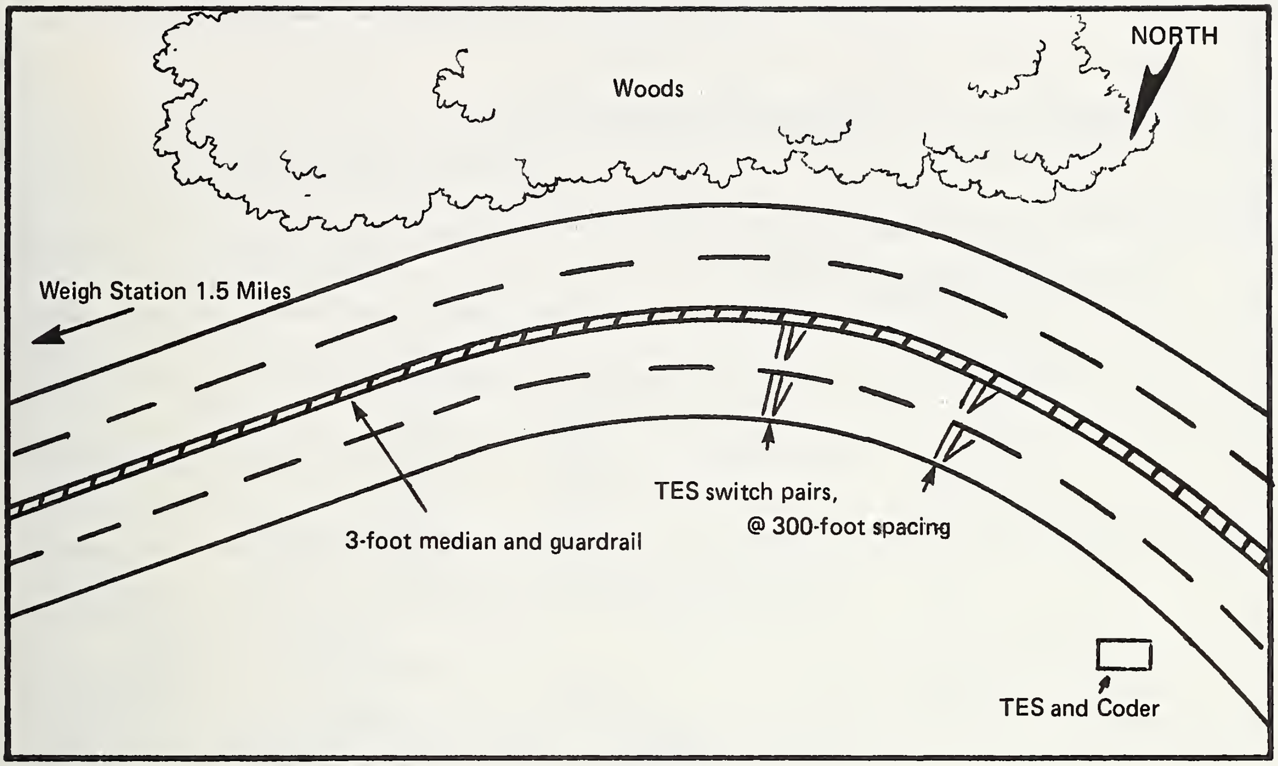
GEOMETRY:

2-Lane Roadway
L = 912′, Δ = 41°, D avg. = 4.5°

LOCATION:

State Route 299
2 miles West of Wiskeytown, Ca.

SITE: F: Placerville, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Grade and Curve, Non-Freeway

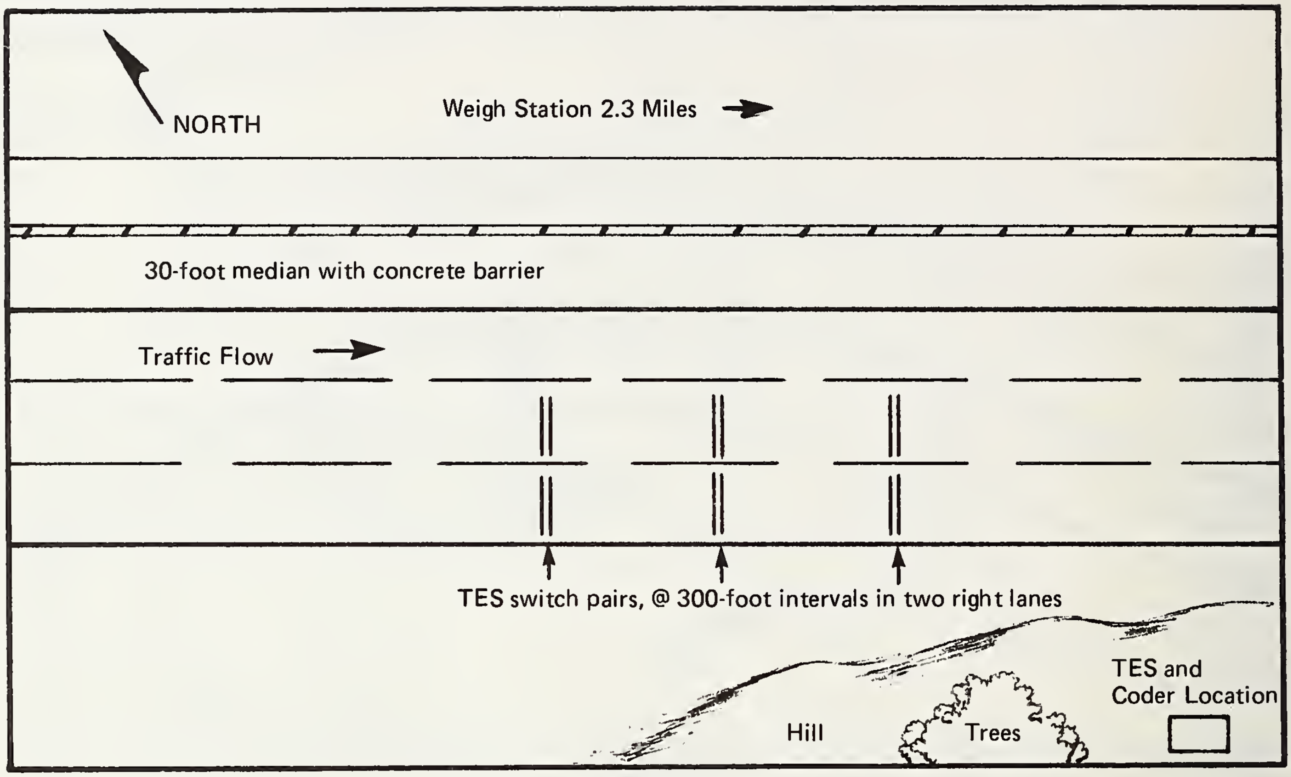
GEOMETRY:

4-Lane Divide Roadway;
L = 1340′, $\Delta = 54^\circ$, D avg.= 4°, G = -6%

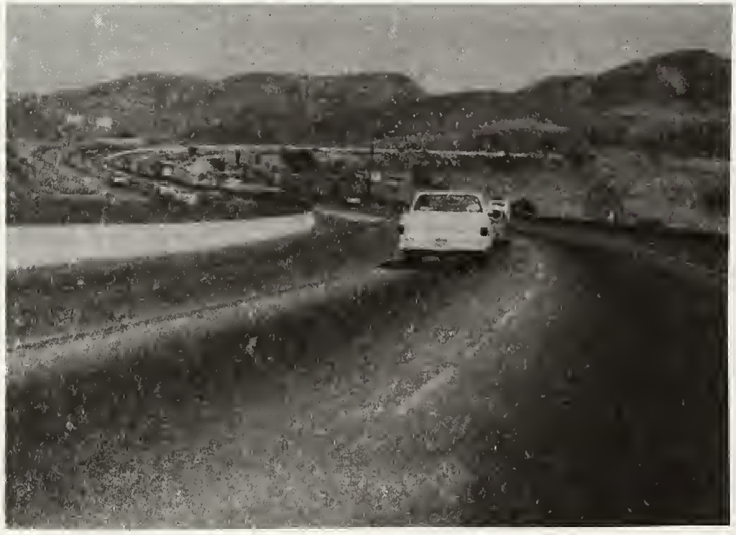
LOCATION:

US Route 50, 8 miles West of
Placerville, Ca.

SITE: G: Canejo, California



DIAGRAM



DRIVER VIEW OF SITE

TYPOLOGY:

Grade;
Short, Steep, Positive

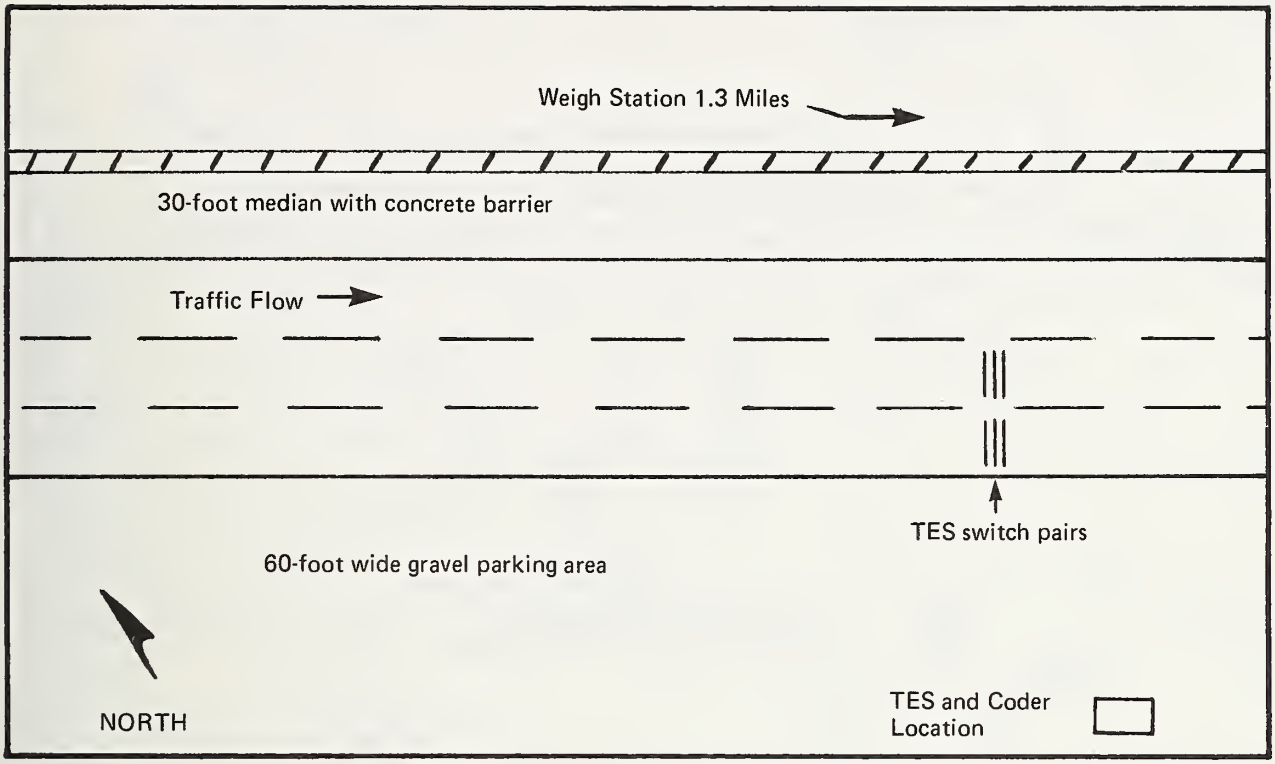
GEOMETRY:

G=7.0%, L=.6 mile

LOCATION:

US 101, Southbound Canejo, Ca.

SITE: H: Canejo, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Grade;
Long, Steep, Positive

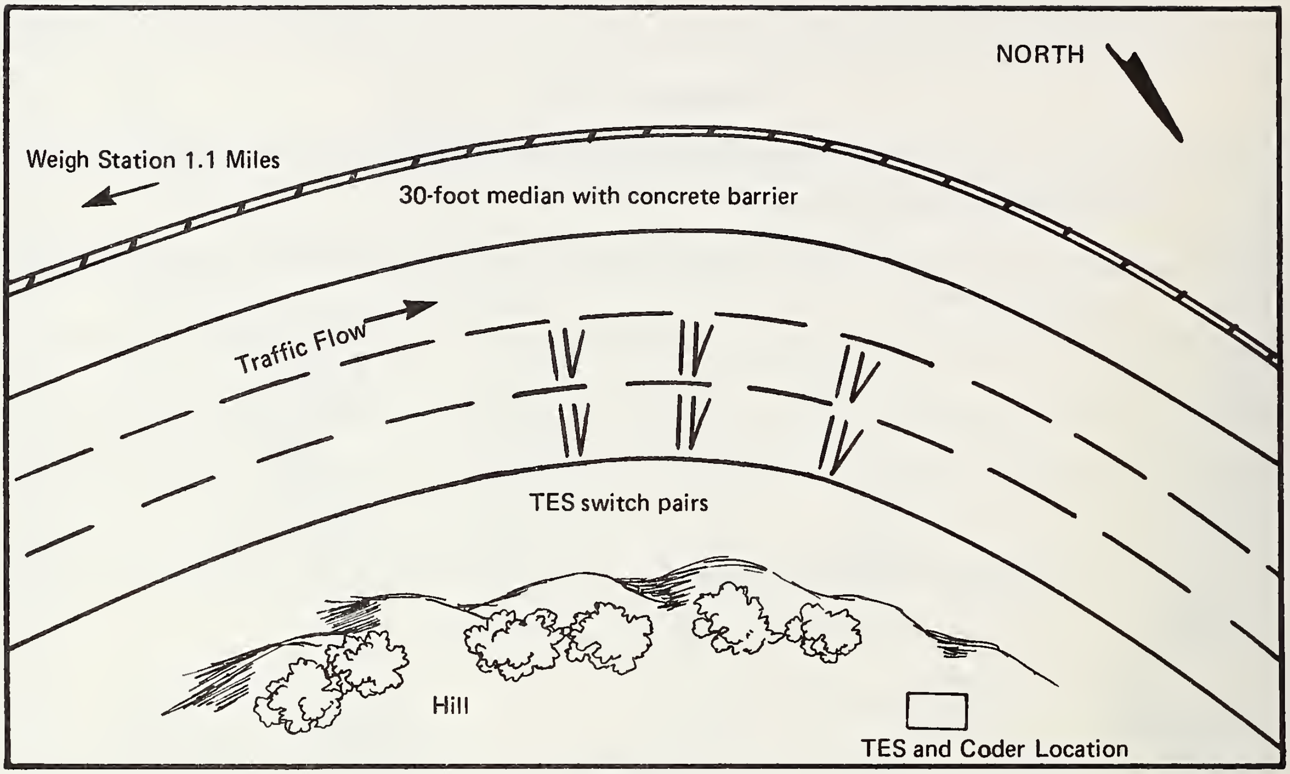
GEOMETRY:

G=7.0% L1.6 miles

LOCATION:

US 101, Southbound Canejo, Ca.

SITE: I: Canejo, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Freeway Curve and Grade

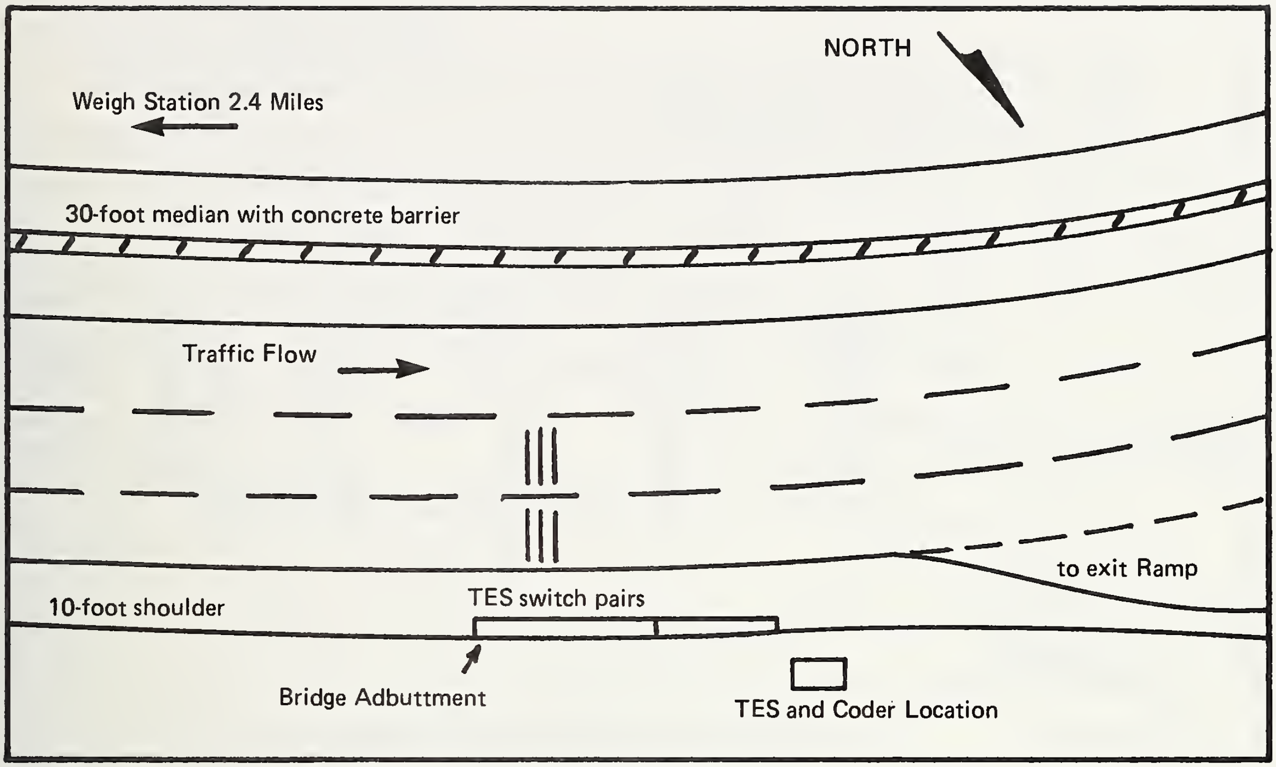
GEOMETRY:

L = 1950′, Δ = 58°, D = 3°,
G = 7.0% L = 1.0 miles

LOCATION:

US 101, Northbound Canejo, Ca.

SITE: J: Canejo, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Grade,
Long, Steep, Negative

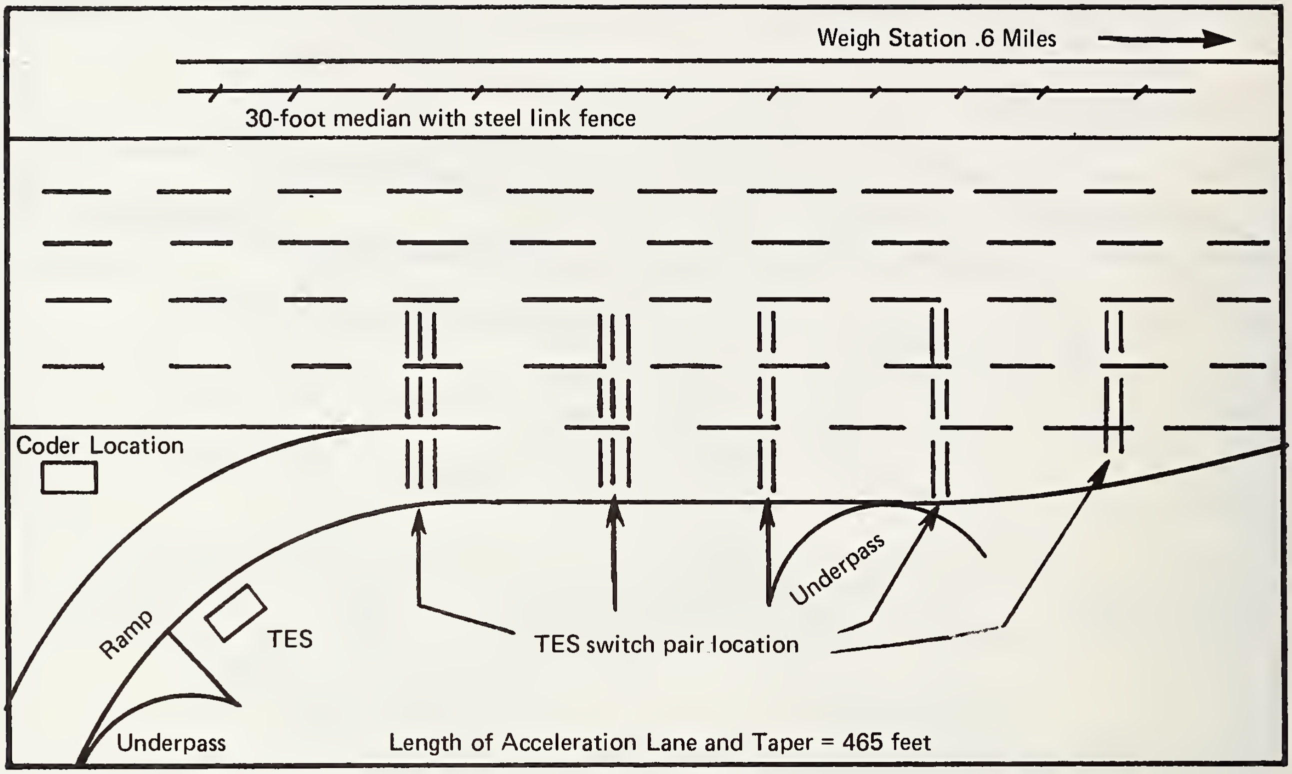
GEOMETRY:

$L = 1.8$ miles, $G = -7.0\%$

LOCATION:

US 101, Northbound Canejo, Ca.

SITE: K: Carson, California



DIAGRAM

VIEW OF SITE

TYPOLOGY:

Freeway Interchange, Entrance Merge

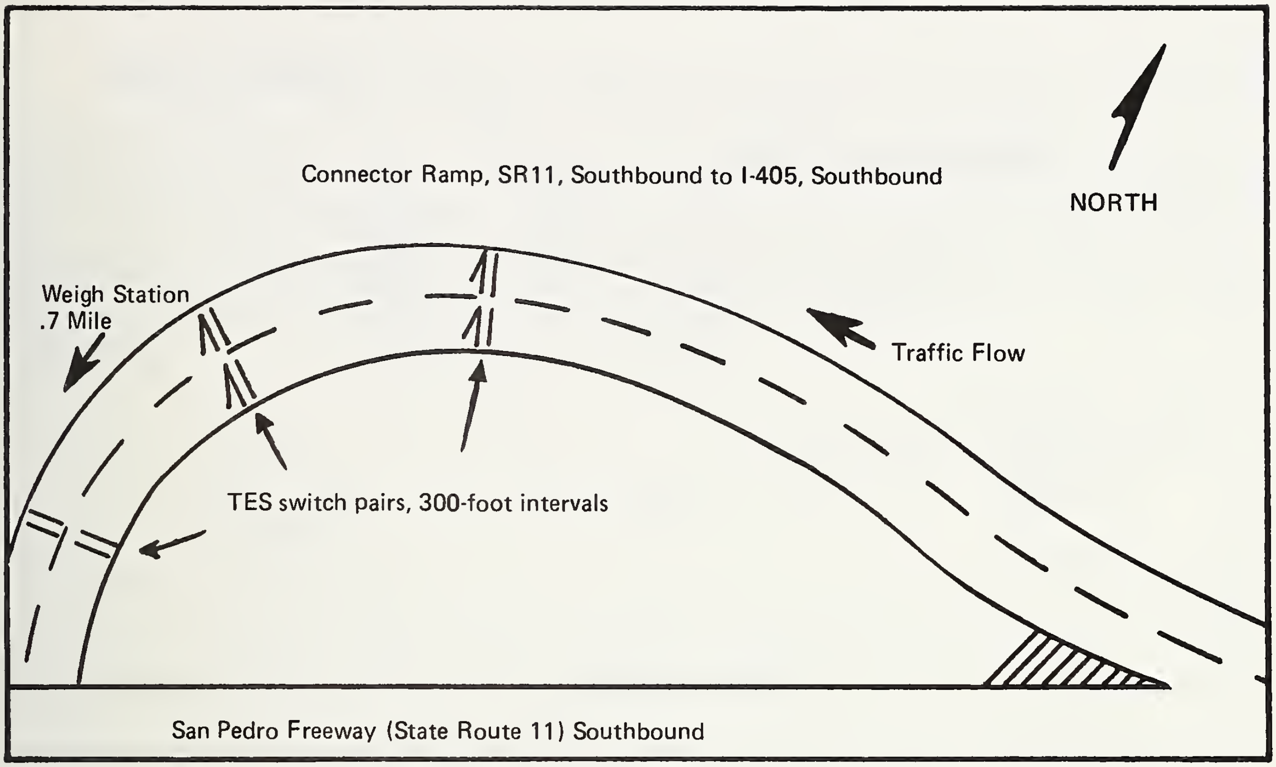
GEOMETRY:

Single Lane On-Ramp

LOCATION:

I-405 (San Diego Freeway) Southbound at St. Route 11 (San Pedro Freeway) Interchange; Carson, Ca.

SITE: L: Carson, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Curve, Tight Ramp

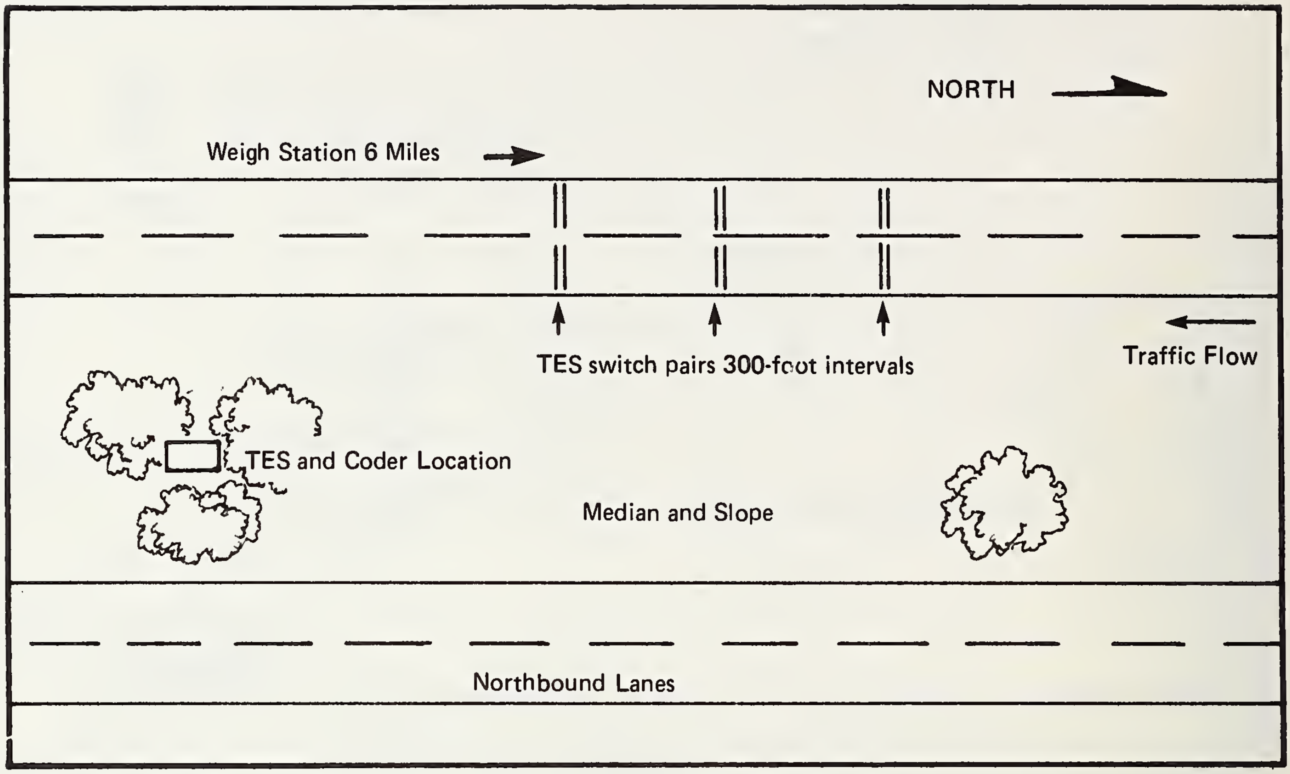
GEOMETRY:

Spiral Curve, 100° Over 955 feet
Max D $>4^\circ$

LOCATION:

SR11, I-405 Interchange
Carson, Ca.

SITE: M: Cottonwood, California



DIAGRAM

DRIVER VIEW OF SITE

TYPOLOGY:

Grade;
Long, 3%, Negative

GEOMETRY:

G=3.1%, L=1.2 miles

LOCATION:

I-5, Southbound 4 miles
South of Cottonwood

APPENDIX B

This appendix contains explanations of the traffic operations measures used in all steps of the analyses. Included here are variable names which correspond to matrices presented in Appendix D, measures definitions, rationales for the inclusion of each measure in the analysis, references to literature in which these concepts are applied, and calculation procedures.

Measure: Speed Variation

Variable Name: SPEED VAR

Definition: A speed change function derived from the following variance function:

$$\text{SPEED VAR} = 1/N \sum_{i=1}^{N} (\text{Speed}_i - \text{Mean Speed})^2$$

where N = number of speed measurements
i = specific switchpair locations.

Concept/Rationale: Speed change within an instrumented section of highway is measured as a function of differences between spot speeds and the mean speed for the section. This function comprises a direct measure of flow perturbation and will be examined for its relation to designated truck-descriptive variables.

Reference: Heinback and Vick, 1968.
Greenshields, 1965, and others.

Measured Population: All target trucks, all sites.

Calculation Procedure: Using vehicle speeds obtained at each switchpair, apply equation noted above.

Measure: Acceleration Variation

Variable Name: ACCEL VAR

Definition: An acceleration change function derived from the following variance function:

$$\text{ACCEL VAR} = 1/N \quad \overset{N}{\underset{i=1}{}} \quad (\text{Acceleration}_i - \text{Mean Acceleration})^2$$

where N = number of acceleration measurements
i = specific switchpair locations.

Concept/Rationale: Acceleration change within an instrumented section of highway is measured as a function of differences between specific accelerations and the mean acceleration value for the section. This function comprises a direct measure of flow perturbation and will be examined for its relation to designated truck descriptive variables.

References: Heinback and Vick, 1968.
Greenshields, 1965 and others.

Measured Population: All target trucks, all sites.

Calculation Procedure: Using vehicle accelerations obtained between switchpairs (MACL), apply equation noted above.

Measure: Maximum Acceleration

Variable Name: MAX ACCEL

Definition: The largest positive value of acceleration measured between successive switchpairs within the TES array.

Concept/Rationale: Maximum acceleration provides a measure of large speed increases and is used as an index of flow quality.

Measured Population: All target trucks, all sites.

Calculation Procedure: Given more than one value for mean acceleration (MACL) in an array, select the largest positive value as MAX ACCEL.

Measure: Maximum Deceleration

Variable Name: MAX DECEL

Definition: The largest negative value of acceleration measured between successive switchpairs within the TES array.

Concept/Rationale: Maximum deceleration provides a measure of large speed decreases and is used as an index of flow quality.

Measured Population: All target trucks, all sites.

Calculation Procedure: Given more than one value for mean acceleration (MACL), select the largest negative value as MAX DECEL.

Measure: Drive Slowly

Variable Name: DRIVE SLOW

Definition: Spot speed which is slower than the mean speed for the entire vehicle sample by at least one standard deviation.

Concept/Rationale: Any vehicle moving more slowly than the mean for the traffic stream causes some perturbation in traffic flow. Variance in speed distribution is a measure of overall stream flow stability. One standard deviation from the mean is used to segregate target trucks causing severe speed differences, hence substantial flow disturbance, in the traffic stream.

Reference: Hanscom and Berger, 1976.

Measured Population: All target trucks, all sites.

Calculation Procedure: Using periodic speed distributions for the entire vehicle sample, obtain mean and standard deviations for each lane. Identify target trucks exhibiting a speed of one standard deviation less than the mean, or slower (This variable is already calculated).

Measure: Drive Fast

Variable Name: DRIVE FAST

Definition: Spot speed which is faster than the mean for the entire vehicle sample by at least one standard deviation.

Concept/Rationale: Any vehicle moving faster than the mean for the traffic stream causes some perturbation in traffic flow. Variance in speed distribution provides a measure of overall stream flow stability. Variation of one standard deviation from the mean is used to segregate target truck causing severe speed differences, hence substantial flow disturbance, in the traffic stream.

Reference: Hanscom and Berger, 1976.

Measured Population: All target trucks, all sites.

Calculation Procedure: Using periodic speed distributions for the entire vehicle sample, obtain mean and deviations for each lane. Identify target trucks exhibiting a speed of one standard deviation above the mean, or faster (This variable is already calculated).

Measure: Critical Headway

Variable Names: MINTH/1, MINTH/2, MINTH/10

Definition: Difference in arrival times at a specific point between the target truck and lead vehicle is critically short (three values are 1.0 seconds or less, 2.0 seconds or less, and 10.0 seconds or less).

Concept/Rationale: Short headways are suggestive of rear-end accident potential as well as flow instability. Two values are used in order to examine both the severity of the perturbation and the availability of sample size. "Headway violations" have been cited in the literature as a safety hazard.

Reference: Kolsrud, 1972.
Hanscom and Berger, 1976.

Measured Population: All target trucks, all sites.

Calculation Procedure: Given values of time headway (TH) for target trucks at each TES switchpair, select the smallest value in array for each target truck. Values of 1.0 second or less = MINTH/1, and so on.

Measure: Critical Tailway

Variable Names: MINTTY/1, MINTTY/2, MINTTY/10

Definition: Critically short difference in arrival times at a specific point of the target and lead vehicle (two values are 1.0 seconds or less, and 2.0 seconds or less).

Concept/Rationale: Short tailways are suggestive of rear-end accident potential as well as flow instability. Two values are used in order to examine both the severity of the perturbation and the availability of sample size. "Headway violations" have been cited in the literature as a safety hazard.

References: Kolsrud, 1972.
Hanscom and Berger, 1976.

Measured Population: All target trucks, all sites.

Calculation Procedure: Given values of time tailway (TTY) for target truck at each TES switchpair, select the smallest value in array for each target truck. Values of 1.0 second or less = MINTTY/1, and so on.

Measure: Critical Rear-End Closure Rate

Variable Name: RECLOS 1, RECLOS 2, and RECLOS 10

Definition: Relative closure speed between target truck and following vehicle in cases of critically short tailway (two values of tailway are 1.0 seconds or less, and 2.0 seconds or less).

Concept/Rationale: Rear-end collision potential is measured by closure rate (relative speed) for closely following vehicles. Typical of this hazard is a high-speed car approaching a slow truck climbing a grade. Two values of tailway are used to permit analyses based on perturbation severity and sample size availability.

Reference: Hanscom and Berger, 1976.

Measured Population: All target trucks, all sites.

Calculation Procedure: Given values of rear closure rate (B-S) for target truck at each TES switchpair, select largest positive value in array associated with short tailway (TTY of 1.0 seconds or less (RECLOS 1) and tailway of 2.0 seconds or less (RECLOS 2).

Measure: Critical Front-End Closure Rate

Variable Names: FRCLOS 1, FRCLOS 2, and FRCLOS 10

Definition: Relative closure speed between target truck and lead vehicle in cases of critically short headway (two values of headway are 1.0 seconds or less, and 2.0 seconds or less).

Concept/Rationale: Rear-end collision potential is measured by closure rate (relative speeds) for closely following vehicles. Typical of this hazard is a high speed truck on a downgrade approaching a slow vehicle. Two values of headway are used to permit analyses based on perturbation severity and sample size availability.

Reference: Hanscom and Berger, 1976.

Measured Population: All target trucks, all sites.

Calculation Procedure: Given values of front closure rate (S-H) for target truck at each TES switchpair, select largest positive value in array associated with headways (TH) of 1.0 seconds or less (FRCLOS 1) and headways of 2.0 seconds or less (FRCLOS 2), and so on.

Measure: Projected time to collision

Variable Names: COLTIME 1, COLTIME 2, COLTIME 10

Definition: In cases of critically short headways or tailways in combination with relative closing speeds between successive vehicles, the amount of time required to completely close the inter-vehicle gap assuming no speed or path changes. Three levels of this measure include vehicles at following times of 1.0 second or less, 2.0 seconds or less, and 10.0 seconds or less.

Concept/Rationale: The projected time to collision assumes no speed or path changes in cases of closely following vehicles characterized by closing relative speeds. This measure takes into account the severity of the rear-end accident potential as a direct indication of safety hazard.

Reference: Hayward, pp. 24-34, Highway Research Record 384, 1972.

Measured Population: All target trucks, all sites.

Calculation Procedure: Target vehicles for the computation of this measure are those for which RECLOS 1, RECLOS 2, RECLOS 10, FRCLOS 1, FRCLOS 2, and FRCLOS 10 were earlier discussed. Inter-vehicle gap must be computed using existing gap measure, DH or DB, and vehicle length. Vehicle length is available using TES wheelbase information in combination with manually measured truck overhand data (on coding form) and an assumed constant value for non-truck overhang. Projected collision time is inter-vehicle gap distance divided by closure speed (B-S, or S-H).

Measure: Driver Effort

Variable Name: DRIVERE4T

Definition: Product speed change and lateral placement change between successive switch pair locations.

Concept/Rationale: Driver effort is related to flow measures of changes in speed and direction. This concept follows from Greenshield driverometer measures of space mean speed changes and steering wheel position changes, the product of which has been used to characterize the quality of traffic flow.

Reference: HRB Special Report 130, page 13.

Measured Population: Target trucks which do not change lanes in TES array. Use sites containing successive traps measure lateral placement (sites A, D, E, K, L).

Calculation Procedure: Given spot speed and lateral placement at two successive trap locations (e.g., S_1, S_2 and D_1, D_2), calculate product of differences as follows: $(S_1 - S_2) \times (D_1 - D_2)$. Use absolute values of $(S_1 - S_2)$ and $(D_1 - D_2)$. For arrays containing more than two traps, compute an average value.

Measure: Speed of Following Vehicle

Variable Name: FOLLOWSPD

Definition: The speed of a vehicle following behind a truck at a tailway of 1.24 seconds or less.

Concept/Rationale: The effect of trucks on traffic flow can be measured by the performance of following vehicles. Of specific interest is reduced speeds of vehicles following slow trucks on upgrades and in situations where passing opportunities are restricted.

Measured Population: All target trucks at upgrade sites (B, C, G, and H), and in the upgrade direction at two-lane sites (D and E westbound).

Calculation Procedure: For target trucks with time tailways (TTY) of 1.24 seconds or less, use value of rear closure speed (B-S) to compute speed of following vehicles as follows: FOLLOWSPD = (B-S) + S, where S is speed of target truck.

Measure: Following vehicle delay

Variable Name: FOLLOWDLY

Definition: Spot speed difference between the average flow for all vehicles on a specific highway section and that of a vehicle following a target truck. Delay as a time measure is directly related to speed difference over any specified distance.

Concept/Rationale: In the case of reduced speed of a vehicle following a slowly moving truck, delay is determined from the difference between normal traffic flow (in absence of the slow truck) and the observed speed of the following vehicle. Given this spot reduction in speed, a time delay function can be derived assuming a sustained speed reduction over a specified distance. For the purpose of this calculation, however, the speed reduction delay value is used due to its direct proportionality with a time function. The target condition for application of this measure is slowly moving trucks on upgrades.

Measured Population: All target trucks at upgrade sites (B, C, G, and H), and in the upgrade direction at two-lane sites (D and E westbound).

Calculation Procedure: Compute value of speed for closely following vehicle (FOLLOWSPD) as previously discussed. For each TES summary period, compute the difference between average speed for the total traffic population and the value of FOLLOWSPD. This speed difference measure can be used as the value for following delay (FOLLOWDLY) due to its direct proportionality with a time delay measure obtained by assuming a sustained reduced speed over a specific distance.

Measure: Following Queue Length

Variable Name: Q-LENGTH

Definition: Queue length behind a target truck is the number of successive following vehicles at time headways of 1.24 seconds or less.

Concept/Rationale: Queue characteristics behind trucks provide a measure of both flow instability potential (high density) and delay (restricted flow). Target situations are upgrades where traffic may be affected by slow trucks, two-lane roadways where passing may be impeded, and on-ramps where capacity may be affected.

Measured Population: All target trucks, all sites.

Calculation Procedure: Isolate target trucks with tailways of 1.24 seconds or less. Locate records for following vehicles (using successive trap arrivals, or matching time tailway (TTY) to time headway (TH) to identify following vehicles' TES record). Count the number of vehicles following at headways of 1.24 seconds or less.

Measure: Average Speed of Queued Following Vehicles

Variable Name: AVG Q-SPEED

Definition: The average value of speeds for vehicles in queue behind a target truck. The queue is defined as all successive vehicles following behind the truck at headways of 1.24 seconds or less.

Concept/Rationale: Queues behind trucks provide a delay measure by contrasting queued vehicle speeds with average flow speeds for a specific highway section under comparable flow conditions. The target condition for application of this measure is slowly moving trucks up a grade under restricted passing conditions.

Measured Population: All target trucks at upgrade sites (B, C, G, and H), and in the upgrade direction at two-lane sites (D and E westbound).

Calculation Procedure: Isolate target trucks with tailways of 1.24 seconds or less. Locate records for following vehicles (using successive trap arrivals, or matching time tailway (TTY) to time headway (TH) to identify following vehicles' TES record. Vehicles following at headways of 1.24 seconds or less comprise the queue. Compute average speed for vehicles in queue.

Measure: Following Queue Delay

Variable Name: Q-DELAY

Definition: Difference between average speed for all vehicles on a specific highway section and the average speed of queued vehicles behind a target truck multiplied by the number of vehicles in the queue. Delay as a time measure can be derived from the speed difference over any specified distance.

Concept/Rationale: In cases of reduced speeds for vehicles queued behind a slowly moving truck, delay is derived from the difference between normal traffic flow speeds (in absence of the slow truck) and the observed speed of the queue. Total delay for the queue must take into account the number of vehicles in the queue. Given the average speed reduction multiplied by the number of vehicles in queue, a time delay function results when this total speed reduction is assumed to be sustained over any specific distance. For the purpose of this calculation, however, the speed difference value is used due to its direct proportionality with a time function. The target condition for application of this measure is slowly moving trucks up a grade under restricted passing conditions.

Measured Population: All target trucks at upgrade sites (B, C, G, and H), and in the upgrade directions at two-lane sites (D and E westbound).

Calculation Procedure: Compute average speeds of queued vehicles (AVG Q-SPEED), as previously discussed. For each TES summary period, compute the difference between average speed for total traffic population and each value of AVG Q-SPEED. This speed reduction measure can be used as the Q-DELAY value due to its direct proportionality with a time function of measure obtained by assuming a sustained reduced speed over a constant distance.

Measure: Interaction type

Variable Name: NTERACT

Definition: Truck interactions with other vehicles in their vicinity are categorized into six interaction types according to vehicle proximity. Categorical variable designations are: 0 = no interacting vehicle; 1 = side interaction, on left; 2 = side interaction, on right; 3 = front interaction, time headway = 2.0 seconds or less; 4 = rear interaction, time tailway = 2.0 seconds or less.

Concept/Rationale: Identification of a target truck by interaction type is needed to determine its effect on traffic flow and stability. Examples are as follows. Free flowing (no interacting vehicle) trucks do not affect total stream flow. Front and rear interactions (NTERACT = 5) will be used in combination with relative speed data to assess rear-end accident potential. Side interactions are required to assess passing probabilities.

Measured Population: All target trucks, all sites.

Calculation Procedure: Compare arrival times for lead/following vehicles at specific traps and side vehicles at adjacent traps. See attachment for designation of arrival time differences.

Measure: Probability of truck being passed

Variable Name: PROBPAST

Definition: The proportion of trucks observed in the study sample which are in close proximity to other vehicles in the adjacent lane to their left.

Concept/Rationale: The probability of trucks being passed (especially on upgrades) is taken as a stream flow parameter. The proportion of trucks being passed will be examined in terms of measures of truck-related factors to determine if heavier trucks are more often passed on upgrades, etc.

Measured Population: All target trucks, where passing is permitted (all sites except E). Use only trucks traveling in the right of two instrumented lanes.

Calculation Procedure: In the case of target trucks for which the value of NTERACT = 2 (car beside, on left), the value of PROBPAST = 1. For all other target trucks tracked in the right of two adjacent instrumented lanes, the value of PROBPAST = 0.

Measure: Probability of truck passing another vehicle.

Variable Name: PROBPASSN

Definition: The proportion of trucks observed in the study sample which are in close proximity to other vehicles in the adjacent lane to their right.

Concept/Rationale: The probability of trucks passing other vehicles (especially on downgrades) is taken as a stream flow parameter. The proportion of trucks passing other vehicles will be examined in terms of measures of truck-related factors to determine if heavier trucks more often pass on downgrades, etc.

Measured Population: All target trucks, where passing is permitted (all sites except E). Use only truck traveling in the right of two instrumented lanes.

Calculation Procedure: In the case of target trucks for which the value of NTERACT = 1 (car beside, on right), the value of PROBPASSN = 1 for all other target trucks tracked in the right of two adjacent instrumented lanes, the value of PROBPASSN = 0.

Measure: Relative passing speed (truck being passed)

Variable Name: RELPASSPD

Definition: Difference in speed between truck and the passing vehicle.

Concept/Rationale: A measure of the perturbation effect resulting from a passing interaction is the relative speed difference between the two vehicles. This speed difference will be examined in terms of its relationship with truck factors.

Measured Population: All target trucks, where passing is permitted (all sites except E). Use only truck traveling in the right of two instrumented lanes.

Calculation Procedure: In the cases of trucks with a value of PROBPAST = 1, compute the difference in speeds between the interacting vehicle and the target truck. RELPASSPD = interacting vehicle speed minus the target truck's speed.

Measure: Relative passing speed (truck passing)

Variable Name: RELPSGSPD

Definition: Difference in speed between truck and vehicle being passed.

Concept/Rationale: A measure of the perturbation effect resulting from a passing interaction is the relative speed difference between the two vehicles. This speed difference will be examined in terms of its relationship with truck factors.

Measured Population: All target trucks, where passing is permitted (all sites except E). Use only truck traveling in the right of two instrumented lanes.

Calculation Procedure: In the cases of trucks with a value of PROPASSN = 1, compute the difference in speeds between the interactive vehicle and the target truck. RELPSGSPD = target truck speed minus the speed of the vehicle being passed.

APPENDIX C

Multiplicative Model, Estimation of Parameters

by Robert Sterrett, Jr., Consultant

Inspection of graphs of speed versus gross weight suggested a multiplicative production function. A multiplicative model can accommodate the apparent faster than linear decrease in speed with an increase in gross weight.

The multiplicative model has the form:

$$y = e^{\alpha_2} x_1^{\alpha_1} x_2^{\alpha_2}$$

where:

y = the dependent variable

e = the base of the natural logarithms

x_1 = the i^{th} independent variable, and the

α_1 = coefficients to be determined by the fitting algorithm

This functional form has enjoyed wide application in the physical and sociological sciences. The form is frequently called the Cobb-Douglas production function since economists Paul Douglas and Charles Cobb used it to model economic output.

The Cobb-Douglas model is:

$$x = AL^{\alpha}K^{\beta}$$

where:

x = the total economic output

L = labor input in person-hours

K = the stock of capital equipment

A = a scaling constant, and

α,β = the elasticities* of labor and capital, respectively.

An example of the multiplicative model in physical systems is Newton's theory of gravitation:

$$F = Gm_1m_2R^{-2}$$

where:

F = the gravitational force

G = the universal gravitational constant

m_1,m_2 = the masses under consideration

R = the distance between the masses

The mathematical properties of this form account for its utility. These properties include:

- Invariance - the coefficients (elasticities) are infariant under positive scaling of the independent variables and a constant across the domains of the independent variables.
- Diminishing Returns - when the elasticities are negative, a continuing increase in the independents produces a smaller and smaller absolute decrease in the dependent variable.

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*The elasticity is another convenient way to characterize a relationship between two variables. In the above relationship, X will change α% for every 1% change in L. X will change β% for every 1% change in K. Elasticities may be computed for linear at x_0 relationships also. For y=ax+b, the elasticity between y and x at x_0 is $\frac{a}{y_0}$ =X where $y_0 = ax_0+b$.

The last property especially was relevant for the mean speed equation since the graphs indicated a less than linear decrease in speed for corresponding increase in gross weight.

To estimate α_0 and α_1 in:

mean speed = e^{α_0} (gross weight)$^{\alpha_1}$

the natural logs of both sides

$\log_e$ (mean speed) = $\alpha_0+\alpha_1 \log_e$ (gross weight)

This is the traditional linear regression problem.

The above approach is not strictly correct. The problem lies in the unfortunate fact that since the logarithm is not a linear transformation, the solution of the log-linear model is not the exact solution of the multiplicative model (see W.A. Dotson article). However, experience has shown that the log-log model is a reasonable approximation in many instances. These estimates can be used as starting values in an iterative solution technique.

Reference

Encyclopedia Britanica, Econometrics, Volume 6, p. 200.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

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* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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