National Cooperative Highway Research Program

NCHRP Synthesis 241

Truck Operating Characteristics

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 241

Truck Operating Characteristics

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff Transportation Research Board

This synthesis will be of interest to engineers and administrators responsible for the design, construction, and maintenance of highways and bridges, as well as to engineering design consultants. It will also provide useful information to the trucking industry, especially to designers, as they consider the highway interface with regard to the design and operation of heavy trucks. It provides information on the influence of the design and operating characteristics of heavy trucks on highway design, maintenance, and operational performance.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

Designers of heavy trucks and of the highway infrastructure that is needed to support them, are faced with changing requirements for both systems to operate effectively and safely. Because truck designs tend to evolve more rapidly than highways can be rebuilt

or redesigned, inefficiencies can result. This report of the Transportation Research Board describes heavy truck design factors and operating characteristics and their influence on highway planning, design, and performance. The key truck operating characteristics, such as weights and sizes, mechanical properties, turning requirements, accelerating and braking, crash avoidance, pavement and bridge loadings, and the effects on traffic flow are discussed. To more clearly illustrate the subject, matrices of truck and roadway characteristics that are associated with each of these elements are presented.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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ACKNOWLEDGMENTS

Paul S. Fancher, Jr., Research Scientist, The University of Michigan Transportation Research Institute and Thomas D. Gillespie, Ph.D., Director, The Great Lakes Center for Truck and Transit Research, University of Michigan were responsible for collecting the data and preparing the report. Dr. William D. Glauz, formerly of Midwest Research Institute, and Dr. Andrew C. Lemer, Matrix Group, Inc., made significant contributions to this synthesis.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Kenneth L. Heald, Chief Engineer, Western Highway Institute/ATAF, San Bruno, California; Garrick Hu, Vice President, Mack Truck Company; Elaine King, Senior Program Officer, Transportation Research Board; Hugh W. McGee, Principal, Bellomo-McGee, Inc., Vienna, Virginia; Mark Morrison, Regional Traffic Engineer, Wisconsin Department of Transportation; John R. Pearson, Director, Transportation Association of Canada; William A. Prosser, Geometric Design Engineer, Federal Highway Administration; and Justin True, Program Manager, Federal Highway Administration.

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TRUCK OPERATING CHARACTERISTICS

SUMMARY

This report comprises a review and synthesis of current practice in the design of heavy trucks and the influence of their design, operating characteristics, and performance properties on highway design, maintenance, and operational performance. Heavy trucks are defined as motor vehicles of classes 7 and 8, that have gross vehicle weights (GVW) or gross combination weights (GCW) of 12 000 kg (26,000 lb) and greater. They operate as tractor units hauling single, double, or triple trailers. Emphasis is placed on class 8 vehicles with a federal GCW limit of 36 000 kg (80,000), but weights of the largest trucks operating on highways may be greater in some regions of North America. Heavy truck size, weight, and consequent operating characteristics often represent the most severe requirements that highway geometric and pavement design standards must accommodate.

The research included an extensive review of literature and a survey of practice reported by transportation agencies in 48 states, seven Canadian provincial transportation agencies, and two U.S. transportation authorities. A less extensive and more informal survey of the U.S. truck design industry was also conducted. The survey of highway practice included pavement life, bridge life, sight distance, intersection geometrics, lane width and widening on curves, horizontal curves, run-off ramps and speed control on grades, climbing lanes, entrance and exit ramps, interchange ramps, sign placement, signal timing, and special situations agencies might face. Current design practice in the United States is largely derived from the American Association of State Highway and Transportation Officials (AASHTO) *Policy on Geometric Design of Highways and Streets* and from guidance issued by the Federal Highway Administration, and requirements in the *Manual on Uniform Traffic Control Devices* (MUTCD).

States reported that AASHTO and MUTCD policies are used in approximately 90 percent of the situations considered. However, the survey indicated that states have adopted a variety of specific practices to meet their own needs. A trend toward accommodating longer and heavier vehicles is cited as the motivation for many of the differences between state practices and national models. Most frequently reported are differences about assumed vehicle weights in estimating bridge life and assumed vehicle dimension in determining allowable offtracking in intersection design. Canadian practices, based often on Transport Association of Canada and Canadian Standards Association codes and procedures, differ more substantially from U.S. models.

State highway laws and design standards have considerable influence on truck design, determining allowable limits on such characteristics as height and width, tire tread width, and distance between trailer axles. However, heavy trucks are largely custom made to

meet buyer's requirements, which in turn are established by anticipated needs of shippers. One truck manufacturer reports that the company is prepared to build more than 47,000 different designs of tractors. This needed diversity in truck types, sizes, and configuration has led vehicle manufacturers to become both versatile and efficient in producing different models.

The differences between (1) private enterprise for trucks and trucking and (2) public accountability for highway operations and maintenance are considerable. As a result, there is potentially a divergence between the characteristics of heavy trucks in operation and the assumed truck characteristics that highways are designed to accommodate. However, both highway and vehicle designers seek to enhance trucking safety and productivity.

This synthesis summarizes current generic mechanical characteristics of trucks and design characteristics of roadways as they relate to operating situations for trucks traveling on roadways. The interaction of truck and highway determines the safety, productivity, and other aspects of performance. Situations involving truck performance that require special attention are:

- Turning—at intersections (including offtracking and friction demand), on ramps (including rollover considerations), and on horizontal curves;
- Acceleration and braking—crossing roadways and at-grade rail intersections, signal timing considerations, hill climbing, and downhill descent;
- Crash avoidance—rollover, obstacle evasion, rear-end collisions, and run-off-road situations;
- Pavement loading, highway fatigue, rutting, and bridge loading; and
- Congestion, capacity, and passing sight distance.

Several areas are suggested in which changes might yield improved truck/highway performance. In general, many of the variations in state regulations may offer significant gains in operating efficiency for the local truck/highway system. Aggregate productivity of the U.S. truck/highway system, as measured by payload delivered in relation to such factors as pavement wear, bridge fatigue, and traffic delays, warrants greater attention. In addition, better understanding by highway designers of actual truck operating characteristics in such situations as accelerating and braking to control speed, turning on ramps and in intersections, and negotiating steep grades would enable development of effective design tools and standards.

CHAPTER ONE

INTRODUCTION AND DISCUSSION OF THE PROBLEM

INTRODUCTION

Heavy vehicles operating on the nation's road network significantly influence the safety and efficiency of the highway transportation system. Trucks are often criticized for their effects on highway and bridge wear, highway safety, and traffic congestion. Yet it is recognized that heavy truck transportation is a service critical to the nation's industrial base and to the population's need for food and goods.

It is thus in the best interest of all to encourage evolution of both the road system and the truck transportation system toward ensuring the compatibility between the two, particularly in the matters of

- Designing roads to accommodate heavy vehicles,
- Designing heavy vehicles to operate on those roads, and
- Adopting policies that will lead to road and vehicle design that improves the safety and efficiency of heavy vehicle transportation.

At the operational level, compatibility is determined by the basic design of vehicles and road structures as well as the operational and maintenance procedures applied to each.

The objective of this report is to provide a synthesis of knowledge concerning the relationships between (a) highway design, maintenance, and operational performance and (b) the design, operating characteristics, and performance properties of heavy trucks. This knowledge base is intended to be a resource for policy makers, administrators, practicing engineers, and researchers faced with problems related to providing excellence in highway transportation.

The synthesis focuses on current and projected heavy trucks in North America, 12 000 kg (26,000 lb) and heavier, as defined by their physical characteristics (e.g., size and weight, dimensions, articulation geometry, axle locations and loads, etc.) and their operational performance (e.g., braking capability, offtracking on curves, tractive power, etc.). Relationships between vehicle characteristics and infrastructure design parameters are addressed. The result is a synthesis of knowledge that can be used to trace the influences of truck characteristics and properties on highway policy, planning, design, and operation.

THE PROBLEM

Influence of Truck Characteristics on Highway Design and Operation

Numerous relationships and factors play important roles in determining how roads and trucks are designed. With regard to design, the perspective narrows from a broad overview of the truck transportation system to a view that looks at the performance of the system in specific operating situations. In part, this focused view derives from the process of reaching agreements on regulations and design policies. Newland (*1*) has stated, "Regulations necessarily simplify and compromise." In order to have breadth, agreements need to cover a great variety of circumstances. The basic issues need to be addressed in a manner that is simple to understand yet sufficiently detailed to satisfy those involved in developing and adhering to the regulations.

Design policies are also aimed at condensing numerous possibilities using straightforward procedures for planning roads and vehicles. Often this means selecting a design case and designing to obtain a performance level for that case. In this sense, both design polices and regulations necessarily simplify and compromise.

In the case of truck transportation, the design of trucks and roads has developed somewhat independently, with weight and dimension regulations serving as a common ground that seeks compatibility between trucks and roads. A basic understanding of that process is fundamental to recognizing how today's trucks have evolved and to projecting what future trucks might be like.

For example, a transportation employee offered the following scenario when asked, as part of a survey conducted in preparing this synthesis, How are vehicle length constraints determined?

> In order to obtain greater productivity, a trucking interest will go to the legislature and ask for provisions that allow a slightly longer trailer. Given that the trucking interest is successful in getting a bill introduced, a legislative committee will then ask the transportation department why slightly longer trailers shouldn't be allowed. Depending on the evidence supplied by the transportation department and the results of lobbying and negotiations, the bill will be either passed or rejected. The result has been that these types of bills pass frequently enough that increases in semitrailer lengths have occurred recently in many states.

Suppose that a state approves an increase in allowable trailer length from 14.6 m (48 ft) to 17.4 m (57 ft). However, many of the roadways that are already in place were designed for the 14.6-m (48-ft), or even shorter, trailers. This means that to meet the demands posed by the longer trailers, highway departments may need to rebuild intersections so that long trailers making turns will not interfere with the flow of traffic and compromise safety. They may also choose to modify their design policies to provide roads that will enable more satisfactory performance. This example illustrates how feedback about changes in size and weight regulations can set in motion plans for road modifications that are compatible with those changes.

Road and vehicle designs are developed to serve the needs of the transportation system as viewed from the perspectives of (1) those charged with making the highway infrastructure last, and (2) those whose livelihood depends on delivering the goods. Roadway design is characterized by the use of policies developed by organizations like AASHTO *(2)* and FHWA *(3)*. Truck design, however, is a private, competitive enterprise. This means that there are proprietary aspects to certain features of truck design. Even so, both truck and road designs can be discussed in terms of basic operating situations.

The performance of the truck/highway system in a selected operating situation depends on both the truck and road characteristics. However, people who build and maintain roads will have different performance goals than truck builders, operators, and shippers. Truckers may tend to evaluate performance in terms of productivity and safety, while personnel from a transportation organization may tend to be concerned with maintaining the infrastructure, traffic flow, and safety. The following examples are offered to help clarify the nature of the different perspectives on performance between truckers and transportation personnel:

- One conceptually very basic operating situation involves nothing more than carrying a load over the road. From the trucker's perspective, the maximum allowable wheel loads determine how much heavy or dense cargo can be carried by the vehicle. For lighter cargo, trailer volume is the constraining parameter. From the transportation agency's perspective, the wheel loads and their distribution along the vehicle determine the amount of pavement wear and bridge fatigue that will result from repeated passes of this type of vehicle. The basic issue in this example is the amount of wheel load allowed. The road characteristics of importance are the material properties of the roads and bridges and the fatigue strengths of these structures.
- Another basic operating situation is the speed of trucks on an upgrade. The person specifying the characteristics of a desired truck could select the power/weight ratio that would allow the vehicle to climb a specified "design hill" of given steepness and length in a desired length of time. In this same operating situation the road designer may be concerned with the need for a climbing lane on this grade. If the speed of the truck falls far enough below the expected speeds of other vehicles, the truck could be a hazard or cause delays to other traffic. The road designer may use the characteristics of a "design truck" with a specified power/weight ratio to estimate where the climbing should start so that slow-moving vehicles will be able to move over and avoid being a traffic impediment.

As seen in these two examples, the characteristics of both the trucks and the highways are involved in determining the overall performance of the transportation system. This clearly illustrates the opportunity for improving the quality of the transportation system if the designs of trucks and roads are coordinated appropriately through the communication and exchange of design information.

Operational Situations on the Highway

A listing of situations comparable to those above would be long, indeed, and include truck-turning situations, truck acceleration and braking concerns, crash avoidance situations, traffic control systems, and the many other issues addressed in subsequent chapters of this synthesis.

The long list of maneuvering and traveling conditions that could be created applies primarily to the geometric design on the roadway and the performance of heavy vehicles as part of the traffic using the road. In these situations, performance is measured for trucks by productivity (in terms of size of loads safely delivered, distances covered, travel times required, all at the lowest possible cost). For roads, performance is measured by the level of service provided. For both trucks and roads, performance depends on the crash (accident) record and the potential for crashes. There are matters of access to be resolved in either providing road layouts and traffic controls that are compatible with large trucks or limiting the routes that large trucks may use. There are also tradeoffs between the high-speed mobility achieved through limited-access highways and the need to provide access to meet local needs.

In parts of this synthesis, the process of using bridge and pavement loading constraints is referred to as "designing trucks for roads," and the process whereby truck operating characteristics are considered in the geometric design of roads is referred to as "designing roads for trucks." Perhaps the knowledge and experience accumulated while applying these processes will aid in the evolution of system designs whereby the efficiency and safety of the truck transportation system is enhanced by considering truck and highway factors simultaneously. In that regard, a purpose of this synthesis is to aid in contributing to the truck information used by transportation personnel, as well as informing trucking interests about the properties of roads.

Addressing the Problem of the Compatibility of Trucks and Roadways

The next chapter is a step in the direction of coordination between truck and road designers. In presenting the process used in developing this synthesis, it cites information from surveys of both groups relating to design practices that influence compatibility. Chapter 3 contains a discussion of trucks and trucking in general and the truck design parameters of importance to road designers. Chapter 4 provides more detailed information on the specific truck properties that figure in subsequent chapters.

Chapters 5 through 9 address the major highway operational situations that are influenced by truck characteristics, grouped according to turning movements, acceleration and deceleration situations, crash avoidance, pavement and bridge loading, and congestion, roadway capacity, and passing maneuvers. Chapter 10 contains the conclusions of the synthesis. Following that are a list of references, a bibliography, and a glossary of terms. Appendix A is the survey questionnaire that was sent to highway agencies, and Appendix B is the survey that was sent to truck manufacturers and designers.

CHAPTER TWO

REVIEW OF CURRENT PRACTICE

Information for the synthesis was derived from published literature, a survey of state departments of transportation and Canadian province design engineers and truckers, a review of current research, and attendance at a series of meetings aimed at exchanging ideas concerning truck design and highway design. Highlights from these endeavors are provided in this chapter.

LITERATURE SURVEY

A bibliography of references was assembled from a search of the Transportation Research Information Services (TRIS) data bases by Transportation Research Board (TRB) staff and a search of the University of Michigan Transportation Research Institute (UMTRI) library. Key references that are cited frequently in this synthesis include

- Geometric Design and Operational Considerations for Trucks (*4*)
- A Policy on Geometric Design of Highways and Streets (*2*) (often referred to as the "Green Book")
- Manual on Uniform Traffic Control Devices (*3*)
- Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance (*5*)
- Truck Research Profiles: 1991 Update (*6*)
- Third International Symposium on Heavy Vehicle Weights and Dimensions (*11*).

SURVEY OF PRACTICE

A survey of practice was conducted by sending a questionnaire to the TRB representatives in state DOTs in the United States and their counterparts in the Canadian provinces. Forty-eight states and seven provinces plus a turnpike authority and a port authority responded. The questionnaire asked for indications of design policies and procedures that differed from those stated by AASHTO (*2*) or in the MUTCD (*3*).

Another questionnaire went to people involved with trucking. The purpose was to obtain information as to which mechanical properties of large trucks are believed to be in conflict with roadway design elements and which roadway design elements support the operation of large trucks. Vehicle designers found the questions to be aimed at highway designers. Nevertheless, vehicle designers provided very useful comments explaining their processes and concerns.

The design elements covered in the survey of highway practice were

- pavement life,
- bridge life,
- sight distance,
- intersection geometrics,
- lane width and widening on curves,
- horizontal curves,
- speed control on grades and run-off (or escape) ramps,
- climbing lanes,
- entrance and exit ramps,
- interchange ramps,
- sign placement,
- and signal timing, plus any other element the respondents wished to include.

The survey identified a number of situations in which states have design policies that differ from those of AASHTO (*2*) or the MUTCD (*3*). Canadian provinces generally indicated that they follow Transport Association of Canada procedures and bridge codes such as those of the Canadian Standards Association. For every design element considered, more than one state had a policy that differs from or supplements the corresponding AASHTO policy. The greatest number of differences (13 in the United States and 4 in Canada) concern bridge life. The next largest number of differences (9) pertains to intersection geometrics. The differences for bridges generally apply to heavier design loads and for intersections to offtracking allowances for vehicles with long trailers. The trends toward accommodating longer and heavier vehicles are mentioned in a number of cases. There also were design policy differences about signal timing, pavement life, sign placement, lane width, and pavement widening. Nevertheless, as one would expect, the surveys showed that on the whole, current practice in highway design is largely determined by AASHTO policies.

Tables 1 and 2 indicate the extent of the occurrences of the differences for U.S. organizations and Canadian organizations, respectively. The tables reveal that within the states, AASHTO/MUTCD policies are used, on the average, in approximately 90 percent of the situations reviewed. Canadian practice differs from U.S. practice, on the average, in approximately 42 percent of the cases considered.

REVIEW OF CURRENT RESEARCH

The goal of this synthesis was to gather material on problems for which new or improved approaches are being developed. Based on the literature survey, especially the last two key references listed above (*6,11*), several important research

TABLE 1
DIFFERENCES FROM AASHTO POLICIES—U.S. ORGANIZATIONS

		Difference from AASHTO			Of the Yes/No Responses	
No.	Element	No	Yes	NA	% Using AASHTO	% Not Using AASHTO
1	Pavement Life	44	6	0	88	12
2	Bridge Life	37	13	0	74	26
3	Sight Distance	48	2	0	96	4
4	Intersection Geometrics	41	9	0	82	18
5	Lane Width, Pavement Widening on Curves	44	6	0	88	12
6	Horizontal Curves (Radius and Superelevation)	48	2	0	96	4
7	Speed Control on Grades, Run-Off Ramps	46	4	0	92	8
8	Climbing Lanes (Critical Length of Grade)	47	3	0	94	6
9	Entrance/Exit Ramps	47	3	0	94	6
10	Interchange Ramps	48	2	0	96	4
11	Sign Placement	44	6	0	88	12
12	Signal Timing	43	7	0	86	14
13	Other Elements	12	7	31	63	37
	Averages				90	10

issues emerged on the following subjects involving the interactions between heavy vehicles and roads:

From the International Symposium

From the international symposium (*11*), the issues are:

- Safety—crash avoidance, vehicle performance testing
- Road use taxes—who pays how much for using the infrastructure
- Traffic growth—the amount of road freight measured in terms of load and distance
- Road and bridge mechanics—failure mechanisms, wearing properties
- Road loading—vehicle dynamics, performance measurements, spatial repeatability and
- Regulations—road-friendly vehicles and vehicle components, performance testing for road friendliness, "gentle juggernauts" (public views on safety, noise, and pollution).

From TRB Circular 399

From TRB Circular 399 (*6*) these issues are:

- Safety—accidents, brake systems, axle placement, geometrics, surface friction, vehicle configurations, lane restrictions, interchanges, climbing lanes, passing, handling and stability
- Pavement and bridge performance—weigh-in-motion, load equivalence relationships, dynamic axle loads, pavement distress, loads on bridges, impacts of longer combination vehicles (LCVs), load distribution of suspensions, seasonal load restrictions, pavement/vehicle interactions, rutting, super-single tires
- Trucking productivity—containers, overweight fines, regulations, consumer benefits of LCVs, access for larger trucks, truck data collection
- Combination vehicle operation—use in urban areas, offtracking, operational considerations, dynamic performance, passenger-car equivalents, vehicle dynamics, weights and dimensions.

Knowledge of Pavement Loads and of Wear and Damage

The literature strongly indicates that the following trends in the state of knowledge of pavement loading, pavement wear, and pavement damage are prevalent:

- Knowledge concerning the fundamental mechanisms of road wear is needed; the fourth power law (from AASHTO empirical equations) cannot be relied on; assumptions concerning pavement cracking appear to be inadequate.
- Because of spatial repeatability, dynamic loading effects are substantially underestimated if they are assumed to occur at random locations.
- There are good prospects for reliable pavement load measurements.
- More reliable calculations of pavement loads are now possible because vehicle dynamics are well understood.
- Models of road life will have to be based on conjectural models of road wear.

Trends in Regulations

With regard to regulations encouraging road-friendly vehicles, the following topics are being considered by researchers:

TABLE 2
DIFFERENCES FROM AASHTO POLICIES—CANADIAN ORGANIZATIONS

		Difference from AASHTO			Of the Yes/No Responses	
No.	Element	No	Yes	NA	% Using AASHTO	% Not Using AASHTO
1	Pavement Life	44	6	0	88	12
1	Pavement Life	1	3	3	25	75
2	Bridge Life	0	4	3	0	100
3	Sight Distance	3	3	1	50	50
4	Intersection Geometrics	2	4	1	33	67
5	Lane Width, Pavement Widening on Curves	4	2	1	67	33
6	Horizontal Curves (Radius and Superelevation)	5	1	1	83	17
7	Speed Control on Grades, Run-Off Ramps	5	0	2	100	0
8	Climbing Lanes (Critical Length of Grade)	3	3	1	50	50
9	Entrance/Exit Ramps	3	2	2	60	40
10	Interchange Ramps	5	1	1	83	17
11	Sign Placement	4	0	3	100	0
12	Signal Timing	2	2	3	50	50
13	Other Elements	0	1	6	0	14
	Averages				58	42

- Favoring air suspensions over steel suspensions by giving load allowances
- Requiring uniform load sharing between axles in multi-axle suspensions
- Setting performance requirements for dynamics of tandem suspensions
- Restricting the use of super-single tires on trailer axles.
- Setting limits on tire air pressures
- Developing a performance test for road-friendly vehicle/suspension/tire systems
- Lowering individual suspension loads while allowing additional payload (the "Turner truck" concept).

With regard to developing regulations that encourage highway safety and productivity, the following research topics have been considered:

- Permitting longer and heavier vehicle configurations that meet safety-related performance requirements concerning braking, rollover threshold, obstacle avoidance, directional control and stability, and off-tracking
- Providing incentives in terms of productivity for using safety-related features such as B-trains, innovative dollies, antilock braking systems, etc.

CHAPTER THREE

DESIGN OF HEAVY TRUCKS AND TRAILERS

The views of trailer designers are illustrated in one response to the survey of people involved in trucking:

> The goal of trailer designers is to provide a trailer with the largest cubic or weight capacity allowed by highway laws. This goal has resulted in trends to lower van-trailer floors and tractor fifth-wheel heights and [to use] low-profile tires, lighter-weight, super-single or wide-base tires, light-weight composite materials, thinner van-trailer side walls, and larger van rear-door openings.

> Highway limitations restrict the design of trailers to accommodate international intermodal container weights, 2.6 m- (8.5ft-) wide trailers on all highways to improve rollover stability, and increased use of multi-axle trailers operating with higher loads. Innovation would be served if some highway limitations could be set forth as performance rather than design limits.

Vehicle designers try to produce a product that has unique advantages compared to other products on the road, while highway designers tend to encourage policies that promote roads with uniform characteristics for the level of service intended. Perhaps this is as it should be, but it means that highway designers and heavy vehicle designers can have difficulties in communicating with each other if their differences in outlook are not recognized.

Although one could simply list the features that define particular vehicles, such an approach would miss the point that there is demand for a great variety of possible truck configurations. Almost any selection of a limited set of truck characteristics would represent a grand simplification of a very complex subject with an extensive scope. To put these matters in perspective, this chapter contains discussions of some very fundamental questions. These discussions are a synthesis of thoughts and knowledge acquired and stimulated from two meetings of people interested in bringing highway and truck designers together (*7,8*).

WHAT IS A HEAVY TRUCK?

This is a seemingly simple question. Almost everyone knows what a truck is, but the basic idea of a truck applies to such a wide variety of vehicles that an unqualified definition has limited utility for synthesizing information about the influence of truck operating characteristics on highway design and performance.

The trucks considered here are the heavier ones used for carrying goods and special equipment on U.S. highways. These vehicles are known as class 7 and class 8 trucks. They are trucks with gross vehicle weights (GVW) or gross combination weights (GCW) of 12 000 to 15 000 kg (26,000 to 33,000 lb) for class 7 vehicles and over 15 000 kg (33,000 lb) for class 8 heavy trucks. Class 8 trucks generally have a GCW limit of 36 000 kg (80,000) lb, although heavier vehicles are allowed in many states and in Canada and Mexico.

The exact dimensions and weights of the vehicles actually in use differ from place to place and from one trucking application to another. In practice, almost every truck is different from every other truck in some respect and dimensions and axle loads for nominally the same type of vehicle may differ depending on who is specifying the vehicle's properties. A set of vehicle configurations illustrating vehicles that are representative of those with large weights and dimensions are portrayed in Figures 1 through 7 (*9*).

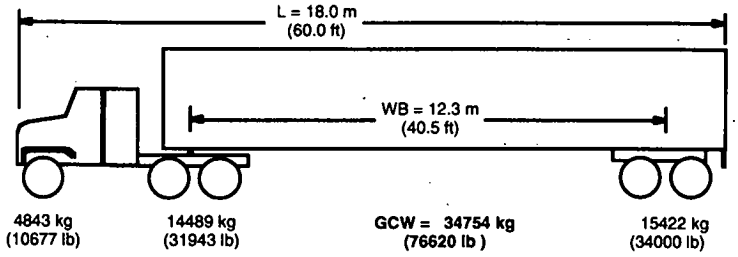
The configurations outlined in Figures 1 and 2 were given nationwide status by the Surface Transportation Assistance Act (STAA) of 1982 and are allowed throughout the national truck network. The other vehicles are known as longer combination vehicles (LCVs). A tractor-semitrailer with a 16-m (53-ft) box is now permitted in nearly every state. A tractor-semitrailer with a 17-m (57-ft) box (Figure 3) is allowed in several states. The configurations shown in Figures 5, 6, and 7 are allowed in some states or on certain highways in other states. The Turner Truck, illustrated in Figure 4, is one of several configurations proposed in TRB Special Report 227 (*10*) that exceed the 36 000 kg (80,000 lb) weight limit but, because of their extra axles, are proposed to be less damaging to pavements and bridges than many trucks within the legal weight limits. Such trucks are not in general use in the United States.

Examples of vehicles that can legally carry higher than normal loads with only moderate pavement stress are illustrated in Figure 8. Routinely used in Michigan, they have many lightly loaded axles, and so cause less pavement damage than the vehicles illustrated in Figure 9, which have fewer axles that are more heavily loaded.

WHAT ARE THE IMPORTANT FEATURES OF A HEAVY TRUCK?

The answer to this seemingly straightforward question depends on the perspective of the person answering the question. The following discussion reflects the views of some of the stakeholders in heavy truck transportation.

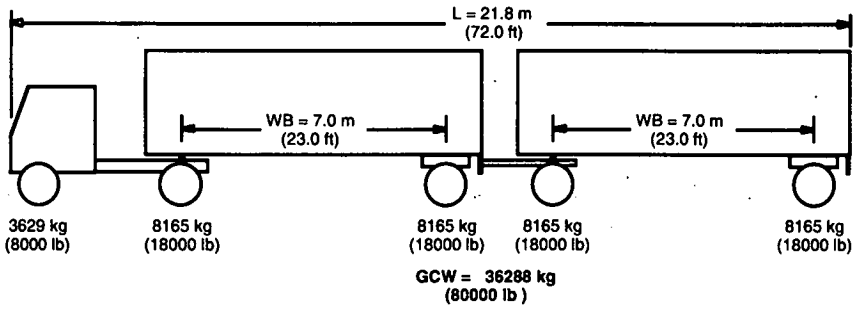
Perhaps one might choose to start with the views of truck-tractor manufacturers. At a recent meeting between truck manufacturers and highway designers (*7*), a representative of the truck manufacturing community pointed out that his organization was prepared to build approximately 47,000 different designs of tractors. There were 170 characteristics that were usually used in specifying a truck-tractor. The following example



Payload volume: 103.98 cu m (3672 cu ft)

Payload weight: 23,220 kg (51,190 lbs)

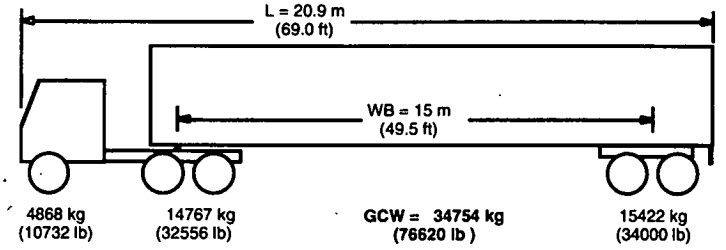
FIGURE 1 Tractor-semitrailer (14.6-m (48-ft) trailer).



Payload volume: 121.31 cu m (4284 cu ft)

Payload weight: 24,267 kg (53,500 lbs)

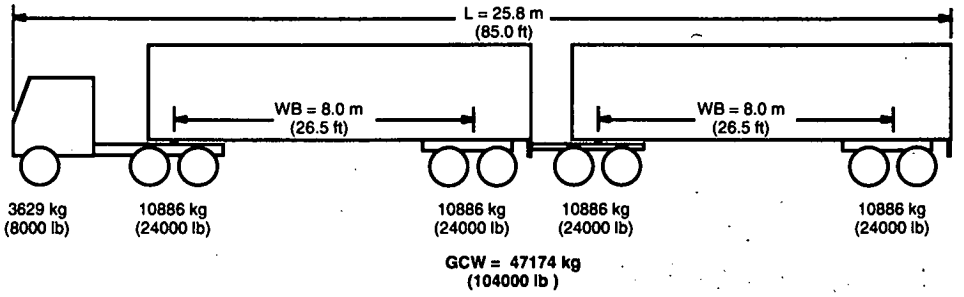
FIGURE 2 Western double (twin 8.5-m (28-ft) trailers) (*10*).



Payload volume: 123.49 cu m (4361 cu ft)

Payload weight: 22417 kg (49,420 lbs)

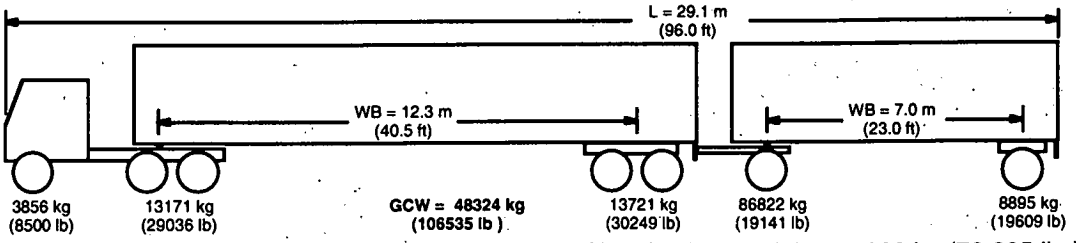
FIGURE 3 Tractor-semitrailer (17.1-m (57-ft) trailer).



Payload volume: 147.3 cu m (5202 cu ft)

Payload weight: 31,135 kg (68,640 lbs)

FIGURE 4 Turner truck (twin 10.2-m (34-ft) trailers with tandem axles).



Payload volume: 164.63 cu m (5814 cu ft) Payload weight: 32,933 kg (72,605 lbs)

FIGURE 5 Rocky Mountain double.

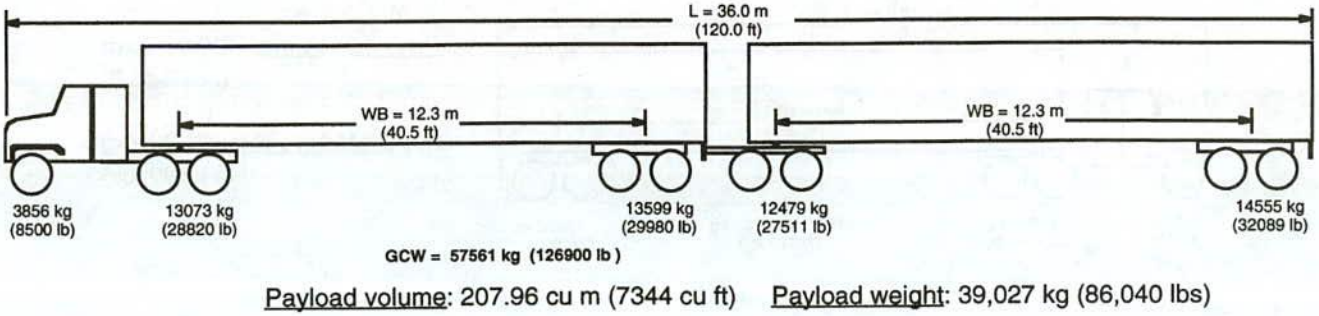


FIGURE 6 Turnpike double.

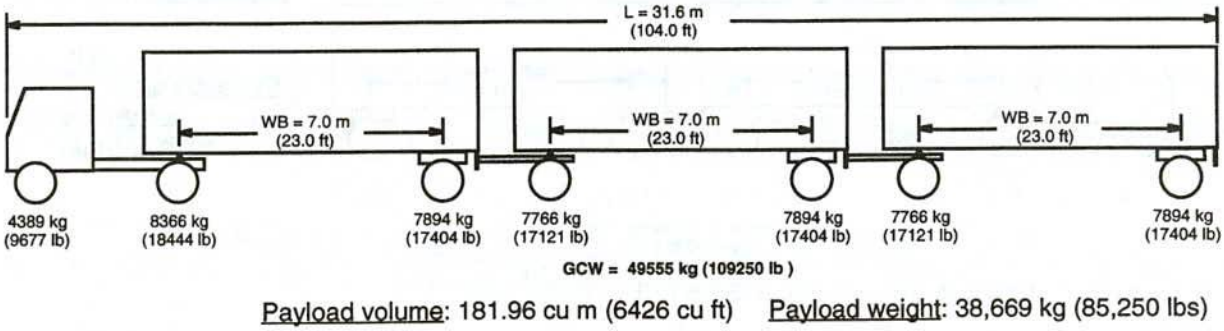


FIGURE 7 Triple (with three 8.5-m (28-ft) trailers).

(*11*) provides insight into the multitude of truck variations. One price list for a conventional-cab truck tractor shows 88 separate items with options, such as:

- 21 different seats
- 11 different mirrors
- 13 different fuel tanks
- 18 different rear axles
- 11 different rear suspension assemblies
- 51 engines matched with a matrix of 55 optional transmissions.

From these numbers, which are for one specific type of tractor, one can see that it is easy to have 47,000 different variations just in terms of tractors alone.

Now shift to the focus of the trailer manufacturer, whose goal is to provide a trailer with as much cubic or weight capacity as the law allows. The important features of a trailer from that viewpoint appear to be (1) the style of trailer needed to contain and support the type of cargo (liquid, dry bulk, packages, large solid objects, etc.), (2) enough cubic space to carry either the maximum amount of cargo needed in a particular type of shipment or the amount of payload that will bring the

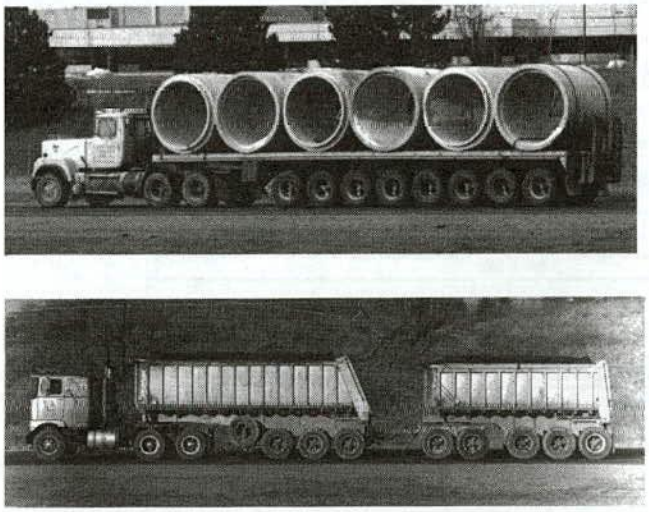


FIGURE 8 Trucks with many lightly loaded axles.

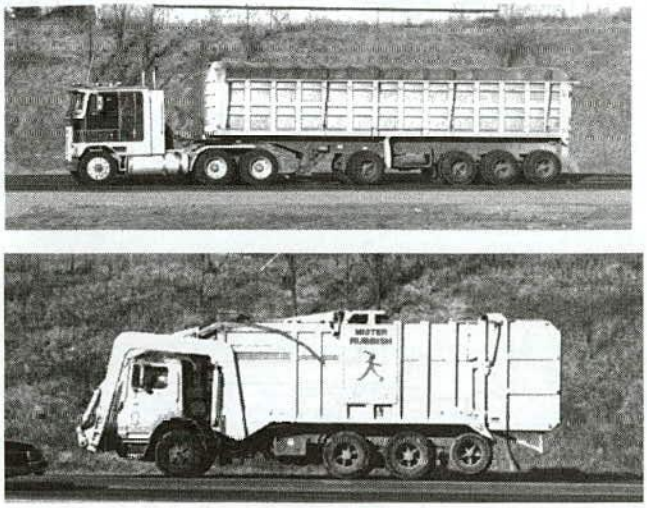


FIGURE 9 Trucks with fewer heavily loaded axles.

total vehicle to the legal maximum GCW, (3) the tare weight of the trailer, and (4) the density of the cargo and the placement of wheels and axles to satisfy bridge limitations.

Next, consider a special group of people who might be called "fleet managers." Fleet managers determine their market and predict its future in order to invest in equipment that will perform the transportation mission efficiently. If there is a continuing demand for one type of service, they can focus on creating a truck configuration for that job. If they decide to make their services available for many different types of hauling jobs, their equipment needs to be as flexible as possible to accommodate various types of loads. In this case, their equipment may not be as efficient as specialized equipment, but it will be capable of serving a wider market.

In the matter of safety, the need for good drivers is generally recognized. Even though advances are being made in making heavy trucks easier to drive, there has been a continuing emphasis on drivers knowing their equipment and using their equipment within prescribed safe operating envelopes. Safety researchers have been working on screening and testing procedures for evaluating such truck safety-related factors as rollover, directional stability, dynamic tracking in obstacle avoidance maneuvers, braking, and so forth. By applying physics principles and engineering methods, researchers have also related vehicle performance in safety-related situations to vehicle design and configurational properties.

The Environmental Protection Agency (EPA) in the United States is empowered to protect the environment by enforcing emissions, fuel economy, and noise standards. The diesel engines used in heavy trucks are continually being transformed to meet EPA requirements. To achieve fuel efficiency goals, tire rolling resistance has been reduced, aerodynamic shields have been introduced, and "slippery" engines and transmissions have been developed. Coincidentally, these improvements in the acceleration area that have reduced drag, and allowed speeds to increase, have also increased the demands on braking systems without requiring that braking systems be upgraded to compensate for the loss in drag.

Finally, consider the highway designers. All of the previous discussion has implications as to what projected trucks might be like. The projected state of the infrastructure also influences how trucks will be designed, but infrastructure providers tend to view the important features of heavy trucks as those that have direct impact on infrastructure life and highway design.

At the meeting between truck manufacturers and highway designers noted previously (*7*), experts in highway design covered many topics relative to trucks, including pavements, bridges and structures, geometric design, roadside features, traffic control devices, and safety in work zones.

Examination of the AASHTO Green Book (*2*), the *Highway Capacity Manual* (HCM) (*12*), and the ITE Informational Report (*4*) indicates that highway designers consider truck operational or performance characteristics in many situations. Those considered important include:

- Offtracking at low speeds, swept path, pavement width
- Acceleration performance in intersection situations
- Acceleration on upgrades, climbing lanes
- Speed control on downgrades, escape ramps
- Deceleration capabilities on wet roads, stopping sight distance
- Effect of truck traffic on highway capacity
- Passenger car equivalents
- Driver's eye height
- Weight/power ratio
- Turning templates, minimum turning radii
- Stability, rollover threshold, rearward amplification, and yaw
- Vehicle speed at impending skid or rollover on horizontal curves
- Crest vertical curve lengths, stopping sight distance for trucks
- Deceleration lengths for exit terminals, interchange ramps
- Longitudinal placement of advanced warning signs
- Truck adjustment factors for intersection level of service
- Passing sight distance for trucks.

WHAT ASPECTS OF TRUCKS AND TRUCKING INFLUENCE HIGHWAY POLICY, PLANNING, DESIGN, AND PERFORMANCE?

The desire for greater productivity in goods transportation creates pressure for highway policies that allow larger and heavier trucks. On the other hand, the effect of truck size and weight on the wear and fatigue of bridges and pavements is a major factor in setting policy constraints on road use. The safety-related performance of heavy trucks is another factor that is considered in making policy decisions. To some extent it appears that the driving public is concerned about the size, appearance, and performance of the vehicles they see on the road, and this influences policies concerning trucks.

Highway planning is clearly influenced by policy. The planning process involves projecting the amount and type of total traffic and truck traffic needed and expected. Regarding truck traffic, planning should allow for providing efficient mobility between important centers and facilities and for providing local access to locations where goods are produced, distributed, or sold.

The AASHTO policy on geometric design (*2*) involves various "design vehicles." These design vehicles are approximations of real vehicles. They serve to give the highway designer something to work with in designing a bridge or laying out an intersection. The performance of a road in terms of life, level of service, safety record, etc. depends on the characteristics of the vehicles that actually use the road, the characteristics of the road as it actually exists in service, and the characteristics of the drivers involved. Although the distinction between design vehicles and actual vehicle characteristics seems apparent, there is a need to emphasize the difference by noting that what happens in operational situations depends upon actual characteristics. In addition, the features of heavy trucks that highway designers do not take into account, but that are nevertheless important, may have a major influence on the operational per-

formance of highways that have been designed on the basis of a limited set of truck operating characteristics.

The continuing implementation of the North American Free Trade Agreement (NAFTA) between Mexico, Canada, and the United States will place additional and major demands on vehicle and roadway designers. If truck transportation of goods is to flow freely across the national borders, as is the agreement's intent, standardization of truck characteristics, especially as to weight and dimension will be mandatory. NAFTA has been in effect only since January 1994, and its impact has been less than dramatic. However, the nature of the compromises that will need to be made are somewhat evident. For example, whereas the U.S. maximum GCW in most states is 36 000 kg (80,000 lb), Canadian interprovince allowances are much greater. Five-axle tractor-semitrailers can weigh as much as 43 000 kg (95,000 lb), and seven- or eight-axle doubles may weigh as much as 58 000 kg (128,500 lb) (*13*). In Mexico, on the other hand, 16-m (53-ft) trailers are not permitted, although they are now typical in the United States (*14*). The main problem in Mexico, however, is truck overloading. It is reported that more than one-third of all Mexican trucks are typically 30 to 50 percent overloaded, with illegal weights reported of up to 54 000 kg (120,000 lb) for a 5-axle tractor-semitrailer, and more for 6-axle combinations (*15*). These observations suggest that weight limits may need to be liberalized in the United States if NAFTA is to function as envisioned.

In short, basic truck layouts are arranged to conform with requirements set by those responsible for political decisions concerning the integrity of the infrastructure and the economic and environmental well-being of the citizenry. Other aspects and features of trucks are determined by their users in an attempt to be productive and profitable in satisfying shippers' needs. The operating performance of trucks on the road depends on the skill and integrity of the people who maintain, load, and drive the vehicles as well as the properties of the road and its level of maintenance.

Policy-making organizations in state governments are continuing to consider ways to improve transportation services under their purview. The survey of current highway design policies conducted in preparing this synthesis indicates that where state policies differ from AASHTO policies, the states tend to allow more productive vehicles. The differences involve allowing longer and heavier vehicles and designing intersections and bridges to accommodate such vehicles.

CHAPTER FOUR

TRUCK CHARACTERISTICS OF INTEREST IN OPERATIONAL SITUATIONS

The way in which a truck interacts with the road largely depends on the truck characteristics and the situation in which it is operating. This chapter presents a discussion of these important truck characteristics, and the following chapters focus on them in a variety of operating situations.

BASIC CHARACTERISTICS OF A HEAVY COMMERCIAL VEHICLE

At the most fundamental level, a heavy vehicle is characterized by the following elements, all of which affect its compatibility with the highway:

1. Payload being transported
2. Vehicle structure needed to contain and support the payload
3. Suspension system to cushion the load and smooth out the ride (also to provide structural integrity and durability)
4. Axles, wheels, and tires needed to support the vehicle on the road and to meet regulatory requirements
5. Engine and drive system to propel the vehicle
6. Braking system for slowing and stopping
7. Steering system to control path and direction
8. Hitches located and arranged to allow interconnection and interchangeability of units in combination vehicles
9. Position and space from which a driver controls, guides, and navigates the vehicle throughout a trip.

Items 1 through 4 determine the loading of the tires against the road. The vertical forces that act on the vehicle are of the same magnitude as the vertical forces that act on the road. In this sense, vehicle and road designers have the same forces to accommodate. Even though vehicle and road designers treat these forces quite differently, they are both very concerned with the structural integrity of their products and the rate at which their products wear out or fail. Although vehicle designers and road designers work independently now, it is in the interests of both to understand as much as they can about the factors that determine the amplitudes of these forces and their effects on pavements, bridges, vehicles, and their payloads.

Items 5 through 7 are instrumental in controlling the forces for accelerating, stopping, and turning the vehicle. The magnitudes of the vertical loads and the amount of tire/road friction determine the maximum level of control force that the tires can produce. Although these forces need to be considered in establishing the shear force resistance of the road surface (the friction requirements), they are most important to highway operations, in determining the vehicle accelerations and frictional demands involved when maneuvering the vehicle in response to highway and traffic conditions.

Hitches (item 8) influence the loading of the tires, allow articulation, and provide the means by which one unit steers another. Common types of hitches are fifth wheels, pintle hooks, and turntables. Each of these (and others) imposes differing types of constraints on the units they join. These differences account for the variations in the loading and steering functions of each type of hitch.

In operational situations the eye height and range of vision of the truck driver is an important aspect of the cab layout (item 9). From the highway design perspective, the resulting sight distance of the driver should be a consideration.

WEIGHTS AND DIMENSIONS

Most widely recognized as specific to maintaining highway compatibility are the weights and dimensions associated with a vehicle combination. Weights and dimensions are the primary parameters by which acceptable vehicles are defined in road use laws; they are largely expressed as limitations (maxima or minima). For example, so-called bridge formulas provide limits on the allowable load carried by any contiguous set of axles of a heavy vehicle. The load limit depends on the distance between the first and last axles (the extremes) in any set of axles. Every state also has maximum allowable axle loads and combination weights, which tend to be fairly uniform as the result of following the federal Interstate model. Less uniformity exists for restrictions on maximum trailer lengths, widths, and heights for various vehicle types. The latest rules are tabulated by various organizations. (See for example the "state profiles" prepared by the American Trucking Associations (*16*).)

Given the shipping and trucking industry's interest in being as productive as the rules allow, the capabilities of popular vehicles tend to press the limits of the road use laws. In some cases the regulatory formulas have been adjusted slightly to improve productivity. For example, companies carrying dense cargo have wanted to place their vehicle's axles as closely as allowed because the vehicles could operate effectively with less length than the bridge formula requires. To accommodate this, Bridge Formula B (see more detailed discussion in chapter 8), which applies to the National Highway System and systemwide in many states, contains a "tank trailer notch" (*17*), which allows four axles to carry 31 000 kg (68,000 lb) if the outside axles are separated by 11 m (36 ft). The idea here is that a small

concession in the bridge formula allows a more productive vehicle with improved maneuverability for getting in and out of relatively tight places.

Regardless of the reasons for the weight and dimension regulations, they closely represent the characteristics expected of the heaviest trucks when they are fully and legally laden. For example, the five-axle tractor-semitrailer vehicle with a 14.5-m (48-ft) trailer and having 36 000 kg (80,000 lb) of maximum gross combination weight (GCW) represents a fairly efficient vehicle given the current road use laws and the density of many types of cargo. Even so, changes in road use laws that allow truckers to realize productivity advantages may cause truck fleet composition to change rapidly.

Ultimately, trucks are designed for the roads they use even though the properties of trucks are the controls used in the design of certain road features. The axle loads and dimensions given previously in chapter 3 are representative of the fully loaded larger vehicles used on U.S. roads. More broadly, the relevant weight and dimensional properties of trucks will likely include one or more of the following characteristics:

- Total weight, gross vehicle weight (GVW) and gross combination weight (GCW)
- Overall lengths for different types of vehicles
- Overall height
- Overall width
- Wheelbases from the king-pin to the center-of-the-rear-axle-set on a semitrailer
- Distances from axles and axle spreads in axle groups
- Axle loads for single axles and sets of axles (tandems, tridems, etc.)
- Lengths of vehicle units (tractors, semitrailers, cargo containers)
- Overhang from the last axle to the rear of the unit
- Tire width.

Even though these are not necessarily the only, or best, characteristics for determining vehicle performance and pavement or bridge loading, they are attractive for enforcement purposes in that most can be readily measured. Knowing where the tires are and what load they carry goes a long way toward defining a vehicle's performance. Such knowledge is also key to predicting the static loading of the pavement and bridges (ignoring the dynamic effects).

Weight Characteristics

The weight and the weight distribution of a truck are important in nearly all operating situations with the possible exception of low-speed offtracking and being passed by another vehicle, which are operational situations primarily related to elements of length. To the extent that engine power is limited or is not greater for heavier vehicles, heavier vehicles have lower acceleration capabilities. This means that longer times and distances are needed for a heavier vehicle to complete a maneuver. Conversely, from a regulatory view, if maneuvering times and distances are to be commensurate for all heavy vehicles, the heavier vehicles will need to have higher tractive force-generating capabilities. Trucking interests, on the other hand, may be willing to give up some performance capability if that would lead to greater productivity, efficiency, or profitability.

Weight is important in such operating situations as constraining speed on a downgrade, emergency stopping, maintaining headway in traffic, responding to traffic controls at intersections, accelerating to cross an intersection, and maintaining speed on an upgrade.

Weight is also important in pavement and bridge wear and fatigue. Even though bridge and pavement design have traditionally been based on ensuring the life of the infrastructure, there is evidence of an element of productivity involved in the thinking of some policy makers. The diversity of weight rules among various states indicates, to some extent, the influences of productivity interests. The findings (from the survey of practice) pertaining to building sturdier bridges and allowing longer vehicles indicates that some states and provinces have been setting design targets (standards, policies, etc.) to accommodate the use of more productive vehicles.

The weight distribution of a vehicle is important to its dynamic stability and performance. The location of the center of mass, or center of gravity (cg), is an important mechanical property of a vehicle or the units that make up a combination vehicle. The longitudinal position of the cg with respect to the axles is important to turning and braking situations but knowledge of the axle loads and positions and hitch locations is nearly equivalent information. The height of the cg is another matter. This is a critical factor in determining the rollover propensity of a vehicle. The primary factor in determining rollover resistance is the ratio of cg height to the lateral track width, the width between the tire sets on the right and left sides of the vehicle.

The weight and weight distribution of an operating heavy truck depend primarily on the load. For example, a typical tractor-semitrailer with a 14.6-m (48-ft) trailer can gross 36 000 kg (80,000 lb) under current regulations. The weight of the tractor alone will typically be from 7000 to 9000 kg (15,000 to 20,000 lb). In addition, the empty semitrailer might weigh from 4500 to 7000 kg (10,000 to 15,000 lb). If the tare weight (i.e., the empty weight of the vehicle that must be moved to provide productivity) of the tractor-semitrailer is 14 000 kg (30,000 lb), the load may weigh up to 23 000 kg (50,000 lb) in a maximum gross operation. For this condition, more than 62 percent of the GCW would be load. Clearly, the properties of the load are critical in determining the maneuvering performance and the loading of the vehicle on roads and bridges.

Loads may be described in various ways. They may be solids, liquids, or compressed gases. They may consist of particles as small as grains of sand, powders, or wheat, or they may consist of large objects such as telephone poles, rolls of steel, I-beams, or large pieces of machinery. The density of the cargo is very important in determining the cg height of the sprung mass (the total weight supported by the suspension). The appropriate densities of some typical products are 150 to 240 kg/m^3 (9 to 15 lbs/ft^3) for general freight; 500 to 650 kg/m^3 (30 to 40 lb/ft^3) for fruits, vegetables, and some types of wood; 700 kg/m^3 (45 lb/ft^3) for gasoline; 1000 kg/m^3 (63 lb/ft^3) for fresh water; 1600 to 1900 kg/m^3 (100 to 120 lb/ft^3) for sand; 2400

kg/m^3 (150 lb/ft^3) for gravel; and 6000 to 8000 kg/m^3 (400 to 500 lb/ft^3) for metals. According to Ervin (*18*), cargo with a density of approximately 220 kg/m^3 (14 lb/ft^3) (including packing space) will fill a 14.6-m (48-ft) van semitrailer so as to reach full gross weight and full cubic volume simultaneously. For a uniform load, this represents the highest possible cg, which for this "worst case" load is at the geometric center of the box of the van semitrailer.

Length Characteristics

As the result of continuing requests for greater cubic capacity to improve productivity, the maximum lengths of heavy trucks have steadily increased. This means that existing intersections and other areas where low-speed turns are performed may not provide enough space for all trucks to stay within the marked lanes and to keep the tires on the pavement. The performance phenomenon of heavy trucks called "offtracking" is a measure of the extent to which the rear wheels of a vehicle deviate from the path of the front wheels. At low speeds, the width of the path swept by the vehicle's extremities can be very large, depending on the distances between hitch points and the wheels or axles of the vehicle.

A basic principle of low-speed offtracking is that the greater the distance from a forward hitch point to a trailing axle group in a semitrailer unit, the greater the offtracking will be (everything else held equal). This principle explains why a long vehicle with several articulation points will have less offtracking than a vehicle of equal or even shorter overall length but with fewer articulation points. A corollary to the low-speed offtracking principle is that the influences of the lengths between hitches and wheels combine in a relationship that favors making all these hitch-to-wheel lengths equal, to obtain minimum offtracking for a given overall length and number of articulation points. For this reason, triple 8.5-m (28-ft) trailers have relatively little offtracking despite the great length of the combination. The ratio of payload cubic capacity to offtracking distance in a tight turn can be much larger for a 32-m (104-ft) long triple with three 8.5-m (28-ft) trailers than for a 20-m (65-ft) tractor-semitrailer combination with a single 16-m (53-ft) trailer. Although seemingly not well understood by highway designers, a basic reason that vehicle designers include articulation points in a vehicle design is to enable it to maneuver better through tight places.

Productivity in many operational situations is determined by the combination of two weight and length dimensions: the tare weight of the vehicle and the cubic volume available for carrying light products and packaged goods. Some minimum vehicle weight is necessary to transport goods, yet moving just the tare weight of the vehicle represents a shipping cost.

In response to the economic necessity to move general freight, the demand for cubic volume (cube) is continually increasing. The demand for triple-trailer combinations consisting of three 8.5-m (28-ft) boxes that provide almost 26 m (84 ft) of length for cargo is intense. For trailer boxes with cross-sectional areas of approximately 9.5 m^2 (70 ft^2), the cube is almost 170 m^3 (6,000 ft^3). Other indications of the demand for cube space are the demands for semitrailers with 17-m (57-ft) boxes. This demand is expected to intensify as products continue to get lighter and demands for larger shipments of light materials or products increases. To the extent that policy and planning decisions are based on the efficiency of the truck transportation system, the payload cubic volume and the tare weight of the vehicle are important weight and dimensional properties of a vehicle.

The occupational purposes of trucks account for a great variety of styles and configurations; Tables 3 and 4 provide examples of ranges of values of the dimensional and weight properties of typical heavy trucks.

COMPONENT MECHANICAL PROPERTIES

The components discussed here are the running gear (tires, wheels, and axles), braking system, propulsion system (engines, transmissions, drive lines, rear axles, differentials, etc.), steering system, suspension system, hitching system, and cabs. These components are discussed with respect to mechanical properties that contribute significantly to the performance of heavy trucks in operational situations on the highway. Emphasis is given to the mechanical properties that are used in, or influence, highway geometric design policies.

Running Gear

The running gear (tires, wheels, and axles) of a heavy truck is often arranged in a package offered by an axle supplier. Brakes, wheels, hubs, bearings, differentials, and axle gearing may be included in this package. Some of these are parts of the directional or speed control systems of the vehicle. The detailed mechanical properties of the wheels and axles are given in other sources in the context of appropriate control system applications. However, since the tires are important to all functions of the vehicle, this section will concentrate on truck tires.

Tires provide the primary forces to support, and to control the motion of, the vehicle. To the extent that developing adequate tire-road friction is possible, the limits of brake torque capability, engine torque, and suspension performance determine the maximum longitudinal and vertical forces acting on the vehicle and the equal but opposite reactions acting on the road.

The range of tire sizes and load ratings used on heavy trucks is quite large. Information on the dimensions and ratings of truck tires is given in the *Tire and Rim Association Yearbook* (*19*). A limited amount of data on the shear force-producing properties of truck tires that were built from 1975 to 1980 is available in the literature (*20*, *21*). Recent interest in truck braking and handling characteristics has led to a research program aimed at developing standard methodologies for testing truck tires (*22*). This means that to predict the performance of specific vehicles in high-speed steering and braking maneuvers on a specific pavement requires that special tire tests be devised to quantify the mechanical properties of the tires involved. Nevertheless, approximate calculations can be made using older tire data that are still representative.

TABLE 3
EXAMPLE RANGES OF DIMENSIONAL PROPERTIES

Characteristic	Vehicle Type	Minimum, m (ft)	Maximum, m (ft)
Wheelbase (Front-rear axle)	2-axle truck or tractor	3 (10)	6.7 (22)
(Kingpin to rear suspension)	3-axle truck or tractor	3.7 (12)	6.7 (22)
	Trailers	4.3 (14)	15 (50)
	Dollies	2 (6)	6 (20)
Overall length	Straight trucks	5 (16)	11 (35)
	Tractor-semitrailers	8.5 (28)	20 (65)
	Doubles/triples	15 (50)	37 (120)
Cargo body length	Straight trucks	3 (10)	8 (26)
	Semitrailers	6 (19)	8 (26)
Overall height	All	2.4 (8)	4 (13.5)
Overall width	All	2.4 (8)	2.6 (8.5)
Axle separation (Multi-axle groups)	Tandems	1.2 (4)	2.4 (8)
	Tridems	1.2 (4)	1.5 (5)
cg height	Straight trucks	1.1 (3.5)	1.8 (6)
	Tractor-semitrailers	1.2 (4)	2.4 (8)
Lateral track width (between	Front axles	2.1 (7)	2.1 (7)
tire set centers)	Rear axles - dual tires	1.8 (6)	2.0 (6.5)
	Rear axles - wide-base single tires	2.0 (6.5)	2.1 (7)
Payload volume, m^3 (ft^3)	Straight trucks	18.4 (650)	57 (2,000)
	Tractor-semitrailer	34 (1,200)	122 (4,300)
	Doubles/triples	99 (3,500)	207 (7,300)
Tire width (at tread)	Conventional tires	0.18 (0.58)	0.23 (0.75)
	Wide-base singles	.25 (0.83)	0.38 (1.25)
Seating height	Conventional	1.8 (6.0)	2.9 (9.4)
	Cab-over-engine	1.8 (6.0)	2.9 (9.4)

The more important tire characteristics that figure in the study of turning maneuvers and braking are the cornering stiffness of the tires and the peak and slide friction values under braking conditions. Since the cornering stiffness of a truck tire varies fairly linearly with vertical load, for purposes of simplification and summary it is convenient to express the lateral force properties in terms of the ratio of cornering stiffness to the vertical load carried by the tire. This ratio is called the "cornering coefficient." Typical values for new bias-ply tires are around 0.1 kg of lateral force per kg of vertical load (or 0.1 lb per lb) per degree of slip angle, where the slip angle is the angle between the direction of travel and the wheel plane. Radial tires tend to be somewhat stiffer than bias-ply tires, with cornering coefficients around 0.15 kg per kg per degree. As the tread wears, the cornering coefficient increases, with increases of around 0.05 kg per kg per degree being typical for a well-worn tire. As a result, a well-worn radial truck tire may have a cornering coefficient twice that of a new bias-ply tire.

According to a component factbook for heavy trucks (*21*), the cornering coefficient is highly important in assessing ve-

TABLE 4
EXAMPLE RANGES OF WEIGHT PROPERTIES

Characteristic	Vehicle Type	Minimum, kg (lb)	Maximum, kg (lb)
Total Weight	3-axle Truck	5400 (12,000)	20 000 (45,000)
Gross Vehicle Weight	5-axle Combinations	11 300 (25,000)	36 000 (80,000)
Gross Combination Weight	Doubles/Triples	13 600 (30,000)	58 000 (127,000)
Weight			
Axle load	Single (steering)	3600 (8,000)	9000 (20,000)
	Single	4500 (10,000)	9000 (20,000)
	Tandem	5400 (12,000)	15 400 (34,000)
	Tridem	4000 (9,000)	17 700 (39,000)

hicle dynamic performance in such maneuvering situations as high speed tracking in turns, handling stability as speed increases, response time to steering commands, rearward amplification of vehicle motions in multi-articulated vehicles, transient braking and turning maneuvers, and directional response to external disturbances.

The Factbook (*21*) also indicates that peak (rolling) and slide traction coefficients of truck tires vary over a wide range depending on tire construction and tread type, the quality of the road's skid resistance, and whether the road is wet. Peak traction coefficients range from 0.83 to 0.51 on wet surfaces and from 0.85 to 0.72 on dry surfaces, with higher values being better. Sliding traction coefficients, corresponding to locked wheel conditions, range from 0.58 to 0.38 on wet surfaces and from 0.60 to 0.51 on dry surfaces. These ranges are representative of truck tire characteristics of the late 1970s to the early 1980s. Further information on newer models of truck tires is given in a special Society of Automotive Engineers (SAE) publication (*23*) and an SAE paper (*24*).

The peak traction values are important in braking situations. For turning situations, the lateral accelerations corresponding to peak traction forces would be sufficient to roll over most fully loaded heavy trucks. On slippery surfaces, it is primarily the pavement surface rather than the tire that determines shear (horizontal) force capability, although truck tires generally have less traction capability than passenger car tires even on poor road surfaces.

Heavily loaded truck tires are usually fairly resistant to hydroplaning on water-covered roads, because of the wide, deep grooves incorporated in truck tires. However, lightly loaded truck tires, such as those on the rear axles of an empty semitrailer or the rear axles of a truck tractor running in a "bobtail" configuration (i.e., without a trailer), may hydroplane due to high inflation pressure and short contact patch lengths (*25*).

In a recent NCHRP study (*5*) on the effects of heavy-vehicle characteristics on pavement response and performance, four tires—11R22.5, 15R22.5, 18R22.5, and a low profile tire—were selected to provide representative tire properties. The first three tires are the nominal sizes needed for front axle loads of 5400, 7300, and 9000 kg (12,000, 16,000, and 20,000 lb), respectively, in a single tire configuration. The 11R22.5 is also suitable for a 9000-kg (20,000 lb) axle using a dual tire arrangement or for use as dual tires on a 15 000-kg (34,000 lb) tandem axle configuration. The low-profile tire is limited to dual tire applications on axles with 7700-kg (17,000 lb) gross axle weight. The wide-base single tires (15R22.5 and 18R22.5) may be used on heavy front axles or as replacements for dual tires on rear axles.

Tread width is very important from a pavement wear standpoint. Some states try to control road damage by specifying a maximum load per cm (in.) of tread width, but they base this on the manufacturer's nominal width (or maximum outside width) instead of the tread width in contact with the pavement (*5*). For example, a 9000-kg (20,000-lb) axle on dual tires may correspond to approximately 110 kg of load per cm of tread width (625 lbs per in.), but this might correspond to only 80 kg/cm (450 lb/in.) of nominal width.

Tire inflation pressure may have been somewhat overlooked in pavement design, but it appears to have a large effect on the fatigue of flexible pavements. A 140-kPa (20 psi) increase in inflation pressure may increase fatigue damage on flexible pavements by 200 percent (*5*). This may be especially pertinent with regard to the smaller low-profile tires which require an inflation pressure 15 to 30 percent higher than standard-profile tires when used on a 15 000-kg (34,000 lb) tandem axle set. It is worth noting that tire manufacturers are concerned that customers recognize there is a fundamental relationship between the load a tire can carry, the inflation pressure, and the tire size (air volume) (*7*). Customers may want a tire that carries a high load and has a small radius and a low inflation pressure, but there is a physical limit to what can be actually accomplished.

Braking Systems

Heavy trucks in North America mainly have S-cam brakes that are pneumatically actuated (*26*). The torque (braking) capabilities of the brakes used on heavy trucks are usually sufficient to generate approximately 0.43 g's of deceleration, based on the maximum static weight carried on the wheel or wheels on which the brake acts (*27*). This presumes a good road surface and tires with good frictional properties. As a consequence of the torque capabilities of their brakes, the stopping distances for heavy trucks will be appreciably longer than those of cars.

Truck braking performance is important to the stopping sight distance requirements in road design. Given that stopping sight distances have typically been passenger vehicle-related and are computed for roads with friction capabilities less than 0.43 (*2*), there is still sufficient torque capability to lock the wheels of a heavy vehicle when operating on a wet road with poor frictional properties.

Antilock brake systems (ABS) can reduce braking distances. More importantly, wheel locking, directional control, and stability problems such as jackknifing and trailer swing in braking on a slippery surface can also be significantly mitigated by ABS. There have been stopping sight distances reported for heavy trucks with antilock systems that are less than the AASHTO criteria for passenger cars (*28,4*). (This is because the truck driver's eye height is higher than that of a car driver and because the ABS will allow the truck driver to make a controlled stop in an efficient manner that uses much of the available tire-road friction.)

Propulsion Systems

Truck engines and drive lines have undergone a great deal of detailed study to improve emissions quality and fuel efficiency. Nevertheless, the torque and power capabilities are of fundamental concern to users and for highway design. The generalized weight/power ratios of heavy trucks are used in highway design of intersections and in determining the location of climbing lanes (*2*). The AASHTO policy, which is based on 180-kg/kw (300-lb/hp) vehicles, may be conservative today with the introduction of up to 370-kw (500-hp) engines for

special-use heavy trucks. However, if heavier vehicles are introduced, these power levels may be needed to maintain 180-kg/kw (300-lb/hp) levels of acceleration performance.

The Truck Inventory and Use Survey (TIUS) (*29*) provides information on the weights carried and the engine power of vehicles as used in trucking operations. The AASHTO Green Book (*2*) contains condensations of these results from the 1985 survey. More recent results may be derived from the later TIUS surveys.

Because (1) highway design tends to focus on using the lower performance end of the vehicle spectrum and (2) older engines still in use may not be as efficient as new equipment, an operational capability of 180 kg/kw (300 lb/hp) could still be representative of "worst case" for highway design purposes, although the *Highway Capacity Manual* (*12*) uses more powerful 120-kg/kw (200-lb/hp), or better, design vehicles.

The combination of engine and gear ratios provides a system that furnishes fairly constant power over the range of typical highway speeds and low acceleration levels. At steady speed, this power level is equal to the product of vehicle speed and the drag forces acting on the vehicle. The primary drag forces are due to tire rolling resistance and aerodynamic drag (*30*). For example, given typical values of rolling resistance and an efficient 240-kw (320-hp) engine, the maximum sustained speed on level ground of a hypothetical 36 000-kg (80,000-lb) truck would be 110 km/hr (68 mph). Many vehicles of that weight have maximum sustained speeds of around 97 km/hr (60 mph) or less.

If the vehicle is on an upgrade, the drag force acting on the vehicle due to gravity is the steepness of the grade times the weight of the vehicle. For comparison, a 1 percent grade is approximately equivalent to the rolling resistance of the tires, which is approximately equal to the aerodynamic drag at 110 km/hr (68 mph). For example, the maximum sustained speed on a 2 percent upgrade is approximately 66 km/hr (41 mph) for the vehicle with the 240-kw (320-hp) engine described in the previous paragraph. The point of this example is that grade has a major influence on the speed of trucks. Even though rolling resistance is low, and aerodynamic drag is being reduced for fuel economy reasons, engine power remains relatively low when climbing grades is required.

The power available to increase speed is what is left over from the power needed to sustain the current speed. As speeds go toward the maximum possible sustained speed, little engine power remains to accelerate the vehicle to a higher speed. The net effect is that trucks require a long time and distance to reach highway speeds.

Steering Systems

Truck steering systems use a design steering ratio (ratio of steering wheel to road wheel angle). However, the actual ratio may be as much as twice as large because the steering system is compliant and because high resisting torques are produced by the road wheels. There also may be suspension and steering system interactions that alter the steering gains (path radius, yaw rate, or lateral acceleration gain) in a steady turn.

The maximum wheel angle of the front wheels influences the minimum turning radius of the vehicle. To first order, the minimum turning radius is equal to the wheelbase of the tractor or truck divided by the sine of the maximum wheel angle. Because most tractors or trucks have at least 30 degrees of wheel cut, the minimum turning radius is approximately two times the wheelbase (distance from the front axle to the center of the rear suspension). For vehicles that need to operate in tight places, such as within truck terminals or in urban street operations, short wheelbase tractors are needed to enable the front unit to make a tight turn. Whether the rear units can follow is primarily a function of the wheelbases of these units. Some of the design vehicles in the AASHTO Green Book (*2*) appear to have rather large minimum turning radii.

Rear multiple-axle sets will generate a moment on the vehicle in the plane of the pavement, resisting the turn. This may become important if the road is slippery, but with normal levels of tire/road friction, this moment does not have great influence on the turning radius (*31*).

Suspension Systems

There are many kinds of suspension on heavy trucks: springs made of steel leaves or composite materials, torsion bars, rubber blocks, air springs, or combinations of these types. The stiffness and damping properties vary over a wide range in different designs. Shock absorbers may be used on front suspensions and air suspension, and may be recommended for suspensions with a tendency toward oscillating.

The suspensions for multiple-axle sets (tandems, tridems, etc.) contain some means of load leveling between axles (i.e., equalization) to protect the vehicle from large loading forces when going over bumps and dips. This also protects the pavement. Common designs of tandem suspensions are four-spring, walking-beam, and air-suspension systems (*32, 5*). Walking-beam systems are not in general use in the United States; they are used primarily for off-road vehicles such as logging, oil field, and construction units. These suspensions are rugged and allow for long excursions of the suspension. They have the disadvantage of tending to have axle tramp oscillations known as "tandem hop."

The performance of the load-equalizing mechanisms on multi-axle suspensions has come under scrutiny in the United Kingdom, where much attention has been given to the amount of road wear done by different types of suspensions and vehicle designs (*33*). If vehicles are to be taxed according to the amount of road wear they cause or are to be rewarded with greater payload allowances if they use road-friendly suspensions, the details of suspension design and the need for suspension test procedures become important. At recent symposia, matters of this type have been given considerable attention (*34, 12, 35*).

The roll-stiffness properties of heavy-truck suspensions are important in the study of rollover situations (*36*). Also, the roll-center height of the suspension is important with respect to roll stability. These characteristics may also have a strong influence on vehicle performance in turning maneuvers involving large amounts of side-to-side load transfer due to acceleration

levels and the cg height of the sprung mass of the vehicle. Example values for roll stiffnesses (*37*) are as follows on a per axle basis (i.e., the total roll stiffness of a tandem suspension is twice the value given):

- Walking beam, per axle—92 000 to 184 000 cm-kg/degree (80,000 to 160,000 in.-lb/degree)
- Four spring, per axle—75 000 to 115 000 cm-kg/degree (65,000 to 100,000 in.-lb/degree)
- Air suspensions, per axle—35 000 to 105 000 cm-kg/degree (30,000 to 90,000 in.-lb/degree)
- Front suspensions—23 000 to 29 000 cm-kg/degree (20,000 to 25,000 in.-lb/degree).

These roll-stiffness values cover a wide range, and they can be altered by the addition of roll bars or other mechanisms for producing roll stiffness. For example, new designs of air suspensions reach 170,000 cm-kg/degree (150,000 in.-lb/degree) (*37*). Nevertheless, these values provide an indication of the capabilities of typical truck suspensions.

Roll-center heights for typical suspensions are around 71 cm (28 in.) above ground level for many tandem suspensions and around 48 cm (19 in.) for front suspensions. These values are used for simplified calculations of truck rollover thresholds and handling performance measures in a steady turn (*38*).

For small suspension motions, particularly for steel spring suspensions, detailed suspension properties are needed to predict pavement loading. This is due to the hysteretic nature of the friction in leaf spring suspensions and the nonlinear characteristics exhibited by these springs (*39*). The results presented in NCHRP 353 (*5*), including those summarized in this synthesis, reflect these properties.

Further information is contained in the data files that go with a new truck simulation capability known as TRUCKSIM (*40*). Examples of suspension properties are also given in the component factbook (*21*). They will be of interest to highway agencies that are concerned with truck performance in safety related maneuvers or with assessing penalties or providing rewards, depending on pavement loading properties.

Hitching Systems and Dollies

Hitching systems, or hitches, interconnect the separate units of a combination vehicle. There are several types of hitches, each of which affects the heavy truck combination in various ways. The primary properties are the degrees of freedom allowed between the units connected together by the hitch. The degrees of freedom, and their importance to the combination vehicle if the hitch allows the particular degree of freedom, are as follows:

- Yaw—rotation about a vertical axis, which enables a combination vehicle to maneuver better in turns.
- Pitch—rotation about a horizontal axis perpendicular to the direction of motion, which will prevent pitch movements from being transferred from a following to a leading unit during braking.
- Roll—rotation about a horizontal axis in the direction of motion, which will prevent the rolling of one unit from causing the connected unit to roll.

The hitches used in the United States are of three primary types: fifth wheel, turntable, and pintle-hook (*21*). Of these, the most common is the fifth wheel, which is typically used to connect a semitrailer to a tractor. The conventional fifth wheel has a landing plate that can tilt in pitch but not in roll; and it accommodates a "king pin" thrusting down into its center about which the connected trailer can rotate in yaw. (The "king-pin-to-rear-axle" is the commonly used measurement to predict, to a first approximation, the amount of low-speed offtracking of a tractor/semitrailer combination.) The fifth-wheel hitch has no roll degree of freedom, so if the tractor and trailer are in line, any rolling of one unit of the combination is shared by the other. However, if the two units are not in line, as in executing a turn, then some pitch is constrained and some relative roll is allowed. At the extreme, when the trailer is at 90 degrees from the tractor, the fifth wheel completely restrains pitch of the trailer relative to the tractor, but offers no constraint to relative roll. (In this position, the trailer could essentially roll completely over without affecting the tractor.)

In contrast to a semitrailer, a full trailer (used in doubles and triples and, especially in the West, with truck-full trailers) is connected to its lead unit by a dolly with a draw bar and a pintle-hook hitch. The dolly (also called an A-dolly to distinguish it from the Canadian B-dolly, discussed later) contains one or more axles, and when installed underneath the front portion of a semitrailer converts it to a full trailer. There are two basic types of dollies, a converter dolly and a fixed dolly, distinguished by the hitching arrangement between the dolly and the semi trailer. The converter dolly contains a fifth wheel, with the degrees of freedom just discussed. The fixed dolly uses a turntable hitch, which allows yaw between the trailer and the dolly, but it is firmly attached to the underside of the trailer so that there can be no roll or pitch between the trailer and the dolly.

A pintle-hook hitch resembles a hook-and-eye arrangement. As such, it provides no restraints on rotational motion in any plane (yaw, pitch, or roll). With a fixed dolly, the draw bar contains a pitch hinge to prevent vertical loading from being transferred to the unit ahead of the full trailer. Converter dollies, however, can transmit significant portions of pitch moments due to braking, via vertical loading on the pintle-hook hitch.

As suggested above, the fifth-wheel hitch allows little or no relative rolling of the connected units, adding roll stability to the combination. Also, with only one articulation point, tractor-semitrailers are not subject to much rearward amplification, but if the king-pin to rear axle distance is fairly long, low-speed offtracking can be large.

The use of dollies also has advantages and disadvantages. The dolly has two articulation points, one at the pintle hook and one at the dolly turntable or fifth wheel. This, together with generally shorter wheelbases, means that such combinations have significantly less low-speed offtracking than tractor-semitrailers of the same overall length, although they have more high-speed offtracking. On the negative side, the additional

articulation points allow rearward amplification, which is especially pronounced in triples with two dollies with pintle-hook hitches. Also, because the pintle hitch is not able to transmit roll moments, a rear trailer could more easily roll over due to lateral accelerations, receiving no roll resistance from the other units.

To aid in reducing rearward amplification, special hitching arrangements may be used. In Canada the B-train configuration is being promoted (*41*). Special dollies with double draw bars, called B-dollies, or special steering features also are available for reducing rearward amplification (*42*). These dollies have one less articulation point than the conventional A-dolly, because of the use of double draw bars.

The major drawbacks to these innovative dollies are that (1) they may be more difficult to deal with in operational usage than the conventional A-dolly, (2) they may cost more and be heavier, (3) they may require more maintenance, and (4) they may not last as long. Furthermore, the conventional dolly works very well in normal maneuvers (those not associated with emergency maneuvers). In addition, rearward amplification is highly dependent on truck speed so that at speeds below approximately 72 km/hr (45 mph) many doubles or triples will have little rearward amplification. For these reasons, it is not apparent to fleet operators why they should absorb the costs associated with a change to other types of dollies and vehicle configurations.

Cabs

Driver eye height is pertinent to computing stopping sight distance. Typical values of driver eye height are 190 cm (75 in.) for conventional cabs and 240 cm (93 in.) for cab-over-engine tractors. The range of driver eye heights is listed as from 180 to 290 cm (71 to 113 in.) (*4*).

Another aspect of truck driver visibility related to cab characteristics is the ability of the driver to see along the right side of the vehicle. Because trucks make wide right turns, there is concern that the driver may not see a vehicle or person that has moved up along the right or blind side of the vehicle. Present highway design for trucks is based on having enough pavement so that trucks do not need to move out of the right lane to make right turns (*9*). However, in places where large trucks are allowed, often the road has not been designed for them, and the drivers of large trucks make wide right turns from left of the right lane so as to stay on the pavement. Drivers of other vehicles normally honor that maneuver and do not move into the space to be used by the truck. There is the potential for a safety problem, however, when the respect of other drivers for trucks depreciates.

CHAPTER FIVE

OPERATING CHARACTERISTICS OF TRUCKS IN TURNING SITUATIONS

Structural matters of pavement fatigue, rutting, and bridge fatigue (discussed in Chapter 8) are evaluated in terms of the long-term influence of accumulated loading cycles. In contrast, the interactions between truck and highway factors that influence traffic flow and highway safety occur instantaneously in turning and in accelerating and decelerating situations.

In this and the next chapter, which examine directional responses and longitudinal speeds of trucks, the discussion will address first the measures used to evaluate performance in the particular driving situation and then the influences of truck and highway characteristics on those measures. This chapter treats turning in two situations: at intersections and on horizontal curves and ramps on high-speed highways.

TURNING AT INTERSECTIONS

Performance Evaluation

Offtracking and swept path dimensions are the measures used to evaluate performance in intersection turning situations. Both are measures of the extent to which the path of the following axles diverges from the path of the front axle; they depend on the minimum turning radius allowed by either vehicle or highway design. The term offtracking as used in this discussion of turning at intersections is often called "low-speed offtracking" because it is a phenomenon that is associated with turning at low speeds. Another phenomenon, "high-speed offtracking," occurs in turning at high speeds and is discussed in the subsection on turning on horizontal curves and ramps.

The AASHTO policy (*2*) assumes minimum turning radii (defined by the path of the outside front wheel of the vehicle) for various design vehicles. Although the policy recognizes that the minimum turning radii are determined by the characteristics of the truck (primarily the tractor wheelbase and maximum steering angle), the values used in the design policy are generally conservative, specifying a minimum turning radius that is easily achieved by most truck-tractors. Consequently, the turning constraint is usually the radius of the turn as accommodated by the roadway rather than the limits of the steering system of the design vehicle. Nevertheless, to be compatible with road design, the vehicle needs to be designed so that it can accomplish the turning radius defined by the intended path on the road.

The minimum turning radius is the input for evaluating highway and vehicle design compatibility at turning situations at intersections. The output is the path of the rearmost inside wheel. In the case of multitrailer combinations (doubles and triples) the rear axle of the last trailer is used. (Note:The path of the rearmost inside wheel, which is an approximation used to simplify offtracking calculations, is reasonably accurate in most circumstances.) For vehicles with multiple closely spaced axles (tandems, tridems, etc.) the set or sets of axles are approximated by one axle positioned at their geometric center, which is used as the "rearmost" axle. The accuracy of these prediction methods diminishes for trucks with the following properties: multiple axle sets of four or more axles, multiple axle sets with a wide separation between the axles of the set, combination vehicles with steerable rear axles, and combination vehicles that have a long overhang at an articulation point. The compatibility of the vehicle and roadway is judged by whether this rearmost inside wheel remains on the pavement.

The performance measure implied by the above discussion is the amount (if any) that the rear inside wheel tracks off the road surface. A standard method for judging intersection turning performance for a proposed or existing intersection is to construct a turning template (map) of the paths of the important points on a design vehicle (*2*), and to superimpose this template onto a layout drawing of the intersection to see if the vehicle's turning capability can be made to fit within the available pavement area. Examples of turning templates for AASHTO design vehicles are given in the AASHTO policy. Figure 10 is an example of a turning template for a long combination vehicle (LCV) operating with a turning radius of 12 m (40 ft) for the outside front corner of the vehicle (*9*). In the case of the 180° turn, the rear inside wheel passes 3.6 m (11.9 ft) *inside* the turn center, resulting in a total swept path of 15.6 m (51.9 ft). For the vehicle and the pavement to be compatible in this turning situation, the pavement area would need to shaped so as to accommodate the path of the inside rear wheel.

Conventional templates will cover various angles of turn, typically from 30 or 90° up to 180°. As is evident in Figure 10, the angle of the turn has a major influence on the minimum radius and the amount of pavement needed. AASHTO policy tabulates minimum radii for their design vehicles for 180° turns. Typical examples of the results are given in Table 5.

The above results are for vehicles with specific internal dimensions locating the axles and articulation points. The symbol code (e.g., WB-67) indicates only the distance (in feet) from the first to the last axle. Offtracking, swept path, and minimum turning radii depend, as well, on the internal dimensions of the vehicle, the most important of which is the longest distance from an articulation point to an axle set. The dimensions between hitch locations and axles are given in AASHTO for these design vehicles. But the minimum inside radii can be considerably different from those listed in this table if the longest internal dimension of a vehicle is considerably different from that used in the AASHTO policy.

THIS TURNING TEMPLATE SHOWS THE TURNING PATHS OF BASELINE VEHICLE SPECIFIED. THE PATHS SHOWN ARE FOR THE LEFT (OUTSIDE) FRONT OVERHANG AND THE RIGHT (INSIDE) REAR MOST WHEEL. THE CENTER OF THE FRONT AXLE FOLLOWS THE CIRCULAR CURVE DEFINED BY A 10.9m (36') RADIUS, HOWEVER, ITS PATH IS NOT SHOWN.

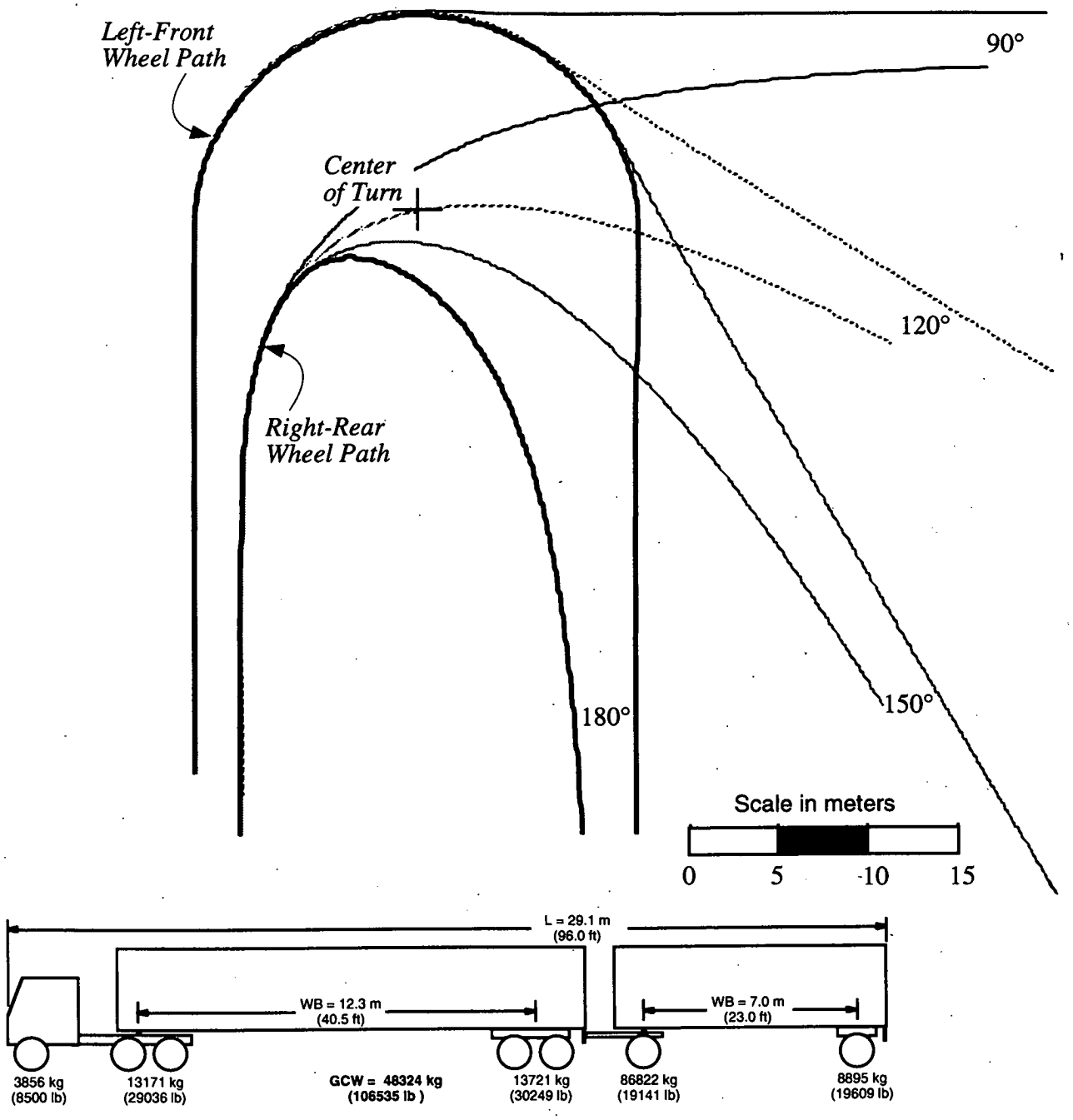


FIGURE 10 Offtracking templates for a Rocky Mountain double.

TABLE 5
MINIMUM 180 ° TURNING RADII FOR DESIGN VEHICLES

Design Vehicle	Symbol	Outside Minimum Turning Radius, m (ft)	Minimum Inside Turning Radius, m (ft)
Single Unit Truck	SU	13 (42)	8.5 (27.8)
Semitrailer Intermediate	WB-40	12 (40)	5.8 (18.9)
Semitrailer Large	WB-50	14 (45)	5.9 (19.2)
Semitrailer-Full Double Trailer STAA	WB-60	14 (45)	6.8 (22.2)
Interstate Semitrailer STAA 14 m (48 ft)	WB-62	14 (45)	2.8 (9.1)
Interstate Semitrailer STAA 16 m (53 ft)	WB-67	14 (45)	0.0 (0.0)
Triple	WB-96	15 (50)	8.2 (27.0)
Turnpike Double	WB-114	18 (60)	5.2 (17.0)

Source: AASHTO (2) and ITE (4)

Results for certain design vehicles in turns of 60°, 90°, and 120° at minimum outside turning radii of 15, 30, and 91 m (50, 100, and 300 ft) are given by ITE (*4*). Examples of the results (expressed in maximum swept path widths) for 90° turns are given in Table 6.

The results given in Tables 5 and 6 are representative of the considerations used in current practice for good friction conditions. However, performance may differ from that indicated in Tables 5 and 6 for vehicles with multi-axle suspensions, or with widely separated axles on a unit not divided by articulation points, when the road is slippery. Accurate numerical solutions for the turning paths of vehicles with multi-axle suspensions may be obtained from detailed computer models, but this is not widely done, currently.

For Canadian application (*43*), vehicle units with multi-axle suspensions are given special treatment as to the friction demand needed to make a tight turn. As a result of theoretical analyses, the vehicles covered in the Canadian Memorandum of Understanding do not employ multi-axle suspensions because calculations predict that these vehicles will not be able to turn properly when the road is slippery. The development of test procedures and experimental confirmation of these policies is needed to ensure that they are appropriate and that they do not unduly restrict vehicle design.

Nevertheless, multi-axle suspensions do create a turn-resisting moment, which may be important to low-speed offtracking on slippery surfaces (*44*). Some of these types of vehicles that would be able to make tight turns when the road is not slippery could have trouble staying within the pavement boundaries when the intersection is slippery.

TABLE 6
TRUCK SWEPT PATH FOR 90° TURNS WITH MINIMUM TURNING RADIUS OF 15 M (50 FT)

Truck Configuration	Swept Width, ft (m)
Tractor with 11 m (37 ft) semitrailer (WB-40)	5.15 (16.9)
Tractor with 14 m (45 ft) semitrailer	6.00 (19.7)
Tractor with 15 m (48 ft) semitrailer	6.28 (20.6)
Long tractor with 15 m (48 ft) semitrailer (WB-62)	6.40 (21.0)
Tractor with 16 m (53 ft) semitrailer	6.71 (22.0)
Short tractor with two 9 m (28.5 ft) trailers (WB-60)	5.12 (16.8)
Long tractor with two 9 m (28.5 ft) trailers	5.24 (17.2)

Source: ITE (*4*) and Harwood et al. (*28*)

Vehicle and Highway Design Characteristics Influencing Performance in Low-speed Offtracking

Figure 11 summarizes the matrix of highway and vehicle characteristics that influence the performance of the vehicle and the highway system with regard to turning within the paved area at intersections. The layout of the steering system and the wheelbase of the tractor or truck influence the minimum turning radius of the vehicle, while the minimum turning radius of the road is directly a part of the geometric design of the intersection. The first level of performance evaluation considers whether the vehicle can achieve the turning radius of the road.

The relationships pertaining to the minimum turning radius of the vehicle and road are portrayed in Table 7. This aspect of evaluation relates to the ability of the truck front wheels to make the turn. As indicated in the table, these relationships can be determined for existing roads and vehicles. It is possible to set up straight-forward tests to evaluate the capability to meet a minimum turning radius constraint.

Table 7 also indicates the relationships pertaining to evaluating minimum (inside) turning radius (e.g., the ability for the rearmost wheels to remain on the pavement). A determination of the maximum swept path, O_{max}, is needed to determine the minimum radius for the vehicle. In this case, as with the minimum turning radius, experimental tests can be made to evaluate the compatibility of particular vehicles with particular road designs.

It is possible to develop offtracking requirements based on internal dimensions (*45*). This formulation can be in a form that resembles Bridge Formula B or some other bridge formula (except that in some ways it is simpler because the results only depend on axle positions and not axle loads).

TURNING ON HORIZONTAL CURVES AND RAMPS

Performance Evaluation

Turning on ramps is a special case of turning on horizontal curves, both of which are addressed here. Ramps are designed much like highway curves except that they usually have tighter radii and lower design speeds than most horizontal curves on

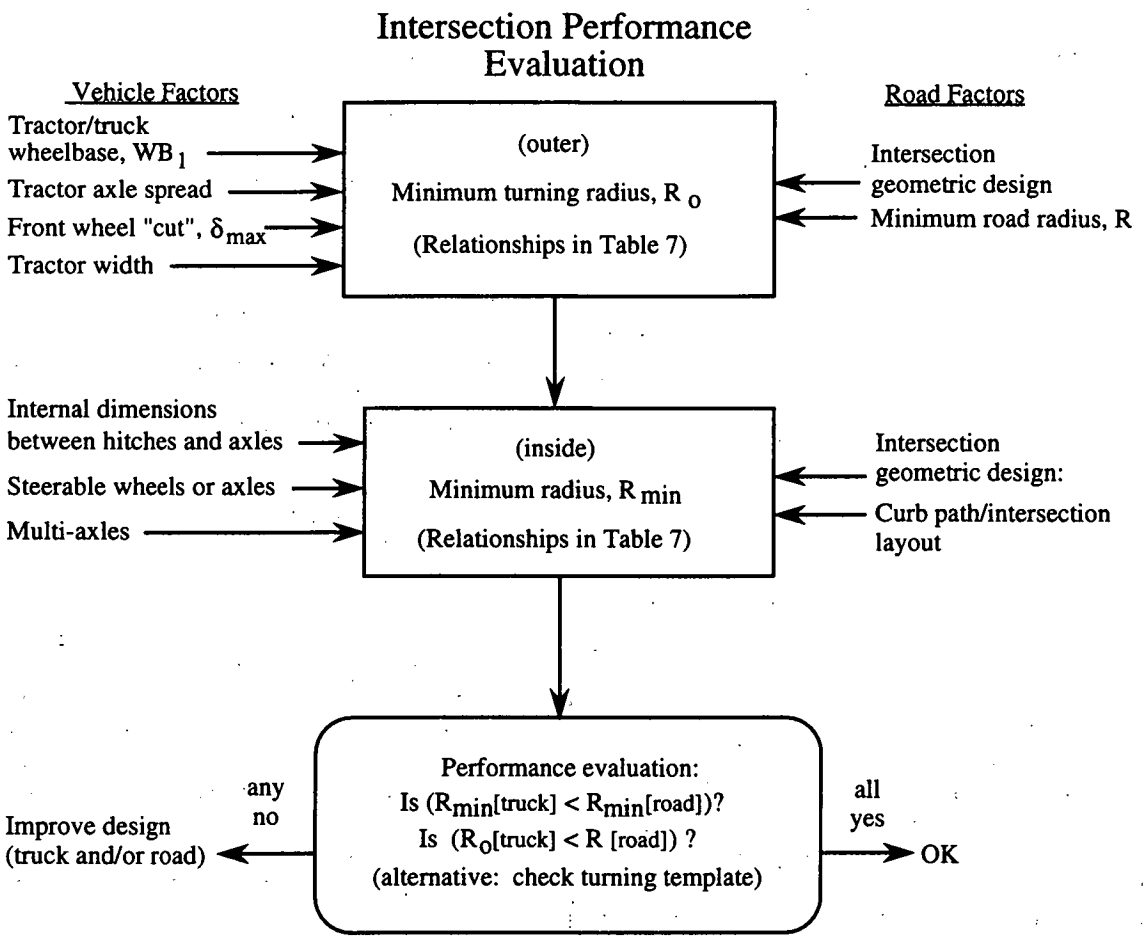


FIGURE 11 Matrix of vehicle and highway factors influencing offtracking at intersections.

highways. Ramps are designed with consideration given to several aspects of vehicle performance. They must provide adequate width to accommodate inboard offtracking during low-speed use and outboard offtracking during high-speed use. (High-speed offtracking is the result of centrifugal forces that tend to move the trailing units of a multi-unit truck configuration outward on the curve relative to the leading unit.) Ramps are usually superelevated to reduce rollover propensity during high-speed use, but with consideration to the risk of sliding off the ramp when vehicles are forced to operate slowly or stop under slippery road conditions. The effect of superelevation on offtracking is addressed by Glauz et al. (*46*). In brief, superelevation serves to decrease high-speed offtracking but to increase low-speed offtracking.

TABLE 7
RELATIONSHIPS FOR EVALUATING TURNING AT INTERSECTIONS

$R_{o,\ truck} \approx [W_{B1}$ - (axlespread/2)] / tan δ_{max} + width of the first unit of the vehicle; or measure directly

$R_{o,\ road} \approx$ see AASHTO policy; or measure maximum swept path directly

$R_{min,\ truck} \approx R_{o,\ truck} - O_{max}$; or measure directly ($O_{max}$ = max. swept path)

$R_{min,\ road} \approx$ see AASHTO policy; or measure directly

In highway design, performance on horizontal curves is evaluated in terms of the lateral acceleration that must be counterbalanced by forces at the tire-road interface (friction factors). The lateral acceleration is what is felt by vehicle occupants when making a steady turn at fixed radius and velocity. The friction factors given in the AASHTO policy (*2*) correspond to the levels of lateral acceleration that are believed to be comfortable at various operating speeds.

Another performance measure has to do with tracking performance on a turn. To compensate for high-speed offtracking and the imprecision of driver steering performance, pavements are sometimes widened on horizontal curves. The ultimate measure of performance in these situations is whether the vehicle's tires remain within the lane or on the pavement.

Vehicle and Highway Design Characteristics Influencing Performance on Horizontal Curves and Ramps

The discussion that follows focuses first on ramps, as they tend to be more critical than highway curves. A few final

comments are then added dealing with highway curves other than ramps.

Recent results have shown that typical U.S. LCVs, including the turnpike double, will not have low-speed offtracking problems on 5-m- (16-ft-) wide ramps with radii greater than 64 m (210 ft) (*9*). See Figure 12. The low-speed offtracking analysis used to reach these results is identical to that described in the previous subsection.

The superelevation on ramps is also determined from horizontal curve policy. In regions with ice and snow, the maximum superelevation, e_{max}, is often limited to about 0.08. The selection of the maximum superelevation is part of the design process for horizontal curves (*2*). Given a maximum superelevation, AASHTO policy (*2*) provides tables relating curvature, radius, superelevation, design speed, and the lengths of superelevation transitions. Furthermore, there are tables that give the maximum side friction factor, f_{max}, and minimum radii for various curves.

The tables for the design of horizontal curves are based on the physics for the vehicle, represented as a point mass, following the curve at the design speed (*4*). The lateral acceleration experienced in a curve is a function of the speed, radius, and superelevation and determines the friction demand of the tires to keep the vehicle on the curve. (The friction factor used in highway curve design is simply a surrogate for lateral acceleration.) In addition, the lateral acceleration in a curve also affects the potential for rollover—especially critical with heavy trucks. The governing relationships for these parameters in curves are given in Table 8.

In current highway design practice, horizontal curves are designed to limit the level of lateral acceleration. However, heavy trucks may roll over at levels of lateral acceleration that are close to those used in highway design (*47, 4*). This problem is found primarily on short radii curves such as those used on ramps. It may also be a problem for urban intersections that allow a maximum side friction factor (lateral acceleration) of

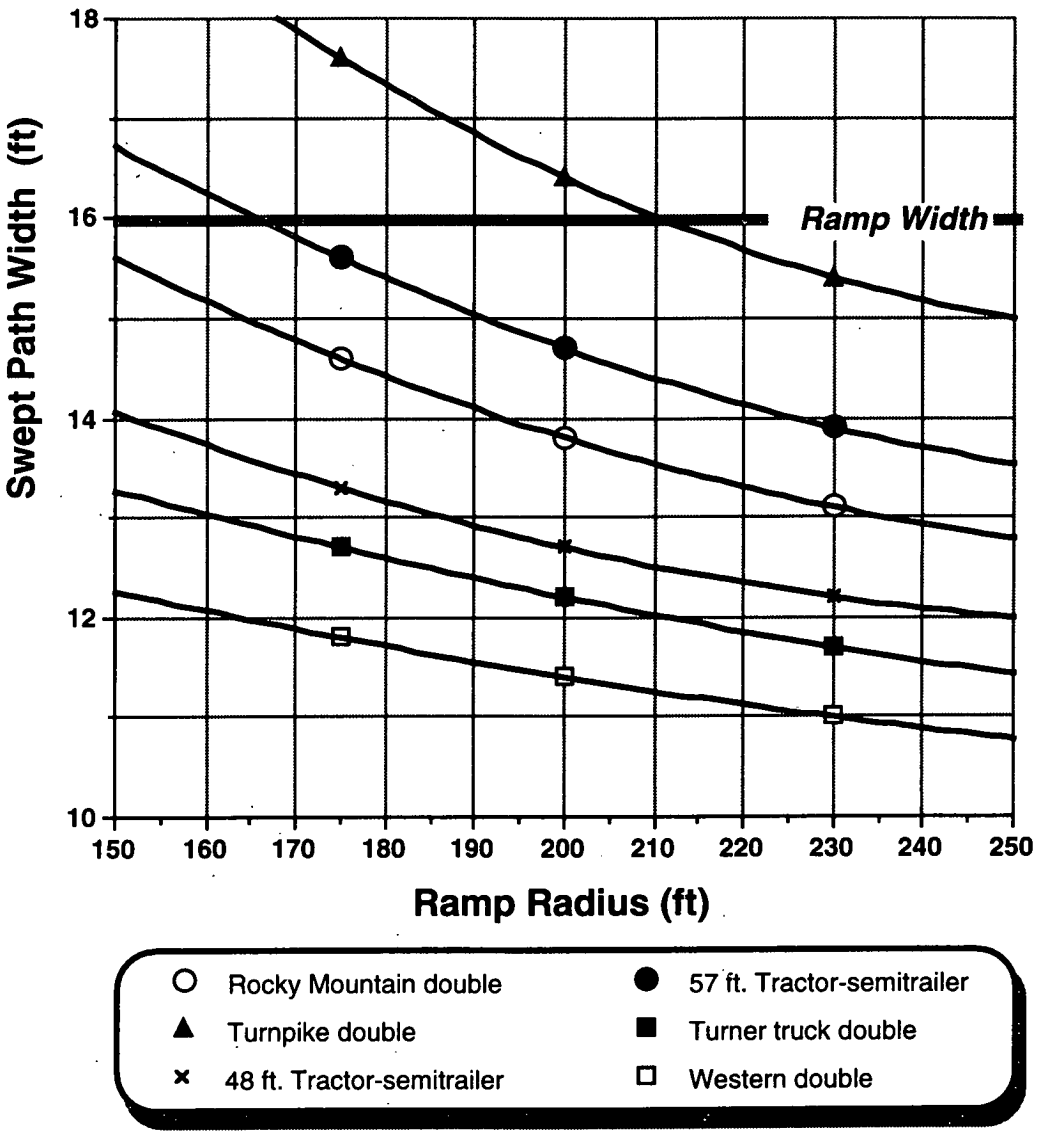


FIGURE 12 Turning on ramps (*9*).

TABLE 8
RELATIONSHIPS GOVERNING TURNING ON HORIZONTAL CURVES

Steady State Equations for Friction Demand

$f \geq V^2 / (gR) - e$

where

f = Friction demand (required to stay on the curve)
V = Vehicle velocity (design speed)
g = Gravitational constant
R = Curve radius
e = Superelevation (m/m or in/in)

Friction Levels at Rollover Limits

$f_{roll} = (RT-SM)/1.15-(e-e_{PC})$

where

f_{roll} = Friction factor at the rollover limit
RT = Rollover threshold (in g's)
SM = Safety margin (in g's)
PC = Point of curvature
e_{PC} = Superelevation at the point of curvature

Regional Differences (where maximum superelevation is limited because of ice and snow)

$f_{roll} = (RT-SM)/1.15-(e-e_{PC}) \geq V^2/(gR)-e, \therefore e_{PC} \leq (RT-SM)/1.15-V^2/(gR)$

Source: ITE (*4*)

0.3. With regard to truck properties, there are heavy trucks with rollover thresholds at lateral accelerations in the neighborhood of 0.3 g's. Hence, there is need to consider the rollover properties of heavy trucks in the design of vehicles and highway curves, especially at ramps and urban intersections.

Work has been done to address the problem of truck rollover on ramps (*47*). The basic relationship given in Table 8 for this purpose relates the acceptable lateral acceleration to a friction factor to be used in the design of the road.

TABLE 10
DESIGN $f_{max} = f_{roll}$ BASED ON ROLLOVER THRESHOLD OF 0.3 g's

RT	e_{max}	f_{roll} for $e_{PC\ spiral}$	f_{roll} for $e_{PC = 2/3e}$
0.3	0.04	0.17	0.16
0.3	0.06	0.17	0.15
0.3	0.08	0.17	0.14
0.3	0.10	0.17	0.14

Source: ITE (*4*)

As shown in Table 9, the speed at a rollover threshold equal to 0.3 g's is often less than 16 km/hr (10 mph) above the design speed on a short-radius ramp. The work of Ervin, McAdam, and Barnes et al. (*47*) has been used in an ITE report (*4*) and elsewhere. The idea here is to provide a means for augmenting the design of ramps to compensate for the tendency of heavy trucks to roll over. As indicated in the relationship given in Table 8, the ramp design could be determined by a friction factor (f_{roll}), which depends on the vehicle's rollover threshold; a safety margin, which usually equals 0.1 g's to compensate for a truck entering a nominally 48 km/hr (30 mph) ramp at 64 km/hr (40 mph); and the amount of superelevation at the point of curvature. There is also a factor of 1.15 to account for the driver not following the ramp curvature perfectly. Typical results for f_{roll} are given in Table 10 for two types of superelevation treatment (e_{PC} spiral and $e_{PC} = 2/3$ e) . The values of design f_{max}, equal to f_{roll} in Table 10, could be used to determine the minimum radius for the design of a ramp with a margin of safety for trucks with a rollover threshold of 0.3 g's.

A summary of the interactions of truck and highway factors influencing turning on ramps is contained in Figure 13. Truck factors influencing low-speed offtracking and rollover threshold are important in this situation. These include the internal dimensions between axles and hitches and rollover-related

TABLE 9
SPEED AT WHICH ROLLOVER IS PREDICTED FOR VEHICLE WITH ROLLOVER THRESHOLD OF 0.3 g's

Design Speed km/hr (mph)	Max e	AASHTO f	R_{min} m (ft)	Speed at RT = 0.3 g km/hr (mph)
32 (20)	0.06	0.17	35 9116	40.2 (25.0)
48 (30)	0.06	0.16	83 (273)	61.8 (38.4)
64 (40)	0.06	0.15	155 (509)	84.3 (52.4)
32 (20)	0.08	0.17	33 (107)	39.7 (24.7)
48 (30)	0.08	0.16	77 (252)	61.0 (37.9)
64 (40)	0.08	0.15	143 (468)	83.0 (51.6)
32 (20)	0.10	0.17	30 (99)	39.3 (24.2)
48 (30)	0.10	0.16	70 (231)	59.9 (37.2)
64 (40)	0.10	0.15	132 (432)	81.9 (50.9)

Sources: ITE (*4*), Harwood et al. (*28*)

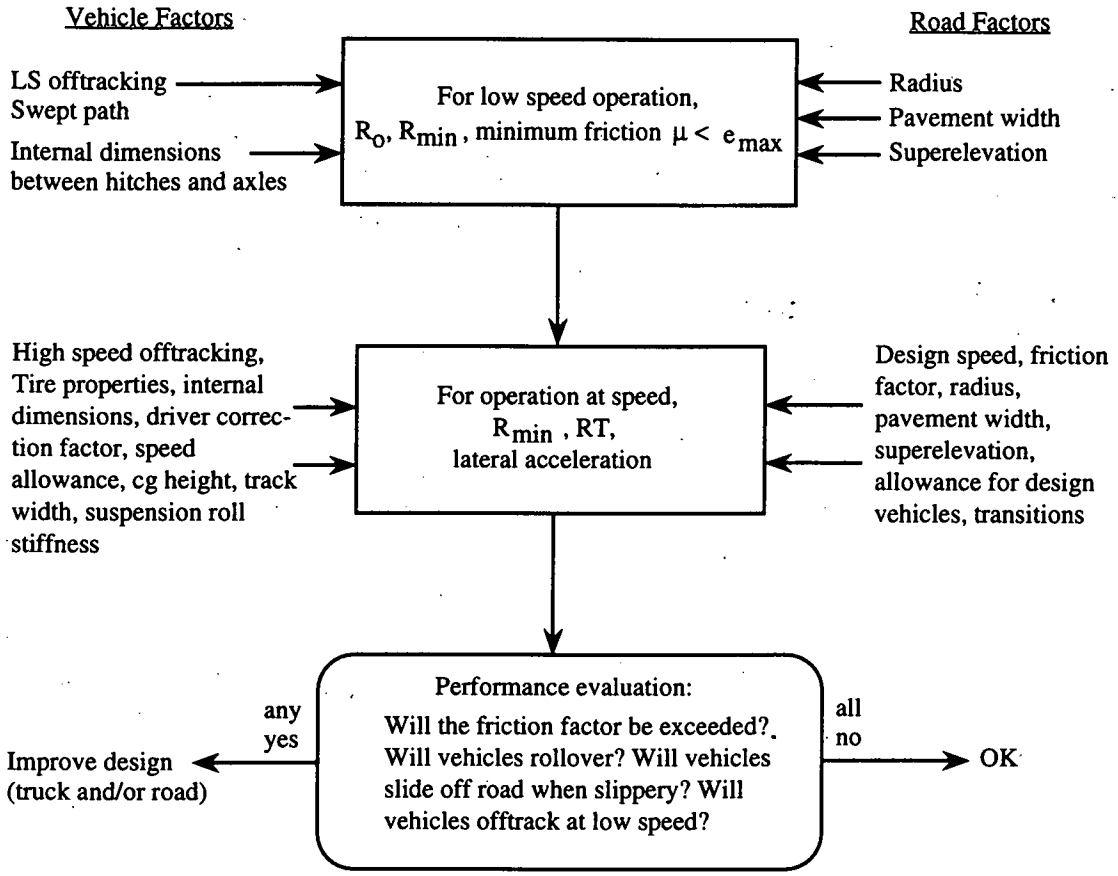


FIGURE 13 Ramp performance evaluation.

items such as (cg height)-to-(track width) and suspension roll stiffnesses. Driver factors such as steering and speed allowances are also included in determining safety margins. The highway factors are primarily those used in curve design—speed, radius, and superelevation. Performance evaluation in this case is based on low-speed offtracking, curve design for a point mass, and rollover compensation.

The highway factors for traveling on horizontal curves, in general, include the traditional design quantities: design speed, maximum friction factor, superelevation, and minimum radius. With regard to ensuring that the truck stays between the road edges, pavement width and choice of design truck come into play. Pavement widths for horizontal curves are presented in the AASHTO policy (*2*). Also, see Table 10 of the ITE report (*4*).

In addition to the truck factors influencing low-speed offtracking, the factors influencing high-speed offtracking are important to performance in a steady turn. The ratio of tire cornering stiffness to the vertical load at each axle is important in determining the amount of high-speed offtracking (*31*). For the current truck population, the amount of high-speed offtracking is on the order of 0.3 m (1 ft) toward the outside of the curve at approximately 80 to 100 km/hr (50 to 60 mph). The information given in the AASHTO policy indicates that pavement widening would be needed only in rare cases involving high degrees of curvature and LCVs.

CHAPTER SIX

OPERATING CHARACTERISTICS OF TRUCKS IN ACCELERATING AND BRAKING SITUATIONS

CROSSING INTERSECTIONS

Performance Evaluation

Performance in accelerating across an intersection depends on (1) the width of the intersection, (2) the length of the vehicle crossing the intersection, (3) the acceleration capability of that vehicle from a standing start, (4) driver perception and reaction time, and (5) the design speed for vehicles traveling on the crossing roadway. These quantities are included in Figure 14, which summarizes the truck and highway factors that influence intersection crossing performance. The goal is to allow enough "intersection sight distance" for the driver of the crossing vehicle to decide if it is reasonable to cross the intersection. The intersection is judged by whether adequate sight distance is available. If the truck is long and its acceleration capability is low, it will take some time for the truck to cross the intersection. If the speed of vehicles on the crossing path is high, the required intersection sight distance could be excessively long.

Vehicle and Highway Design Characteristics Influencing Performance for Crossing Intersections

The required sight distance is computed by multiplying the design speed of the cross road by the sum of the driver's reaction time (2 sec) plus the time it takes the vehicle to cross the intersection. The time for the vehicle to cross the intersection depends on the length of the "hazard distance" and the acceleration capability of the vehicle. The length of the hazard distance is equal to the width of the intersection (including the initial set-back of the truck from the intersection) plus the length of the truck. The time for the vehicle to travel the length of the hazard distance depends on the acceleration characteristics of the vehicle. AASHTO (*2*) provides a graph of the time to reach a specified distance, "acceleration time," versus the distance traveled for a WB-50 design vehicle. This appears to be an estimate for a vehicle with a power/weight ratio of approximately 180 kg/kW (300 lb/hp).

Various researchers—Gillespie (*48*) and Harwood et al.(*28*), for example—have studied the time-distance relationships for heavy trucks. They have derived simple numerical models that approximate calculated results. These models do not treat the vehicle in any detail other than to require knowledge of the maximum speed in the gear selected by the driver. Under these approaches the vehicle size enters the performance evaluation only as to how the length of the vehicle contributes to the length of the hazard distance. The power/weight ratio of the vehicle is not included in these simplified considerations.

Numerous models for predicting the acceleration performance of heavy trucks have been devised. In these models, important vehicle characteristics include engine power capability, engine torque-speed relationships, transmission and rear-end gear ratios, shifting times, drag forces due to rolling resistance, aerodynamics, grade, vehicle mass, and the effective mass contribution due to rotational inertias of the engine, transmission, and tires and wheels. Simplified versions of these models have been developed for use in highway design studies. This is an area where it is hard to know the level of complexity appropriate for vehicle-highway interaction studies, but plots of experimentally measured performance showing time versus distance traveled from a stop would be useful for the design of particular roads based on the types of trucks that will frequent those roads.

Current practice is summarized by the relationships given in Table 11. The times needed to travel various hazard distances are covered by two linear relationships. The first relationship is a close approximation to the previously mentioned curve given by AASHTO (*2*). This relationship is good for hazard dis-

TABLE 11
RELATIONSHIPS: CROSSING INTERSECTIONS

$L_H = W + D_e + L$ and
$SD = KV_d (t_r + t_c)$

where

L_H = Hazard length (ft)
W = Road width (ft)
D_e = Distance from road edge (ft)
L = Vehicle length (ft)
SD = Sight distance (ft)
K = A constant (1.47) for unit consistency
V_d = Design speed of cross road (mph)
t_r = Reaction time (2 sec according to AASHTO (*2*))
t_c = Time to cross intersection (sec)

First relationship

$t_{c(AASHTO)} = L_H/16.67$ ft/sec $+ 4.8$ sec

where

$t_{c(AASHTO)}$ is an approximation to the curve given by AASHTO (*2*) for L_H between 60 and 170 ft

Second relationship

$t_c = L_H / 1.47\ V_{mg} + 3.0$ sec

where

V_{mg} = Maximum speed in gear selected (13 km per hr (8 mph) on level roads per ITE (*4*))

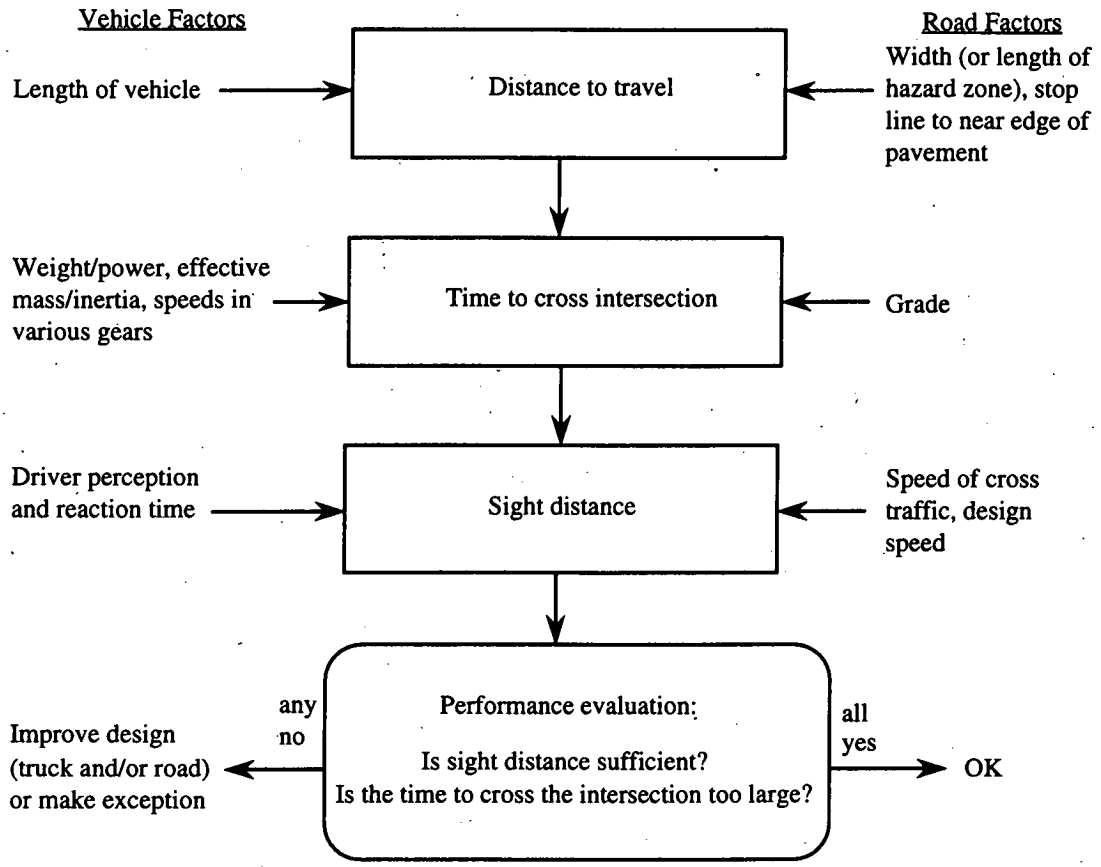


FIGURE 14 Acceleration across intersections performance evaluation.

tances between 15 and 50 m (50 and 170 ft). The second relationship has been used in the ITE report (*4*) and by Harwood et al. (*28*). At 36 m (120 ft) the second relationship yields a crossing time of 13.2 sec while the first relationship yields 12 sec. The second relationship is approximately 10 percent more conservative (longer times and sight distances) than the first relationship. Either relationship might be used conservatively for LCVs that have power/weight ratios that are less than 180 kg/kW (300 lb/hp).

RAIL CROSSINGS

Performance Evaluation

Performance in accelerating from a stop across railroad tracks depends on the width of the tracks, including a clearance margin, the length of the vehicle crossing the tracks, the acceleration capability of that vehicle from a standing start, driver perception and reaction time, and the speed of oncoming trains. Clearly the situation is much like the case of a truck crossing an intersection. However, truck drivers are not supposed to shift gears while crossing the tracks.

Performance of the road-track intersection is evaluated in terms of the sight distance available for the truck driver to use in deciding when it is safe to cross. Values of these sight distances are given in ITE (*4*), which are taken from FHWA (*49*) and Harwood et al. (*28*). Typical results with a train speed of 80 km/hr (50 mph), range from 300 to 360 m (1,000 to 1,200 ft).

There are also sight distance triangles used for specifying performance in railroad-highway situations when the truck is moving. In these cases, the stopping sight distance of the truck matters. Sample results indicating the sight distance along the highway needed for stopping before the track zone are given in ITE (*4*). These results include three sets of values for stopping sight distance based on FHWA values (*49*), a poorly performing truck driver (*28*), and a best performance truck driver (*28*).

Vehicle and Highway Design Characteristics Influencing Performance for Rail Crossings

The sight distance along the road, as described in the previous paragraph, is the distance in which the vehicle can just stop using a prescribed level of braking. AASHTO (*2*) provides friction factors that represent levels of braking decelerations pertaining to poor wet roads. AASHTO also contains driver perception and reaction times for use in computing stopping sight distances. These stopping sight distances represent passenger car tire capabilities and may not be applicable to trucks. Consequently, researchers have developed distances for poor-performance truck drivers and best-performance truck drivers (*28*). The values of deceleration used in the past tend to be large for stops from low speed. Future studies may show that

TABLE 12
RELATIONSHIPS: RAIL CROSSING

$d_H = KV_v t_r + K(V_v^2 / f) + D + d_e$ and
$d_T = (V_T/V_v) [(d_H + D - d_e + L + W)]$

where

d_H	=	Stopping sight distance along roadway (from truck driver to nearest rail)
K	=	A constant as needed for consistency of units
V_v	=	Velocity of the vehicle
t_r	=	Reaction/perception time of driver (2.5 sec according to AASHTO (2))
f	=	Friction factor (AASHTO (2))
V_v^2 / f	=	Braking distance on poor, wet road (AASHTO (2))
D	=	Distance from stop line or front of vehicle to nearest rail (also far rail to back of vehicle as it clears track area in calculation of d_T below) (4.5 m (15 ft) (2))
d_e	=	Front of vehicle to driver (3 m (10 ft) (2))
d_T	=	Sight distance leg along tracks
V_T	=	Maximum velocity of trains
L	=	Length of the vehicle
W	=	Distance between outer rails

truck drivers seldom use more than 0.2 g's for stopping, and then only in emergency braking situations. If the rail-crossing situation is not to be designed for a panic situation, moderate levels of deceleration would seem to be in order.

The design of rail crossings involves the "last point of stopping" (*49*). The idea behind the concept is that once that point is passed, the driver can no longer stop satisfactorily, but nevertheless the driver should be able to proceed at constant speed without a crash. This means that at the last point of stopping the driver should be able to see a train that would intersect the truck path at the crossover point between the tracks and the road. For this to be true, the truck must be able to travel from the last point of stopping to the other side of the tracks before a train reaches the road. The relationships pertaining to these requirements are given in Table 12. (This situation involves a third party in addition to truck and highway interests. The maximum speed of the trains must be known to determine the length of the sight distance triangle along the tracks. If maximum train speeds are increased, the available sight distance may need to be increased accordingly, thereby requiring greater clearance space to provide adequate sight distance.)

Figure 15 summarizes the truck and highway factors that influence the performance of vehicle/highway systems at rail crossings.

SIGNAL TIMING

Performance Evaluation

Performance at signalized intersections depends on the capability of trucks to clear the intersection during the clearance interval and how long it takes trucks to clear the intersection when the light turns green (especially on upgrades). In the survey of practice, it was found that several highway transportation agencies have developed practices for implementing longer green signal intervals to allow trucks to clear intersections, particularly at upgrade locations where truck speeds may be low. Multiple loop detectors have been used to pro-

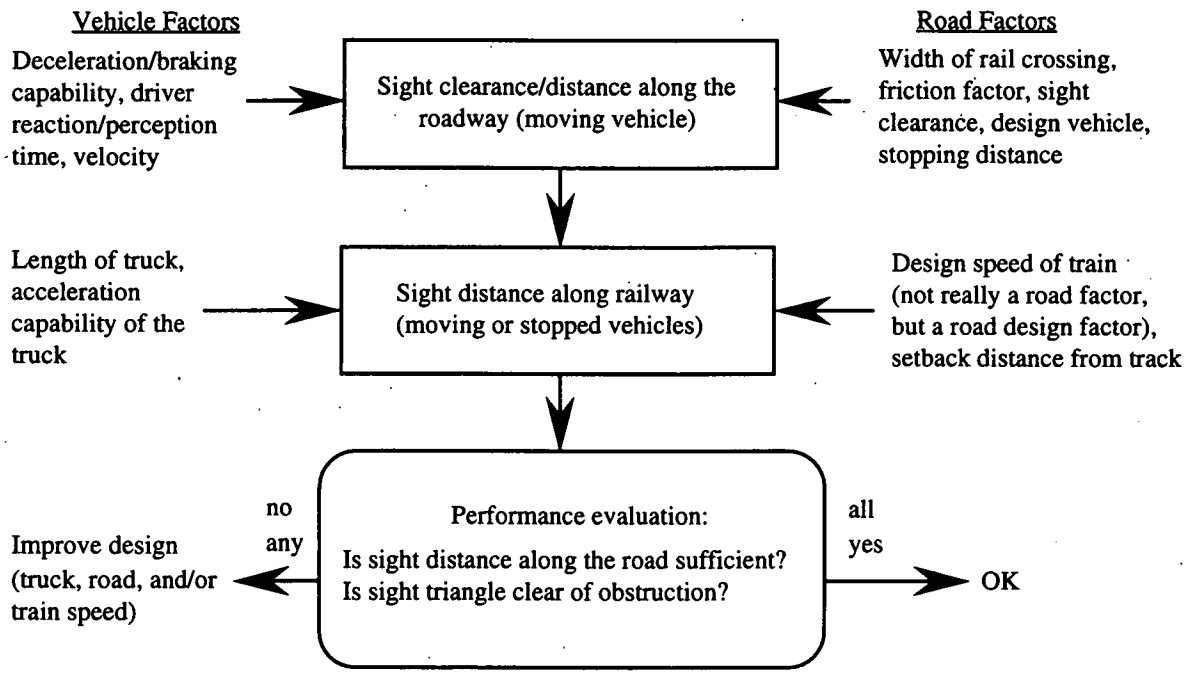


FIGURE 15 Rail crossing performance evaluation.

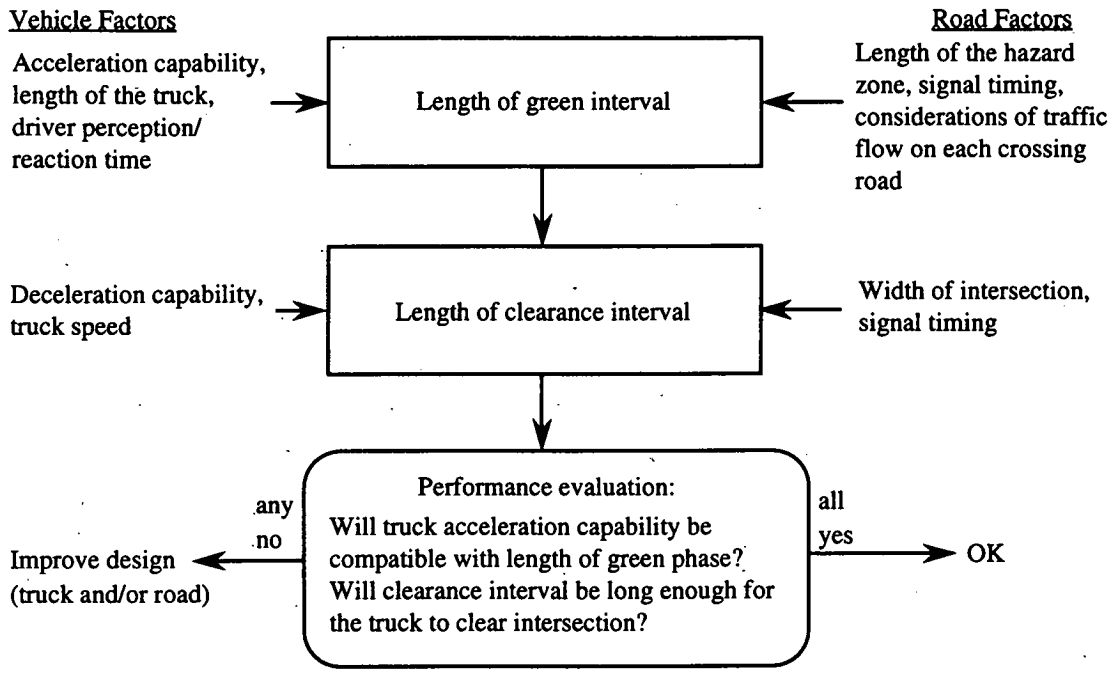


FIGURE 16 Signal timing at intersections peformance evaluation.

vide safe stopping sight distances for trucks approaching intersections.

Vehicle and Highway Design Characteristics Influencing Signal Timing

The vehicle and highway characteristics influencing the ability of trucks to fit in with the timing of the green, yellow, and all-red intervals of signals at intersections are summarized in Figure 16. Relationships that apply to these situations are given in Table 13. These relationships are not used as standards in current practice; nevertheless, they can be used as an indication of the types of problems heavy vehicles are likely to encounter at signalized intersections.

TABLE 13
RELATIONSHIPS: SIGNALIZED INTERSECTIONS

For starting up from a green signal:

$$D = 1/2\ A\ t^2 = W + L$$

where

- D = Distance the truck travels
- A = Acceleration (average) (grade needs to be accounted for here)
- t = Time from when driver responds to the green signal
- W = Width of intersection including clearance zones to stop lines
- L = Length of the truck

For the yellow change interval:

$$P_{LS} = KV_v t_r + K(V_v^2 / 2A) \text{ and}$$
$$t_y = (P_{LS} + W + L) / V_v$$

where

- P_{LS} = Last point of stopping prior to entering intersection
- K = Unit consistency factor
- V_v = Vehicle velocity
- t_r = Driver's perception-reaction time
- A = Deceleration for stopping at an intersection
- t_y = Clearance interval

The acceleration capability of heavy trucks is greatly influenced by the steepness of grade encountered. The steepness of upgrade translates directly into a loss of acceleration capability. For example, a vehicle capable of 0.1 g's acceleration on level ground will be capable of only 0.06 g's of acceleration on a 4 percent upgrade. In contrast to passenger cars, trucks frequently use all of the acceleration capability they have available.

Trucks may also have difficulties during the yellow interval of a signalized intersection. The yellow interval is specified to be 3 to 6 sec in length (*2,4*). A sensitivity analysis by Harwood et al. (*28*) indicates that clearance intervals need to be 40 to 110 percent longer for trucks. For example, for a truck traveling at 48 km/hr (30 mph), using a stopping deceleration of 0.2 g's and a 1.0 second reaction time from the onset of the clearance interval signal yields a stopping distance of 80 m (262 ft). If the truck is 21 m (69 ft) long and the intersection is 14 m (46 ft) wide and allowing a 4 m (13 ft) clearance zone, the vehicle needs to travel 120 m (394 ft) if it is to clear the intersection from a decision point of 80 m (262 ft) when the light turns yellow. For this to happen, the light would need to stay yellow or include an all red phase equal to the total time for the vehicle to clear the intersection, which is 8.8 seconds in this example.

In addition, issues related to the traffic flow and level of service on the crossing roads need to be considered.

HILL CLIMBING

Performance Evaluation

Performance in climbing steep grades depends on the speed-maintaining capability of the truck and the length and slope of the upgrade. Performance of trucks on grades is evaluated by considering whether trucks will slow to 16 km/hr (10 mph) less than the prevailing traveling speed or design speed on the grade. A speed difference of more than 16 km/hr (10 mph) is deemed to be undesirable for safety reasons according to current practice and policy.

If the grade is long enough and steep enough to cause trucks to slow to 16 km/hr (10 mph) less than normal traveling speeds for cars, and if there is sufficient traffic on the road, climbing lanes may be warranted starting at the point where 16 km/hr (10 mph) is lost. The performance of the road is judged by whether passenger cars encounter traffic obstructions.

Vehicle and Highway Design Characteristics Influencing the Need for Climbing Lanes

There are many different models and approaches for computing the acceleration and speed-maintaining capabilities of heavy trucks. The AASHTO policy (2) gives two curves that show speed decreases from 90 km/hr (55 mph) as a function of distance traveled on various grades ranging from 2 to 8 percent. Time-distance relationships such as those presented by AASHTO may be determined from detailed calculations, or they could be based upon measured results from field situations. The simplified relationships, given in Table 14, represent a heuristic approach that can be used to identify the important characteristics of trucks that influence their speed on upgrades. Perhaps investigation of such relationships will lead to a better understanding of the matrix of relationships between vehicle and highway factors.

The relationships in Table 14 approximate vehicle performance at highway speeds. They start with an estimate of acceleration performance of the vehicle working from its sustained speed on a level road. Then the influence of grade on the acceleration and deceleration capability of the truck is examined. The drag operating on the vehicle determines the sustained speed for a vehicle described by its power/weight ratio and the efficiency of the transmission system. The underlying principle is that the net acceleration and deceleration available depends on (1) the level road acceleration capability of the vehicle at speeds below the sustained speed on a level road and (2) the magnitude of the upgrade. If the level of grade exceeds the level road acceleration capability, the vehicle will slow down on the grade.

Distance-speed relationships may be obtained by integrating the net acceleration to obtain velocity as a function of time, and then integrating velocity to obtain distance as a function of time. These time histories can be cross-plotted to present distance versus speed curves.

TABLE 14
HEURISTIC RELATIONSHIPS: UPGRADE PERFORMANCE

Speed-increasing acceleration potential without drag:

$$a_p = F / (W_e/g) = (K / V) * (P / W)$$

where

- a_p = Acceleration potential on level terrain
- F = $\eta * (P/V)$ = An approximation to the force-producing capability of the engine-transmission system at highway speeds
- P = Power
- η = An efficiency factor
- W = Weight of the vehicle
- W_e/g = Effective mass of the vehicle
- g = Acceleration of gravity
- V = Velocity
- K = A factor that depends upon the inertia of the rotating parts and the efficiency of the propulsion system

The quantity, K, can be estimated from the sustained speed on a level road. With zero acceleration the vehicle can sustain a speed, V_s, which must satisfy:

$$[(K / V_s) * (P / W) - a_d] * g = 0, \text{ from which K can be determined.}$$

For operation on a grade:

$$a_n = a_p - a_d - G$$

where

- a_d = Drag deceleration due to rolling resistance, aerodynamic drag, etc.
- a_n = The net acceleration or deceleration rate on an upgrade (in g's)
- G = The upgrade slope
- a_l = Level road acceleration in g's $\approx (V_S - V) / V$

Integral equations for distance-speed relationships

$$V(t) = V_o + \int_0^t a_n(\tau)d\tau = V_o - \Delta V(t) \qquad \text{(A)}$$
$$D(t) = V_o t - \int_0^t \Delta V(\tau)d\tau$$

t = dummy variable for integration

Equation (A) can be solved numerically by approximating a_n over a time step, changing velocity, and iterating until speed has been reduced by 16 km/hr (10 mph).

The relationships presented in Table 14 have been used to construct Figure 17, which presents the matrix of truck and road characteristics influencing performance of the highway system on upgrades.

DOWNHILL DESCENT

Performance Evaluation

The performance of a truck descending a mountain or a long downgrade depends on whether the truck maintains adequate braking capability to the bottom of the mountain and does not

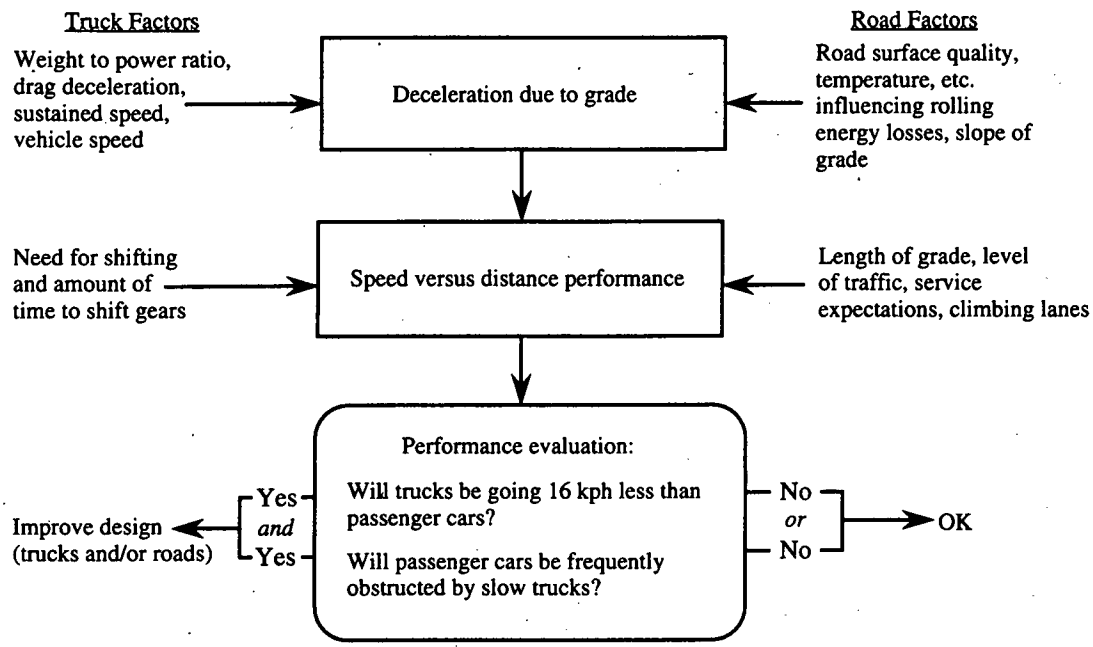


FIGURE 17 Hill climbing performance evaluation.

TABLE 15
RELATIONSHIPS: DOWNHILL DESCENT

Bulk brake temperature

$$mC_p\,(dT/dt) = F_bV - h(V)(T - T_a)$$

where

- m = Brake mass
- C_p = Specific heat
- T = Bulk brake temperature
- t = Time
- F_b = $p\,W\,(G - a_r)$ = Braking force
- V = Velocity
- $h(V)$ = Cooling coefficient (function of velocity)
- T_a = Ambient temperature

Maximum temperature is to be below a specified level (500° in the grade severity rating system).

$$t_{final} = L/V_c$$

where

- $t_{final} = L/V_c$ = Time at which the end of the grade is reached
- L = Length of the grade
- V_c = Control speed selected for descent

$$F_b = p\,W\,(G-a_r)$$

where

- p = Proportion of total braking effort done by the brake (p = 1 for all brakes lumped together
- W = Weight of the vehicle
- G = Slope of the grade
- a_r = Deceleration (in g's) due to rolling resistance, aerodynamic drag, engine retardation, and retarders.

run away (lose speed control capability). There is a grade severity rating system (*50, 51*) that gives recommended truck speeds depending on truck weight for grades of various slopes and lengths. As indicated in the survey of practice, a few highway departments use the grade severity rating system to set speeds for trucks on long, steep downgrades.

In the context of the grade severity rating system, performance in downgrade descents is evaluated in terms of the average brake temperature achieved by the vehicle at the bottom of the grade. The objective is to ensure that the vehicle proceeds down the grade at a speed low enough to keep the brake temperatures below the point where brake fade occurs. Brake fade could lead to runaway. In physical terms, much of the vehicle's potential energy possessed at the top of the grade is dissipated by the truck's brakes. As the brakes absorb potential energy they dissipate thermal energy during the descent. If the vehicle descends slowly enough, there will be sufficient brake cooling during the descent to keep the brakes from overheating.

Auxiliary devices such as engine retarders may be used to save the foundation brakes. Also, the drag of the vehicle serves to reduce the burden on the brakes. However, the current trend to achieve fuel-efficient vehicles has caused the drag forces on trucks to go from being approximately equivalent to the retardation needed to maintain speed on a 3 percent downgrade to being equivalent to the retardation needed to maintain speed on a 2 percent downgrade. To be current, the grade severity rating system needs to be refined to take into account the use of drag reduction features as well as the lack of pressure-temperature balance from brake to brake on a given vehicle (*52*).

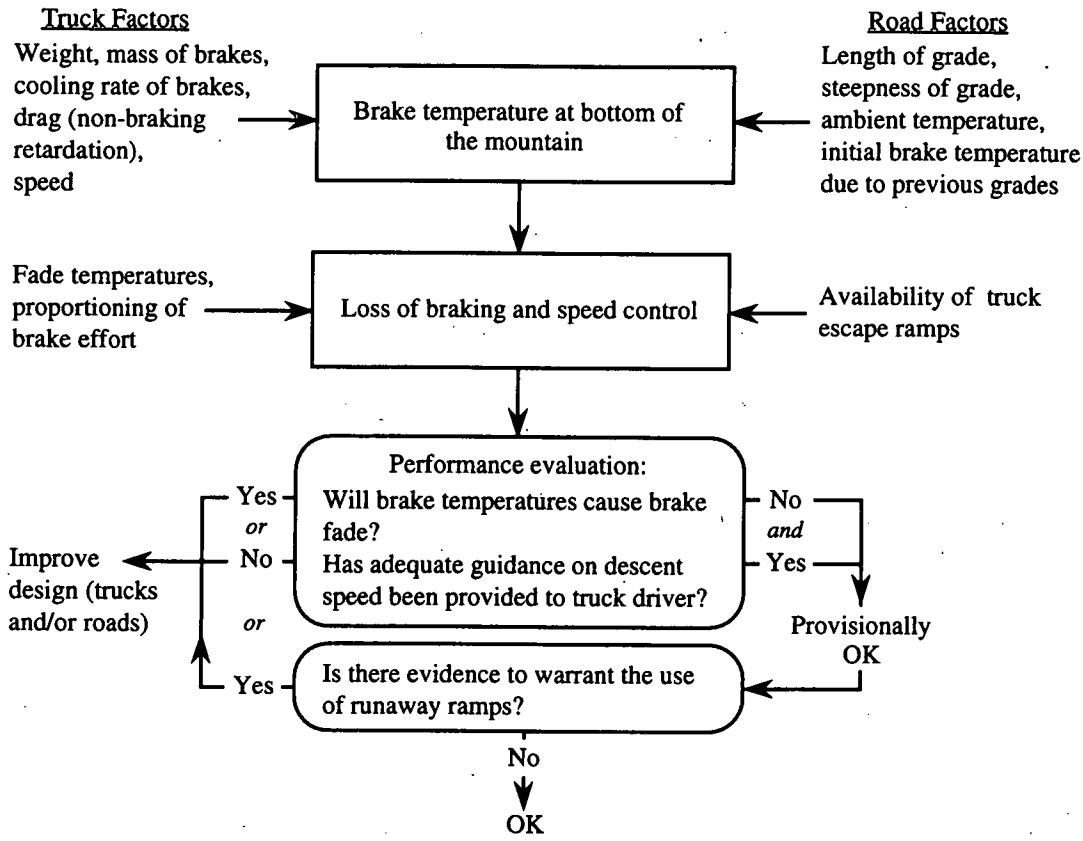


FIGURE 18 Mountain descent performance evaluation.

Vehicle and Highway Design Characteristics Influencing Brake Temperatures in Mountain Descents

The truck factors influencing downhill descent have to do with thermodynamic relationships that determine brake temperatures. As indicated in Figure 18, the primary vehicle factors determining brake temperatures are the weight of the truck, the masses of the brake drums, the cooling coefficients of the brakes, and the proportioning of braking effort between the brakes. If some wheels do not have brakes or have nonfunctional brakes, the brake temperatures on the remaining wheels will be adversely affected. One of the reasons trucks have more difficulty than cars with runaway on mountain grades is that the ratio of thermal capacity (brake mass) to total vehicle weight is much less for trucks than for cars. Another reason is the greater difficulty in specifying and maintaining braking balance between wheels for trucks than for passenger cars.

The details of the relationships between truck and road factors are presented in Table 15. Temperature gradients within the brakes are assumed to be unimportant. The equations are to be solved for the final temperature, T_f, at the bottom of the grade as a function of L, G, and V for various vehicles in various weight ranges. By examining these functions, the appropriate control speed, V_C, can be selected to limit the final temperature to a specified amount (260°C [500°F]) in the grade severity rating system.

The cooling coefficient is determined either from cooling tests or by extrapolation from one vehicle to another. The proportion, p, of the brakes usually requires experimental work to yield accurate values. Simple models for solving numerically for brake temperatures on specified terrain profiles are available (*38*).

CHAPTER SEVEN

OPERATING CHARACTERISTICS OF TRUCKS IN CRASH AVOIDANCE SITUATIONS

The following material addresses maneuvering situations involved with rollover, obstacle avoidance (rearward amplification), rear-end collisions, and run-off-road situations. These situations are related to crash avoidance capabilities and might be considered in initiatives to make truck-highway performance safer, whether or not the trucks are allowed to be bigger.

ROLLOVER

Chapter 5 gave an introduction to rollover in the section on turning on horizontal curves and ramps. The rollover threshold was identified as a design factor for exit ramps in which there was the risk that trucks with high center-of-gravity (cg) loads might be driven at a speed high enough to challenge the roll stability of the vehicle. The truck factors given in Figure 13 include cg height, track width, and suspension roll stiffness—all very important to the rollover resistance of a heavy truck. A matrix of truck, payload, and road characteristics influencing the static rollover threshold is presented in Figure 19. This figure summarizes the following discussion and supplements Figure 13.

Recently, procedures have been developed for screening and testing heavy vehicle combinations or the individual units making up these combinations to ensure that they will have rollover thresholds greater than 0.35 g's in a tilt table test (*36*). (The rollover threshold is the lateral acceleration, in g's, that will result in rolling over of the vehicle. Higher values are better in that they indicate the vehicle is more resistant to rollover.) The screening procedures are based on relatively simple calculations involving track widths, cg heights, and tire and suspension stiffness. The screening calculations are conservative in the sense that the vehicles may actually have rollover thresholds considerably greater than 0.35 g's, but seldom will the rollover threshold be 0.35 g's or less. If a vehicle does not pass the screening test, it can be placed on a tilt table and its rollover threshold measured directly using an SAE procedure (*53*). Measurement schemes applying to individual units of combination vehicles are presented in Winkler, Fancher et al. (*36*).

The rollover threshold of a heavy-truck combination is highly dependent on the nature of the load it is carrying. This is because the major component of the mass of a fully laden vehicle is the payload. Many fully laden tractor-semitrailer vehicles currently have rollover thresholds of less than 0.35 g's. In addition, vehicles with loads that can shift toward the outside of a turn may have lower rollover thresholds. Vehicles containing fluids in partially filled tanks or with hanging cargo are examples of loads that may shift laterally in a turn.

Although the procedures described above pertain to static rollover, the same factors are important in dynamic situations. The use of static rollover performance measures will go a long way toward improving rollover performance in general. Nevertheless, issues of dynamic rollover may be important for special vehicles such as those meant to operate at high speed both on- and off-road.

Canada (*54*) has chosen 0.4 g's as the goal for their heavy vehicles, but the work in the United States has been based on 0.35 g's. As the matter of roll stability is pursued further, one of the important issues will be to determine a level of rollover

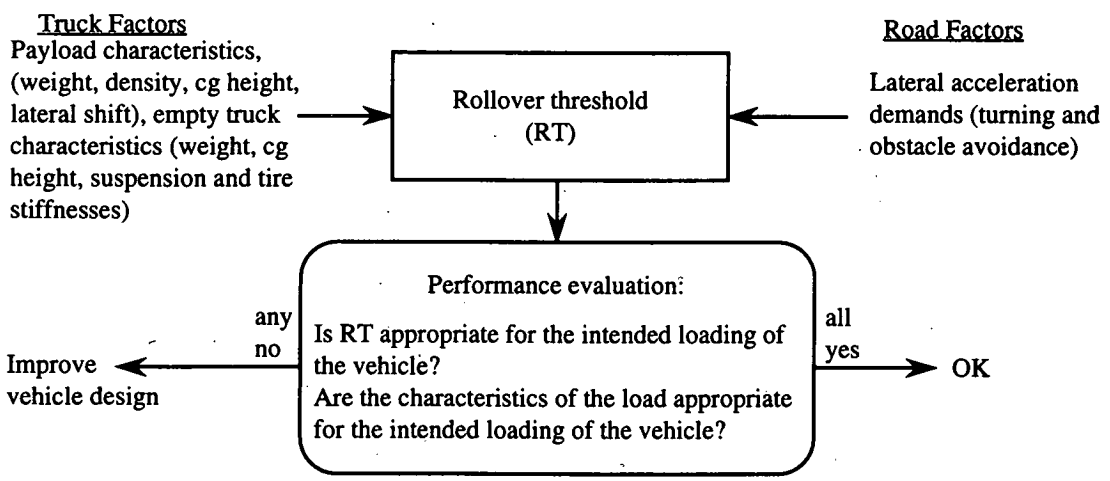


FIGURE 19 Rollover performance evaluation.

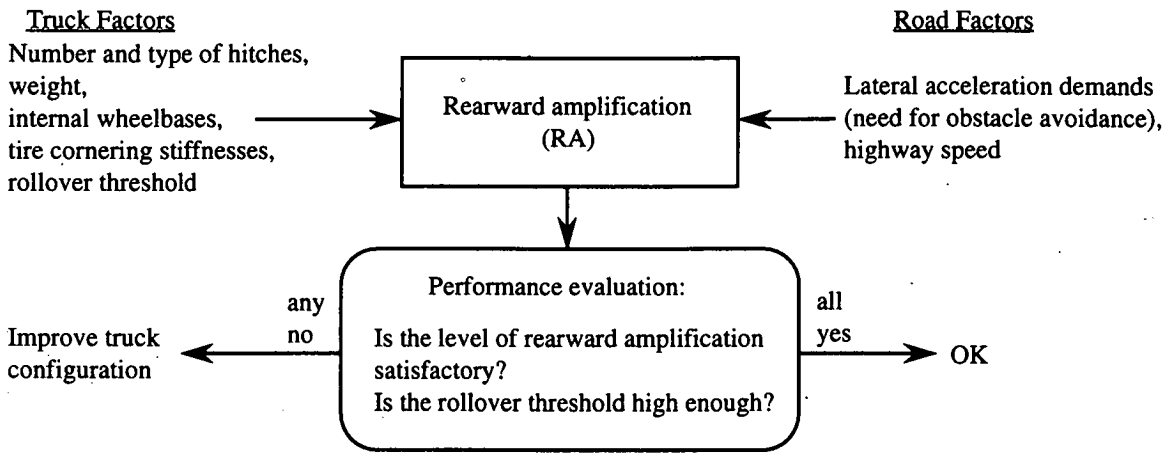


FIGURE 20 Obstacle avoidance performance evaluation.

threshold that is acceptable for the transportation of goods and equipment by heavy trucks.

OBSTACLE AVOIDANCE (REARWARD AMPLIFICATION)

Rearward amplification refers to the tendency of the last unit in a multi-articulated vehicle to experience a greater lateral motion than that experienced by the leading unit in an obstacle avoidance maneuver (*55*). The driver may be able to steer the tractor through a tight spot, but if the maneuver is quick enough the rear trailer may swing well off the path of the tractor, with potentially serious consequences. In addition, if the rear trailer has a low rollover threshold, it may roll over even though the leading truck or tractor-semitrailer does not.

A number of research studies have examined the truck characteristics that contribute to high levels of rearward amplification (*36, 42, 56, 57*). The important vehicle characteristics are the number of articulation points, the lengths of the wheelbases between axle sets, the ratio of tire cornering stiffness to the vertical load carried on the wheel, and the rollover threshold.

Figure 20 presents an evaluation of obstacle avoidance performance on the basis of rearward amplification. As with rollover, there are both screening and testing procedures for assessing the level of rearward amplification (*36*). The screening procedures are based on the operating speeds and acceptable ranges of internal wheelbases within common configurations for multi-articulated trucks that ensure that rearward amplification values will be less than 2.0. (That is, the ratio of the lateral acceleration of the last trailer to that of the tractor in a prescribed obstacle avoidance maneuver does not exceed 2.0.) The reasons for this requirement are (1) units with long wheelbases (longer than those associated with the STAA double) tend to have low rearward amplification so that long trailers do not have a problem with rearward amplification, and (2) the typical STAA Western double with 8.5-m (28-ft) trailers, when loaded to 36 000 kg (80,000 lb), has a rearward amplification of 2.0 (*36*).

The screening procedures are based on analyses whose validity is supported by extensive, but not comprehensive, experimental results. With regard to testing, there are SAE procedures (*55*) for measuring rearward amplification. In these procedures the vehicle is driven over a defined course at a speed of 90 km/hr (55 mph), and accelerometers are used to record lateral accelerations at the front and rear units of the vehicle. The test quantifies rearward amplification in a manner that is suitable for evaluating vehicle performance in a maneuver requiring a sudden lateral shift to avoid an obstacle.

In the sense that the STAA Western double has a rearward amplification of 2.0, as noted above, it is a de facto reference point used in evaluations. There are limited accident data (*17*) indicating that vehicles with trailers shorter than the STAA double tend to be more associated with obstacle-avoidance types of accidents than is the STAA double. If the matter of constraining rearward amplification is to be pursued further, either privately or publicly, a policy needs to be developed as to an acceptable level of rearward amplification. By chance, rather than by design, the current STAA Western double turns out to have a rearward amplification of 2.0. Perhaps this is satisfactory for good drivers who are familiar with the vehicle. It is what is accepted today. However, it is certainly not easy to find convincing evidence for deciding where to draw the line between satisfactory and unsatisfactory performance.

REAR-END COLLISIONS

Rear-end collisions are among the most common types of accidents (*58*). They often seem to be associated with situations in which it appears that the driver had adequate time and distance to avoid the crash. Nevertheless, a countermeasure available to avoid these crashes is the braking capability of the vehicle.

The braking performance of heavy trucks has been studied experimentally by NHTSA (*59*). Their results generally indicate that heavy trucks need approximately 91 m (300 ft) to stop from 100 km/hr (60 mph) on dry road surfaces, once the brakes have been applied. In the case of fully laden vehicles, the deceleration capability (approximately 0.45 g's) is often determined by the brake force limits of the vehicle braking system.

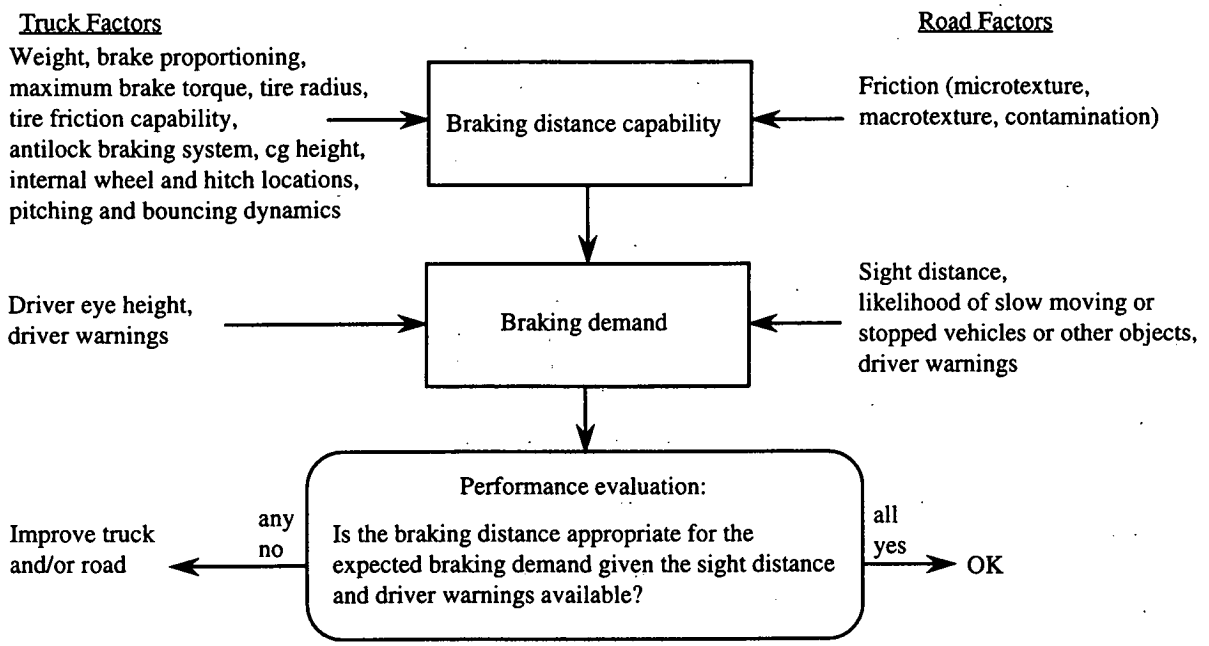


FIGURE 21 Rear-end collision performance evaluation.

With the brakes reasonably proportioned from axle to axle, the tire-road friction demand is not so high that wheel lockup is likely on dry roads. If the brakes are proportioned so that some brakes do more than their appropriate share of the braking, those wheels may lock up. However, on wet roads with friction levels around 0.3, lockup is possible (in the absence of antilock braking systems) and this may lead to poor lateral control or instability. Recent studies (*28,4*) have observed that antilock braking systems on trucks would reduce the need for extremely long stopping sight distances to accommodate trucks. In any event, measures of braking capability could be used to evaluate vehicle performance in situations that are representative of those associated with limited sight distance to obstructions in the road.

Figure 21 attempts to capture the truck and road factors that influence braking performance. The road factors tend to be those that have a bearing on the need for stopping, and the time and distance available for stopping while the truck factors are related to braking performance. Driver alertness has an important influence on whether braking is initiated soon enough so that emergency levels of braking are not required. Increased efforts to warn or alert drivers to the potential need for braking might be effective in preventing some rear-end crashes. At this time the relationship between braking performance capability and the frequency of rear-end collisions is not known. In part, this is due to the difficulty in quantifying driver behavior, particularly risk-taking when traveling in dense traffic.

Nevertheless, braking standards have been adopted in the United States to ensure adequate braking (MVSS 208 for cars and 121 for trucks (*27*)). These standards serve appropriately for establishing a baseline of braking capability for drivers to work with. However, as indicated in Figure 21, the ultimate question is whether the braking capability is commensurate with the braking demand at various highway locations. Consideration of stopping sight distance by highway designers (*2*) is an example of a technique for providing sufficient warning so that the demand for braking should not exceed the available braking capability.

RUN-OFF-ROAD SITUATIONS

Most single-vehicle accidents involve running off the road. For truck drivers this has been a particularly dangerous type of accident if rollover then occurs and the driver is not belted (*60*). Depending on the local roadside environment (for example, the presence or absence of many trees), the most serious consequences of running off the road are either hitting a fixed object or rolling over.

A truck is not likely to run off the road if the driver is steering properly. In some cases, tire failure may cause directional control problems. In poor weather, the driver could be going too fast for the tire-road friction or the available sight distance. There are, however, loading arrangements, typically involving rear-biased loads, that can make trucks directionally unstable at high speeds. It is possible that such instability could contribute to the vehicle rolling over or leaving the road. Even so, for properly maintained and loaded trucks, directional control and stability are not usually problems for vehicles driven at prudent speeds on good roads.

Figure 22 presents these ideas in the form of inputs to a performance evaluation scheme for assessing the consequences of run-off-road events.

The highway community is concerned about the design of horizontal curves. Consequently, conservative values of side friction and superelevation are chosen for the design speed of the road and the radius of curvature desired. Only in very poor

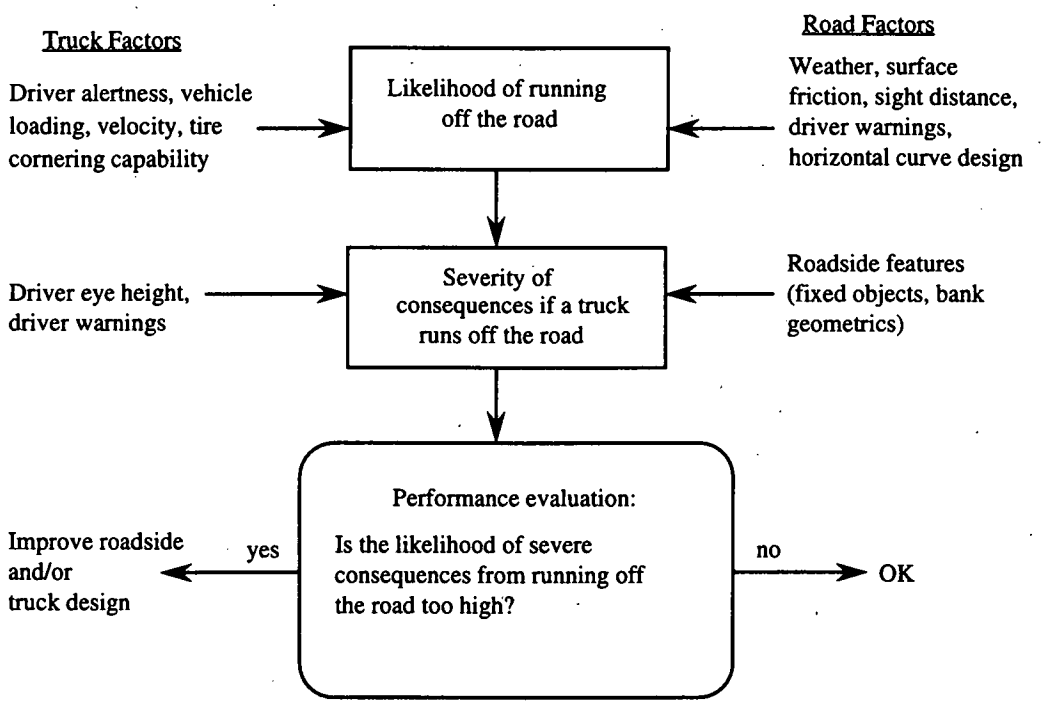


FIGURE 22 Run-off-road performance evaluation.

weather will the demand for lateral force at the tire-road interface be too large, and then only if the speed is too high for the conditions.

Truck users are also sensitive to directional instability and control problems. In rare circumstances, drivers may have to operate potentially unstable configurations, but they usually find that by operating at a low enough speed the truck will be stable and controllable. Given these considerations, the likelihood of running off the road may be associated with poor weather, lack of driver alertness, or other factors.

To mitigate the consequences of running off the road, driver restraints and cab structural and crush properties are important, as well as maintaining a clear zone for the truck to stop gradually without rolling over. The availability and use of seat belts for truck drivers have increased dramatically in recent years (*60*). The recognized need for clear zones was emphasized at the highway vehicle meeting in San Antonio (*7*). If these efforts succeed, one would expect to see a reduction in the severity of the consequences of truck run-off-road events in the future.

CHAPTER EIGHT

PAVEMENT AND BRIDGE LOADING

PAVEMENT LOADING FACTORS

Highways and bridges are designed with the goal of providing service for a minimum defined life period. The way in which a truck loads a pavement will have a direct effect on the life of the highway structure. Wheel loads create stresses that cause fatigue of both rigid (portland cement concrete, or PCC) and flexible (asphalt) pavements. The cumulative effects of fatigue may eventually cause the pavement structure to crack, thus reducing the serviceability of the pavement. On flexible pavements, the wheel loads may also cause rutting in the wheel tracks, which is another form of wear. (In the highway community the cumulative fatigue and rutting are often referred to as "damage.") Similarly, heavy trucks also cause stresses to bridge structures, with high, concentrated loads being more stressful.

To place some control over pavement and bridge stresses, road use laws directly address allowable loading patterns. The trucks in common use reflect configurations that serve their mission within the constraints of road use laws. Current federal limits on truck weight, length, and width are defined by the Surface Transportation Assistance Act (STAA) of 1982 (*61*). These limits apply to all vehicles using the Interstate system and other designated federal-aid highways. The weight limits are nominally defined as

- 9000 kg (20,000 lb) on a single axle
- 15 000 kg (34,000 lb) on a tandem axle group
- 36 000 kg (80,000 lb) maximum gross weight (with a few exceptions)
- Those required to be in compliance with the federal bridge formula (Bridge Formula B).

In addition, some states impose separate constraints on the maximum load that can be carried by truck tires, where those constraints limit the weight that can be carried in accordance with the rated width. Specifically, the limits among the states based on the nominal tire tread width range from 100 to 140 kg/cm (550 to 800 lb/in.) of load.

The actual extent to which a truck contributes to wearing out a pavement depends on many factors, as shown in Figure 23. Ultimately, the magnitude of the wear is dependent on pavement characteristics, including material (asphalt or portland cement concrete), layer thicknesses, and substructure.

An analysis of truck-road load interactions was recently re-

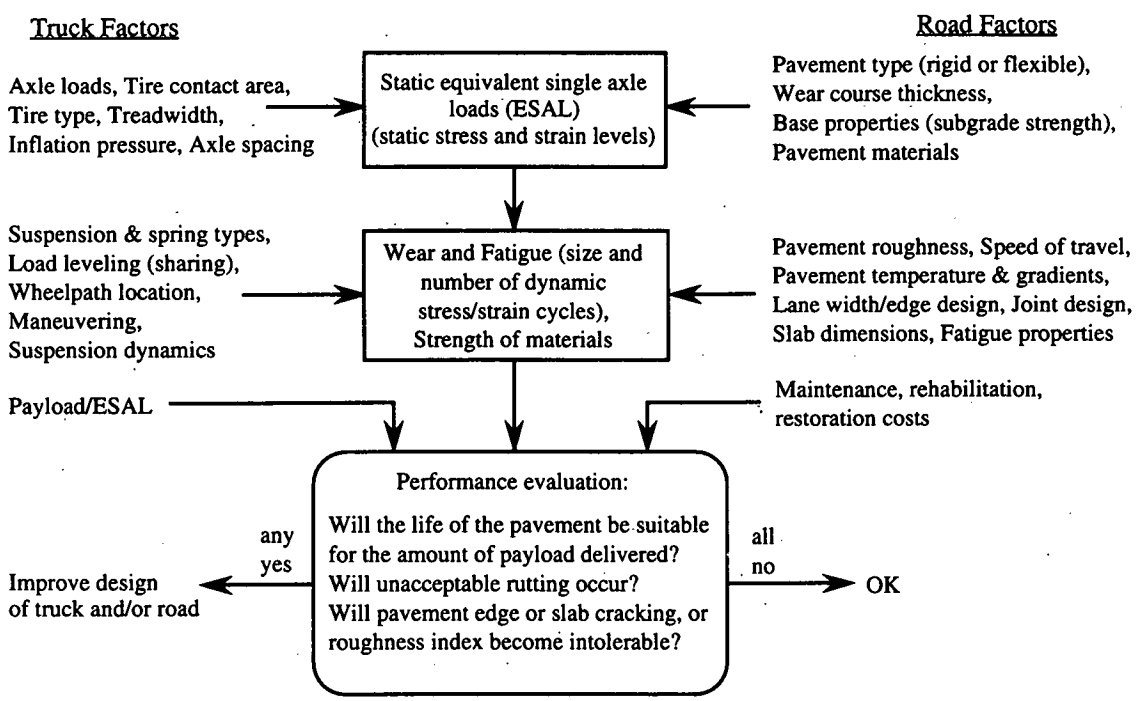
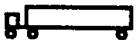
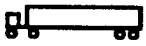
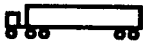
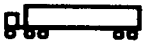
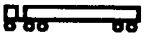
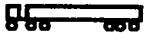
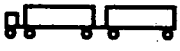


FIGURE 23 Pavement loading performance evaluation.

TABLE 16
TRUCK MATRIX OF SIZES AND WEIGHTS

Truck Num.	Truck Configuration	Configuration Name	GCW m tons (kips0	Axle Loads m tons (kips)	Wheelbases* m (ft)
1-2		2-Axle Straight Truck	15 (32)	5.5/9 (12/20)	4.5 (15)
3-4		3-Axle Straight Truck	21 (46)	5.5/16 (12/34)	5.5 (18)
5-8		3-Axle Refuse Hauler	30 (64)	9/20 (20/44)	5.3 (17.5)
9-12		4-Axle Concrete Mixer	31 (68)	8/18/5.5 (18/38/12)	6.1/3.7 (20/12)
13		3-Axle Tractor-Semitrailer	24 (52)	5.5/9/9 (12/20/20)	3/11 (10/36)
14-15		4-Axle Tractor-Semitrailer	30 (66)	5.5/9/16 (12/20/34)	3.7/11 (12/36)
16-20		5-Axle Tractor-Semitrailer	36 (80)	5.5/16/16 (12/34/34)	3.7/11 (12/36)
21		5-Axle Tractor-Semitrailer	36 (80)	6/15/15 14/33/33	3/11 (10/36)
22		5-Axle Tanker	36 (80)	5.5/16/16 (12/34/34)	3.7/11 (12/36)
23-24		6-Axle Tanker	38 (85)	5.5/16/18 (12/34/39)	3.7/12 (12/38)
25		5-Axle Doubles	36 (80)	4.5/8/8/8/8 (10/18/17/18/17)	3/7/7 (10/22/22)
26		5-Axle Doubles	36 (80)	4.5/9/7/9/7 (10/20/15/20/15)	3/7/7 (10/22/22)
27		7-Axle Doubles	54 (120)	5.5/16/16/9/9 (12/34/34/32/32)	3.7/12/7 (12/38/22)
28		9-Axle Doubles	63 (140)	5.5/15/15/15/15 (12/32/32/32/32)	3.7/12/12 (12/38/38)
29		Turner Doubles	52 (114)	4.5/12/12/12/12 (14/26/26/26/26)	3.7/7/7 (12/22/22)

* Wheelbases to tandem centers. Tandem spreads set at 132 cm (52 in.).
Source: NCHRP Report 353 (*5*)

ported in NCHRP Report 353 (*5*). The results are based on analyses of typical truck configurations, either in common use or contemplated as a future standard. A baseline matrix of 15 truck configurations, representing the primary size and weight variables, was developed. These form the basis for a matrix of 29 truck configurations when variations in suspensions and tires are taken into account.

The matrix of trucks is shown in Table 16 (*5*). The progression in size generally follows the pattern from top to bottom in the table. Each truck is of the largest gross vehicle weight permitted for a given configuration and number of axles. Of the many available tire and suspension options for each of the vehicles in the matrix, the tire and suspension types most commonly selected were used in these analyses.

Straight trucks (numbers 1-12 in the table) represent approximately 70 percent of the registered trucks in the United States (excluding light trucks) and account for about 30 percent of the truck mileage on the highways (*62*). Most frequently, these vehicles have two or three axles, with four axles used in heavier applications such as concrete mixers.

Tractor-semitrailers (numbers 13-24 in the table) represent about 30 percent of the registered heavy vehicles in the United States and are responsible for most of the remaining 70 percent of the heavy-truck highway mileage (*62*). The variations among these heavy trucks of most significance here are the number of axles and the axle loads.

Three bulk-haul tankers are included in the matrix (numbers 22, 23, and 24). The 5-axle tanker is commonly seen through-

out the nation and has little variation in tires and suspensions. Advanced designs for greater safety and productivity feature tridem trailer suspensions with dual tires or wide-base single tires.

Combinations of doubles vary from 17 to 30+ m (55 to 100+ ft) in length. The most common combinations are included in the matrix (numbers 25-29). In the case of the short doubles, two possibilities are examined: the most favorable (uniform) load distribution among the rear axles (25) and the most unfavorable (two axles loaded to maximum) (26). The doubles with tandem suspensions are not limited to 36 000 kg (80,000 lb) gross weight, but they are included to represent likely operating limits where they are allowed. The Turner truck, at the end of the table, represents a very heavy truck designed to minimize pavement damage.

PAVEMENT FATIGUE AND RUTTING

Until empirical results from long-term pavement performance experiments (such as the Strategic Highway Research Program) relate traffic exposure to pavement deterioration, the understanding of pavement wear caused by fatigue and rutting will depend on analytical results such as those obtained in NCHRP 353 (*5*).

Pavement design and wear and damage estimates are commonly based on the concept of the equivalent single axle load (ESAL). An ESAL is a single axle loaded to 8000 kg (18,000 lb). Tandem axles and triaxles carrying various loads and single axles carrying other loads all have assigned ESALs. For example, a tandem axle carrying 15 000 kg (34,000 lb) is considered to be equivalent to 1.1 ESALs on flexible pavements and to about 2.0 ESALs on rigid pavements, as far as pavement life is concerned (*13*).

Figure 24 has been constructed, using results from NCHRP 353 (*5*), to illustrate the productivity achieved for a given amount of rigid pavement fatigue, measured in accordance with the ESAL concept, for various vehicle types. Productivity, in this instance, is defined as payload, and it relates only to the maximum gross potential associated with optimum loading conditions with heavier cargo. Clearly, the most productivity per ESAL is achieved by the Turner truck, with a score of about 23 000 kg (50,000 lb) of payload per ESAL of pavement loading exposure. The refuse hauler, in contrast, achieves only about one-tenth the productivity of the Turner truck. In terms of the amount of payload delivered per ESAL of exposure, the heavier vehicles with multiple axles tend to have a significant advantage over the lighter vehicles with few axles.

As was the case for rigid pavements, the pavement related productivity per ESAL on flexible pavements (see Figure 25) tends to favor the heavier vehicles with many axles. But, the differences between vehicles are not as large because flexible pavements do not benefit as much as rigid pavements from tandem and tridem suspensions. As seen from these figures, gross vehicle weight is not systematically related to fatigue of flexible or rigid pavements. Only to the extent that vehicles

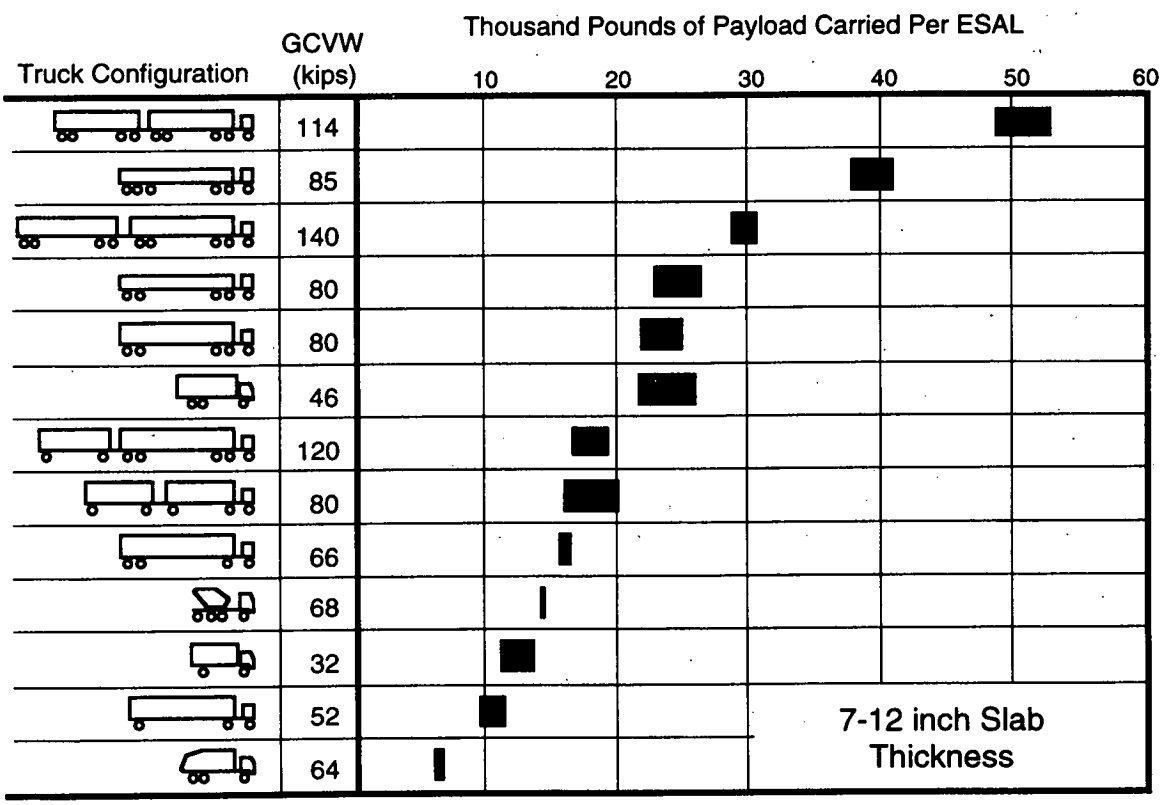


FIGURE 24 Payload carried per ESAL of rigid pavement fatigue (*5*).

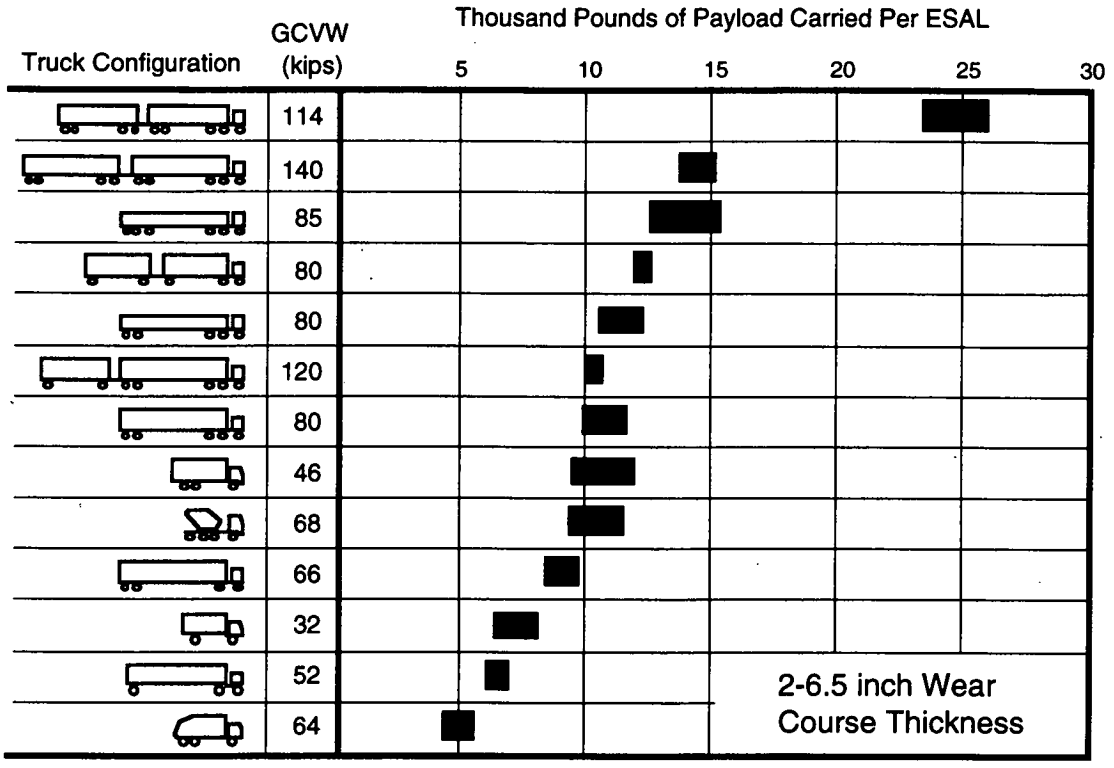


FIGURE 25 Payload carried per ESAL of flexible pavement fatigue (*5*).

with high gross weight may have higher individual axle loads is there an effect.

Gross weight is, however, believed to be the main determinant of the rutting resulting from a vehicle. The results, presented in NCHRP 353 (*5*), suggest that the total vehicle weight largely determines the rutting produced. As the permanent vertical deformation under one axle is not affected by other nearby axles, the rut depth caused by a truck is simply the sum of the rutting caused by each of its axles. Although gross weight is the first-order determinant of rutting, exact proportionality is not obtained because of differences in rutting among the mix of tires used on the vehicles. Figure 26 shows the relative effects on rutting for various vehicle types.

The analysis in NCHRP 353 concludes that the gross weight of a truck is a dominant factor affecting rutting under the assumption that rutting arises from viscoelastic behavior of the pavement material, which leads to plastic deformation. This approach has a major shortcoming, because it leads to the inappropriate conclusion that rutting can be reduced by limiting the gross weight of trucks. From a rutting standpoint, a given amount of cargo should be moved on a minimum number of trucks, to reduce the rutting caused by the tare weight of the additional trucks that otherwise would be needed.

SUMMARY OF FACTORS AFFECTING PAVEMENT LIFE

Drawing from NCHRP Report 353 (*5*), the following statements summarize the specific loading characteristics of vehicles that affect pavement life:

- The statically quantified axle load applied to the pavement is currently the single vehicle factor that has the greatest effect on fatigue of both rigid and flexible pavements.
- Vehicle gross weight is believed to have a direct influence on flexible pavement rutting, because rutting is assumed to be linearly related to weight. However, fatigue is not systematically related to gross weight but varies in accordance with the maximum axle loads on each vehicle combination.
- Axle spacing has a moderate effect on rigid pavement fatigue, particularly as related to the close spacing of the axles within axle groups. Generally speaking, however, axle spacing has little effect on flexible pavement fatigue for the range of pavement thicknesses considered. Surface rutting is also unaffected by axle spacing.
- Static load sharing within a multiple axle group moderately influences fatigue of rigid and flexible pavements as a result of the higher load on one axle when sharing is not equal. Static load sharing has no apparent influence on rutting by virtue of the assumed linear relationship between rutting and axle load.

The loads and load-distribution factors discussed above have been evaluated under the equivalent of static load conditions. The *dynamic component of axle loads* elevates the stresses experienced by a pavement above what are induced by static axle loads. The mean level of fatigue along a pavement is commonly as much as 30 percent higher or lower at specific locations as a result of dynamics, and in the most severely loaded

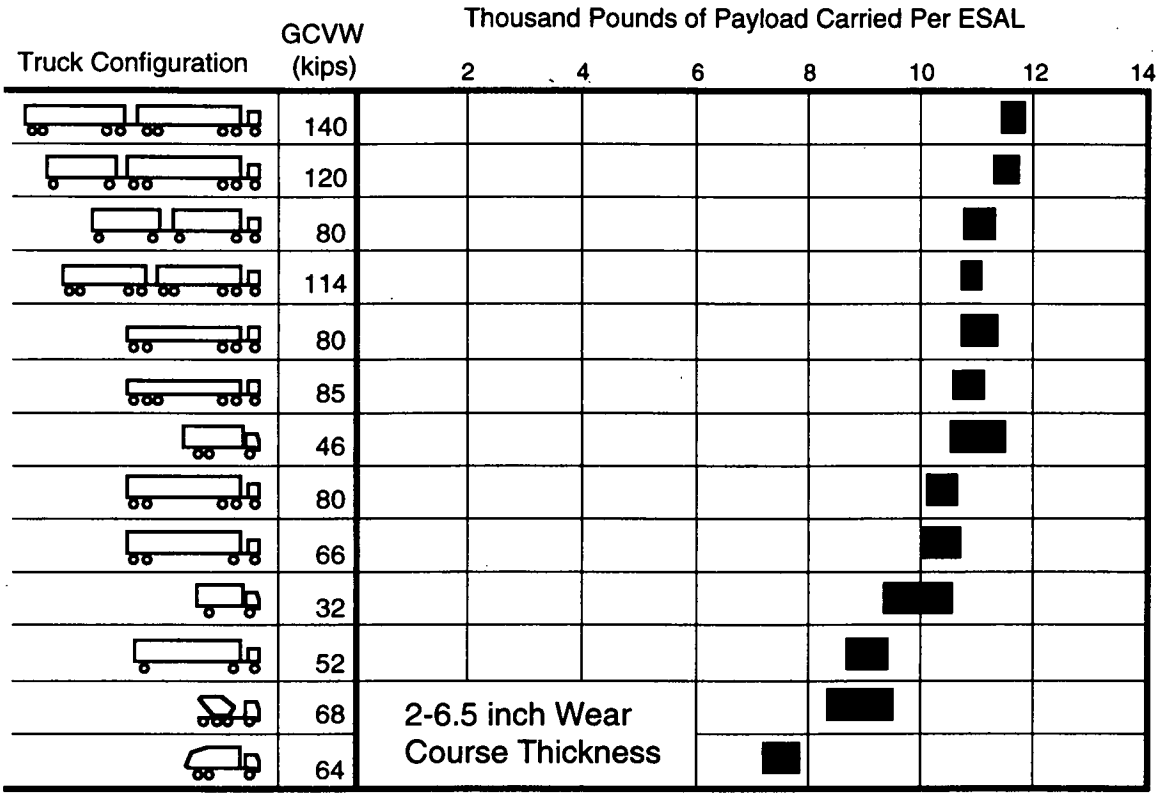


FIGURE 26 Payload carried per ESAL of rut depth (*5*).

pavement sections it may be up to 300 percent higher. The dynamic effects are directly related to vehicle speed, road roughness, tire type, and truck suspension type.

Vehicle speed influences rigid pavement fatigue by increasing peak dynamic wheel loads. Compared to the static case, the pavement fatigue imposed at normal road speeds is 50 to 100 percent greater on a moderately rough road. Fatigue of flexible pavements is affected by speed through its influence on both the magnitude and duration of loading. The increase in dynamic loads with speed is compensated for by the shorter duration of an applied axle load at increased speed. Thus, flexible pavement fatigue remains fairly constant with speed in most cases.

Rutting is diminished at higher speeds by the decreased loading time, and there is little additional increase in the average rut depth along a road arising from dynamic truck behavior.

Drawing further from NCHRP Report 353 (*5*), the following statements summarize other characteristics of vehicles and pavements that affect pavement life:

- Single axle suspension type (air- and leaf-spring) has only a moderate effect on rigid or flexible pavement fatigue.
- Tandem/multiple axle dynamics have a much greater influence on fatigue of rigid and flexible pavements. Fatigue levels may vary by 25 to 50 percent between the best (air-spring) and worst (walking-beam) suspensions. Suspension type has little influence on flexible pavement rutting.
- Maneuvering of trucks can also lead to increased pavement fatigue by temporarily shifting load among axles. During acceleration the load shift onto rear axles is small enough that the direct influence on pavement fatigue is generally insignificant. Similarly, load transfer onto front axles during braking is unlikely to affect rigid pavement fatigue, but localized effects could increase by as much as 100 to 1,000 percent on flexible pavements, depending on the severity of braking. Rutting is not directly affected by the transfer of load between axles during acceleration or deceleration. It should be noted, however, that low speeds or stopping after braking strongly increases the localized rutting, because the truck loads are applied for longer times. Cornering increases pavement fatigue and rutting by shifting the load to one side of a vehicle. Wheel loads on one side of the truck might typically increase by 20 percent, causing a 100 percent increase in fatigue and a 20 percent increase in rutting.
- Lateral variation in wheel path location of trucks, called "wander," may increase wear in some cases and decrease it in others. To the extent that wheel path location varies, the wear is spread over a broader area and accumulation of damage to the point of failure will take longer.
- Variations in tire contact patch size are responsible for the wide variation in the pavement response arising from single, dual, and wide-base tires. Flexible pavement fa-

tigue is highly sensitive to variations in size of the tire contact patch. Single tire loads are so concentrated relative to duals that an axle loaded to 5400 kgs (12,000 lbs) with single tires (typical of a steer axle) will often cause more flexible pavement fatigue than an axle with dual tires loaded to 9000 kgs (20,000 lbs). Rigid pavement fatigue is not as sensitive to tire contact conditions. Rutting is dependent on load and contact area. For a given load, rut *depth* is deeper when it is carried on single tires, although the rut *volume* differs little between single and dual tires.

- Variations in tire inflation pressure affect pavement wear by changing the contact patch size and tire vertical stiffness. The decrease in contact area at high inflation pressures has only a moderate impact on rigid pavement fatigue, but flexible pavement fatigue is strongly affected by these changes and can increase by more than 50 percent with a 10 percent increase in pressure. Rutting increases only slightly with inflation pressure.
- Tire ply type (radial vs. bias) has minimal direct impact on the fatigue of both rigid and flexible pavements. However, trucks with radial-ply tires will tend to track more precisely and the low camber stiffness makes it easier for radial tires to track in existing pavement ruts, whereas trucks with bias-ply tires will tend to climb out of ruts. Thus, radial-ply tires cause more severe rutting than bias-ply tires.
- Roughness excites dynamic behavior of trucks, increasing dynamic loads. The level of roughness on even the smoothest roads increases fatigue by approximately 50 percent over that predicted by corresponding static axle loads. On the roughest roads, fatigue may increase by 200 to 400 percent, depending on the type of road and the truck properties.
- Pavement temperature has a very strong influence on flexible pavement fatigue and rutting, although it is the *temperature gradient* that is most significant to rigid pavements. Rutting of flexible pavements may increase by a factor of 16 or more with a surface temperature change from 25°C to 49°C (77°F to 120°F). Temperature gradients in rigid pavements add curling stresses in the slabs which, for even reasonably modest temperature gradients, can increase by a factor of 10 the fatigue caused by a truck.
- Finally, the pavement layer thicknesses and subgrade strengths have a very strong influence on fatigue and rutting. Overall, typical variations in the thickness of a pavement may affect its damage sensitivity by a factor of 20. Pavement layer thickness is the only factor comparable to axle load in the magnitude of its influence on fatigue.

The summary statements above do not reflect a functional relationship between a given factor and pavement wear, nor do they attempt to identify all interactions among factors. The relative level of wear associated with each variable may change if the nominal level of another variable is altered.

APPLICATION OF FINDINGS TO PAVEMENT DESIGN

While the specific rules for ensuring truck compatibility with road and bridge design are generally incorporated in road use laws, further refinements in the design and use of roads and trucks can reduce the wear of the highway infrastructure.

Rigid Pavement Design

Truck wheel loads on the ends and edges of rigid pavement slabs result in stresses that are up to 75 percent greater than would occur when the truck wheels are in the center of the slab. The region of sensitivity generally extends 0.6 to 1.8 m (2 to 6 ft) from the edges. Pavement design standards should take this variable into consideration.

Lane Width/Edge Treatment: On lanes of 3- to 3.6-m (10- to 12-ft) width, truck wheels will encroach onto the sensitive regions. Longer combination vehicles may be expected to increase exposure of the edges to truck wheel loads due to their potential for greater offtracking at low speed. This effect may be mitigated by use of higher-strength or thicker pavements for narrow lane widths. A common design treatment is to extend the full depth pavement 0.6 to 0.9 m (2 to 3 ft) or more into the shoulder area. Tying the slab to a supplemental concrete shoulder is another way to enhance design in this area.

Joint Design: Stresses near a joint (or joint crack) in a PCC pavement are greater than those in the interior region. Within the area about 1.5 to 1.8 m (5 to 6 ft) longitudinally from the joint, fatigue is elevated by 10 to 25 percent above that at the middle of the slab. To achieve better consistency of strength and durability throughout the pavement, design changes to ameliorate these conditions should be considered. Selectively increasing the slab thickness near the joints would result in a tapered slab design with better durability at the joints, but might prove impractical for other reasons (higher construction costs, greater propensity for mid-slab cracking, etc.). Additional reinforcing steel will not solve this problem (although the additional steel may help to maintain slab integrity once cracks occur).

Slab Length: Variations in the design length of the slab do not offer direct means to alleviate the high-stress end conditions. Slabs shorter than 6 m (20 ft) generally result in elevated stress throughout the mid-slab region because the end effects extend into the mid-slab region. For slabs 9 m (30 ft) or longer, the mid-slab region is free of elevated stress arising from end effects, but it is more prone to mid-slab cracking due to shrinkage and moisture effects. The more significant interaction of slab length comes from the potential influence on truck dynamics. The characteristic shapes of slab curl due to thermal and moisture gradients can tune to the resonances of trucks, elevating dynamic loads. The incremental increase in fatigue from these mechanisms is likely to reach magnitudes of 50 to 100 percent.

Pavement Thickness: The flexural stresses caused by truck wheels diminish with an increase in the modulus of rupture of the concrete, and even more rapidly with an increase in the thickness of rigid pavement slabs. On roads where high axle loads are anticipated, increased thickness is the single most significant means to achieve better pavement performance; fatigue levels vary by a factor of 20 from thin to thick pavements. To a lesser extent, the highway engineer can minimize road wear by maintaining roads in a smooth condition, as the wear increases by a factor of 3 on rough roads.

Flexible Pavement Design

The major issue in flexible pavement performance today is rutting. Rutting is the result of compaction and plastic flow of one or more layers of the pavement. There is no evidence to suggest that control over truck characteristics (such as gross weight, wheel load, or tire pressure) will yield any significant change in rutting experience. Consequently, the rutting problem can only be alleviated by developing asphalt mixes that are more resistant to rutting. Further, compaction of the lower layers is mitigated to a certain extent by thicker overlying layers.

Fatigue of flexible pavements is determined primarily by individual axle loads. Therefore, current design methods based on axle load are appropriate, although they do not directly take into account the dynamic loads. The highway engineer has means to influence and control dynamic loads by specifying acceptance criteria for roughness in new construction, and the road roughness level at which maintenance is warranted on existing pavements.

It may be reasonable to expect that flexible pavements experience elevated strains much the same way as rigid pavements when truck wheels operate near the pavement edges. The primary difference is that the region of sensitivity is smaller for flexible pavements. Design features that provide edge support will add to the durability of flexible pavements under heavy truck loads.

FEDERAL AND STATE REGULATIONS ON PAVEMENT WEAR AND DAMAGE

The basis for road use laws defining dimensional and weight limitations on trucks operating on the highway network is established by federal law for the designated highway systems (i.e., National Highway System, etc.), while the individual states have more discretion concerning most other roads. Judicious modifications to those laws could reduce the wear of the highway system caused by trucks while enhancing transport productivity.

Steering-Axle Loads

The following statements apply only to front steering axles:

- By necessity, the front (steer) axles on trucks use single tire configurations. Although loads to 9000 kg (20,000 lb) are permissible, most trucks operate at about 5400 kg (12,000 lb). Tires rated to accept this load create high stresses in pavement structures. Trucks so loaded and equipped cause potentially more fatigue wear of flexible pavements than a 9000 kg (20,000 lb) load on an axle with dual tires. To keep the wear within the same limits tolerated for the 9000 kg (20,000 lb) axle, steering axle loads with these tires would have to be reduced to the range of 4500 to 5000 kg (10,000 to 11,000 lb). This could be accomplished and road wear could be decreased approximately 10 percent by modifying road use laws to favor a load distribution of 4500 kg (10,000 lb) on the steering axle and increasing the allowance to 16 000 kg (35,000 lb) for tandems.
- Wide-base single tires are used on front steering axles that are required to carry more than 6400 kg (14,000 lb). Despite their larger size, these tires create high stresses in flexible pavements when operated at their rated loads. To keep wear to the same level as is currently tolerated with dual tires on 9000 kg (20,000 lb) axles, it would be necessary to limit loads to 6400 to 8000 kg (14,000 to 18,000 lb), depending on tire size.

Rear Axle Loads

Current road use laws tolerate up to 9000 kg (20,000 lb) on a single rear axle and up to 15 000 kg (34,000 lb) on a tandem axle. Although most trucks use a dual tire arrangement on such axles, wide-base singles are permitted. Many states attempt to control road wear by specifying the maximum load per nominal width of tire. The 9000 kg (20,000 lb) dual-tire axle corresponds to a load of approximately 112 kg/cm (625 lb/in.) of tread width. On wide-base singles, loads to 116 kg/cm (650 lb/in.) of tread width can be tolerated without increasing strains above that experienced with the 9000 kg (20,000 lb) axle with dual tires.

Truck Configurations

Recognizing that an essential function of the highway system is to provide routes of transport for the nation's industrial goods, the larger and heavier truck configurations appear most desirable. From the perspective of transport efficiency, large multi-unit combinations with low axle loads produce less road wear per ton-km (ton-mile) of transport. Among the vehicle configurations examined, the Turner truck and similar combinations are the most favorable.

Tire Pressures

There has been considerable concern that elevated tire pressures on heavy trucks may be contributing to road wear (*63*). Tire pressure has a small effect on fatigue of rigid pavements but a large effect on fatigue of flexible pavements. A 140-kPa (20-psi) increase in pressure can increase fatigue on flexible

pavements by 200 to 300 percent. Road use laws could be amended to limit tire inflation pressures on trucks.

Weight Enforcement

Truck weight enforcement is routinely implemented at roadside weigh scales with truck inspections by motor carrier enforcement officers. Practices are becoming more uniform, but they still vary among the various organizations performing the weighing. Load equality between tandem axles is essential to minimize road stress but is not usually monitored. Consideration should be given to developing an effective process for routine monitoring of tandem load distributions in weight enforcement activities to determine the significance of this factor as a cause of road wear.

Truck and Tire Design

Several aspects of truck and tire design can be identified as areas where improvements can be made to reduce road wear *(5)*:

- Designs that achieve no more than 5 percent load difference between axles, and that maintain good load sharing even when the frame is not level. It has been observed *(64)* that only minor variations in the truck frame pitch angle can disturb the equality of loads on some tandem suspensions.
- Use of air-spring suspensions in lieu of leaf-spring suspensions has the potential to reduce road wear by about 20 percent. Active suspensions could potentially yield another 20 percent improvement. The walking-beam tandem suspension generates high dynamic loads that can be readily reduced by installing shock absorbers between the axles and the truck frame.
- Development of trucks with improved ride. The use of air-spring suspensions is one of the most effective means to improve dynamic behavior and reduce road wear.
- Development of new truck tire profiles with greater tread width in order to bring tire loads down to 120 kg/cm (650 lb/in.) of tread width.

Trucking Operations

As a whole, truck operators have a vested interest in seeing that the highway network, which is the foundation for their livelihood, remains in good condition. "Good citizen" operators and their drivers can take a number of steps to minimize road wear, as follows *(5)*:

- Wherever possible, truck loads should be uniform among rear axles of comparable types. For example, on a 3-axle tractor-semitrailer, road wear is minimized by distributing the load in the trailer to achieve comparable loads on the tractor rear axle and the semitrailer axle.
- On truck combinations where the load is distributed between a single axle and a tandem set, the load should be positioned to keep the load on the single axle no higher than the load on each of the tandem axles.
- The load on the steering axle should be kept to the minimum possible with due consideration for safety and stability.
- Drivers and service personnel should avoid inflating tires beyond the cold pressure setting specified on the tire.
- Drivers should be trained and encouraged to drive in the center of the lane.
- Dual-tire axle configurations are generally preferable, for pavement preservation, to the use of wide-base singles on rear axles, although they recognizably add to tare weight, rolling resistance, and, ultimately, operating cost.
- Shock absorbers need to be maintained in proper working condition.
- If a walking-beam suspension is specified, shock absorbers on the axles should also be specified.

BRIDGE LOADING

Bridge design standards have been based for years on assumed loading from standard design vehicles (heavy trucks). Earlier design vehicles were a 14 000-kg (30,000-lb or 15-ton) single-unit truck with a wheelbase of 4.6 m (14 ft) and an 18 000 kg (40,000 lb or 20 ton) single unit truck with the same wheel base. In each case, 20 percent of the total load was assumed to be on the front axle. That is, the former had axle loads of 2700 kg (6,000 lb) and 11 000 kg (24,000 lb), and the latter had axle loads of 3600 kg (8,000 lb) and 14 500 kg (32,000 lb). Bridges designed on the basis of these vehicles are referred to as H-15 and H-20 bridges, respectively (because of the tonnage of the design vehicle).

In the 1940s, heavier tractor-semitrailers, more reflective of trucks then in use, were introduced as design vehicles. These were a combination vehicle with axle loads of 2700, 11 000, and 11 000 kg (6,000, 24,000, and 24,000 lb) and a combination vehicle with axle loads of 3600, 14 500, and 14 500 kg (8,000, 32,000, and 32,000 lb). The tractor wheelbase remained at 4.6 m (14 ft), but the overall wheelbase was allowed to be variable, up to 13.4 m (44 ft), with the worst case to be used in any specific design. Bridges based on these semitrailer design vehicles are referred to as HS-15 and HS-20 bridges, respectively. Because truck weights have increased further, some states now design for HS-25 loads, which are 25 percent greater than HS-20 loads *(13)*.

The most commonly used design vehicles for bridges currently are the HS-20, which is considered the minimum design on Interstate highways, and the H-15, which is often used for non-Interstate bridges.

The loading of a bridge, and the stressing of its structural members, depends on several truck factors. These are the total truck weight, the loading of the individual axles, and the spacing between axles. The principle, simply stated, is that for a given set of axle loads, the loading of the bridge is lessened if the axles are farther apart. To account for these

factors, highway engineers have developed "bridge formulas." The federal bridge formula developed in 1964, and approved by Congress in 1974, is called Bridge Formula B. It is intended to limit the overstressing of bridges to no more than 5 percent for HS-20 bridges and to no more than 30 percent for H-15 bridges.

Bridge Formula B is traditionally written, in customary U.S. units of measure as

$$W = 500\,[(L\,N / (N - 1)) + 12\,N + 36)]$$

where

W = Maximum weight that may be carried on two or more axles, in lbs,
L = Spacing, in feet, between the outer axles of any two or more consecutive axles, and
N = Number of axles being considered.

(When using the SI (International System of Units), the spacing in meters between axles should be multiplied by 3.3 to obtain L in feet, and the resulting maximum weight, W lbs, should be multiplied by 0.45 to obtain kgs.)

Bridge Formula B is to be applied to all of the sets of consecutive axles on the vehicle. For example, for a vehicle with three axles, the formula applies (with N = 2) to the first and second axles and to the second and third axles, and (with N = 3) to the set of all three axles. In practice, however, not all axle sets are examined in detail, as experience dictates which combinations are controlling. In general, closely spaced and heavily loaded axles are more damaging.

The formula indicates that the allowable bridge load can be increased by increasing either the number of axles, N, or the spacing between the outer axles of the group, L. Both approaches are used by truck designers. However, changing the trailing axle group of a tractor-semitrailer from a tandem to a tridem (changing N from 5 to 6) has only a modest effect. For instance, if L is 13 m (43 ft) from the front steering axle to the last trailer axle, adding a sixth axle adds only 2300 kg (5,000 lb) to the total allowable GCW. Furthermore, highway engineers are concerned that the added axles may not carry their fair share of the load, or may carry no load at all (especially if they are "liftable" axles), which violates the implicit assumptions in the Bridge Formula.

A more common approach in design of specialized trucks is to increase L. Consider, for example, a truck designed to carry very dense cargo, such as gravel. From the standpoint of the volume of cargo space required, a single-unit truck could be designed that could carry the maximum weight allowed of 36 000 kg (80,000 lb). However, the length, L, would be too small to satisfy the Bridge Formula. An alternative design, commonly seen, is to use a single unit truck to carry half the load and pull a full trailer carrying the other half. The length of the draw bar may be quite large to obtain an acceptable L. Similar designs are sometimes used with fuel tankers.

Since the adoption of Bridge Formula B some 20 years ago, various groups have been working to modify it. Trucks have

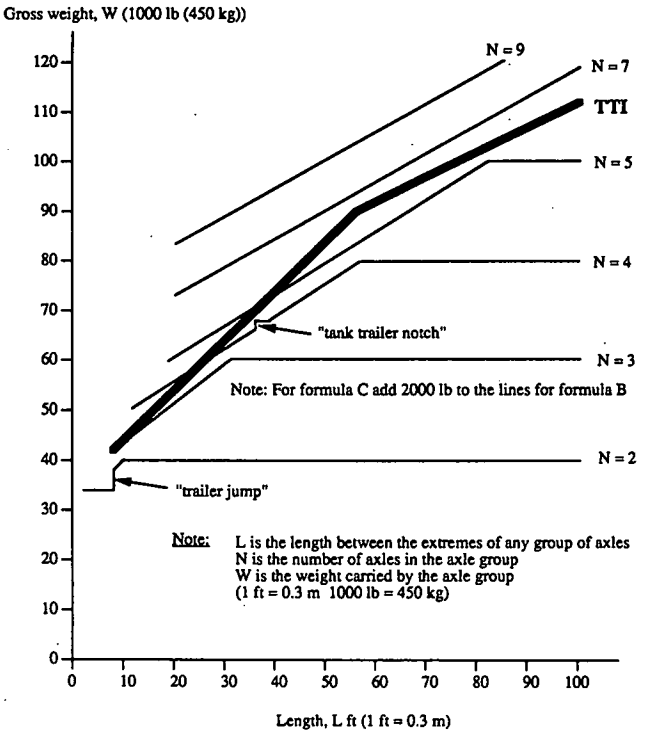


FIGURE 27 TTI HS-20 bridge formula versus Bridge Formula B (*45*).

become heavier. The Bridge Formula allows GCWs of more than 36 000 kg (80,000 lb) for long trucks, but pavement restrictions do not. Operators of heavy shorter trucks, such as concrete mixers and waste haulers, believe the formula is discriminatory. Concepts such as the Turner truck appear to be favorable to bridge loading, but they are not yet accepted.

In response to these types of pressures, the Texas Transportation Institute (TTI) conducted a study for the FHWA (*65*). The findings are summarized in the TRB Special Report 225 (*13*). A number of alternative formulas were proposed. One of these is referred to as the TTI HS-20 formula, which keeps the 5 percent overload criterion for HS-20 bridges but drops the 30 percent criterion for H-15 bridges. The TTI HS-30 formula is

$$W = 1{,}000\,(2\,L + 26) \text{ for } L < 24 \text{ ft, and}$$
$$W = 1{,}000\,(L/2 + 62) \text{ for } L \geq 24 \text{ ft,}$$

where W and L are defined as with Bridge Formula B, and SI units may be substituted as explained earlier. This formula does away with the inclusion of the number of axles, allows somewhat greater loads for shorter axle group lengths, but restricts the maximum loads (relative to Bridge Formula B) on the longest trucks with many axles. Figure 27 compares the TTI HS-20 formula with Bridge Formula B.

It should be expected that in the coming years the venerable Bridge Formula B will be replaced with some modified version, in keeping with the nation's need to continually improve the effectiveness and efficiency of highway transportation of goods.

CHAPTER NINE

TRUCK EFFECTS ON TRAFFIC FLOW

There are two major effects of trucks on traffic flow. First, they reduce the maximum service flow on a segment of highway (measured in terms of vehicles per unit time) because they are longer than cars and have less acceleration capability. Second, their greater length requires vehicles passing them to have a greater passing sight distance. Each of these effects is discussed in this chapter.

HIGHWAY CAPACITY

Knowledge of traffic flow characteristics is fundamental to the planning, design, and operation of transportation systems (*20*). Traffic flow is characterized by the traffic flow rate or volume (vehicles/unit time), speed (distance/unit time), and density (vehicles/unit distance). Using v for the flow rate, u for the speed, and k for the density, as is conventionally done, the flow rate is given by

$$v = u * k.$$

Fundamental to the design and analysis of highway facilities, as described in the *Highway Capacity Manual* (HCM) (*12*) are the concepts of "capacity" and "level of service." The capacity, c, of a facility is the maximum hourly rate at which vehicles (alternatively, persons) can reasonably be expected to traverse a point or uniform section of a roadway. It is expressed as the number of passenger vehicles per hour per lane (pvphrpl). In a recent paper, May (*35*) examines the development of the HCM and where it now appears to be going. For example, in the 1985 HCM, the ideal capacity of a freeway was assumed to be 2,000 pvphrpl. In 1994, the capacity at saturated flow was considered to be 2,200 pvphrpl, and by the year 2,000, May suggests 2,400 pvphrpl might be used for analyzing traffic flow. These changes are believed to be due to changes in vehicles and in driver capabilities and behavior (e.g., drivers seem to be willing to follow closer to other vehicles).

The level of service (LOS) is a qualitative measure that characterizes the operational conditions within a traffic stream. Six levels of service are defined for each type of facility, which are given letter designations of A through F. LOS A is the highest level, characterized as very light, free-flowing traffic. LOS E signifies traffic flowing at capacity; LOS F occurs when the traffic volume flowing into the section of interest is greater than capacity and is characterized as stop-and-go traffic. Highways are normally designed for LOS C or D.

Traffic speeds tend to remain nearly constant on freeways and multilane facilities as volumes increase from LOS A through D, but they decrease somewhat as LOS E is achieved and drop appreciably in LOS F. Levels of service are identified today by the density, k, in passenger cars per km (mile) per lane, as shown in Table 17. For LOS F, the densities are greater than those for LOS E, and are variable.

The "service flow rate" for level of service i, SF_i, for one direction of flow, is given by:

$$SF_i = c * (v/c)_i * N * f_j$$

where $(v/c)_i$ is the maximum volume-to-capacity ratio for LOS i, N is the number of lanes in one direction of flow, and f_j is a series of adjustment factors to account for things such as narrow lane widths, unfamiliar drivers, and heavy vehicles. The latter, f_{HV}, is of interest to this synthesis. The adjustment factor is required because trucks occupy more space than passenger vehicles (thus impact the density). More importantly, they travel more slowly on grades and thus reduce overall traffic speeds.

The heavy vehicle adjustment factor is related to "truck passenger-car equivalents", E_T, by the equation

$$f_{HV} = 1 / [1 + P_T (E_T - 1)]$$

where P_T is the proportion of vehicles in the traffic stream that are trucks, expressed as a decimal. (A more general relation than this is available to also account for the presence of buses and recreational vehicles.)

The HCM (*12*) provides formulas, graphs, and tables for determining service flow rates, the various adjustment factors, and the passenger car equivalents. In addition to basic freeway segments, the HCM treats weaving areas, ramps, and ramp junctions. It also covers multilane rural and two-lane highways as

TABLE 17
LEVEL OF SERVICE ON FOUR-LANE FREEWAYS

Level of Service	Free-Flow Speed km/hr (mph)	Maximum density pc/km/ln (pc/mi/ln)
A	110 (70)	6 (10)
B	110 (70)	10 (16)
C	110 (70)	15 (24)
D	110 (70)	20 (32)
E	110 (70)	22.8 (36.7)
E	105 (65)	24.4 (39.3)
E	97 (60)	25.8 (41.5)
E	90 (55)	27.3 (44.0)

Note: The densities for levels of service A through D are the same for each of the free-flow speeds used (70, 65, 60, 55). Only level E changes as illustrated in the table. The table seems to indicate that LOS A is not possible with a free-flow speed of 105 (65), etc. However, the information for this condition is available and included in the HCM.

Source: HCM (*12*), metric values derived. For other free-flow speeds use HCM figures.

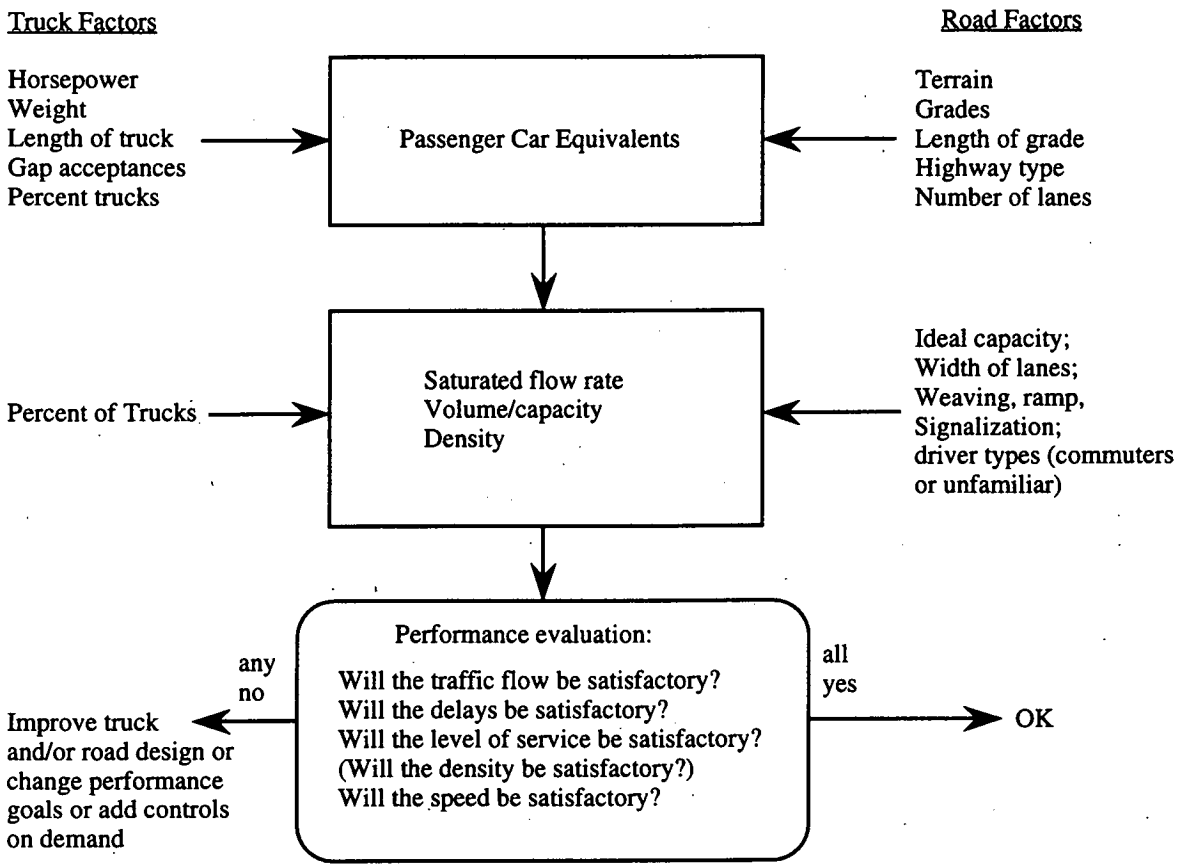


FIGURE 28 Capacity related performance evaluation of roadways with trucks.

well as urban streets, including arterials and signalized and unsignalized intersections. For simplicity, the present discussion is limited to freeway segments.

As indicated above, the impact of trucks on traffic flow is measured through use of passenger car equivalents for trucks, using the procedures presented in the HCM. The idea of how this process works is indicated in Figure 28.

Figure 28 shows that several truck related factors influence the analysis of performance of the transportation system through their impact on passenger car equivalents (PCEs) and traffic flow characteristics. The most important of the truck factors is the weight/power ratio, which is a generalized surrogate for the acceleration capability of the vehicle at any given speed. This ratio is a basic factor in determining PCEs because trucks have limited capabilities for accelerating up to traffic speeds and for maintaining speeds on grades. The acceleration characteristics of a 120 kg/kW (200 lb/hp) truck are particularly low on grades over 2 percent and at speeds near or above 80 km/hr (50 mph). The maximum speed (where no further acceleration is possible) is given as 72 km/hr (45 mph) on a 2 percent upgrade and 37 km/hr (23 mph) on a 6 percent upgrade for such a truck (*12*).

The influences of vehicle length and truck driver gap acceptances are not directly shown in the tables given in the HCM. However, to the extent that the values given in the tables are empirically or theoretically derived, these factors have a bearing on the values given.

Example values of PCEs for trucks, given by the HCM for a mix of trucks with average weight-to-power ratios of 75 to 90 kg/kW (125 to 150 lb/hp) are 1.5 on level terrain, 3.0 on rolling terrain, and 6.0 on mountainous terrain. More detailed examination of the tables in the HCM provides the example values given in Table 18 for these same trucks operating on a four-lane freeway of various grades, all being 0.8 to 1.2 km (1/2 to 3/4 mi) long.

It is noted that the PCEs are smaller for a given grade as the

TABLE 18
PASSENGER CAR EQUIVALENTS (PCES) FOR TRUCKS ON 0.8 TO 1.2 KM UPGRADES

Grade (%)	Percent Trucks 2	5	10	15	20	25
<2	1.5	1.5	1.5	1.5	1.5	1.5
2	1.5	1.5	1.5	1.5	1.5	1.5
3	6.0	4.0	3.0	2.5	2.5	2.0
4	9.5	6.5	5.0	4.5	4.0	3.5
5	12.5	8.5	7.0	6.0	6.0	5.0
6	15.0	10.0	8.0	8.0	7.5	6.5

Source: HCM (*12*)

proportion of trucks increases. However, the truck adjustment factor incorporates both E_T and P_T. For example, on a 4-percent grade, f_{HV} decreases from 0.85 for 2 percent trucks to 0.78 for 5 percent, 0.71 for 10 percent, etc. For roadways with high truck volumes, the heavy vehicle adjustment factors thus reduce the maximum attainable service flow rates to appreciably smaller values than the ideal flow rate for passenger cars.

The examples in Table 18 represent fairly high powered trucks; trucks that are heavier (with higher weight/power ratios) have higher PCEs and lower adjustment factors. Again, on a 4-percent grade of the same length as in Table 18, and for 20 percent trucks, a 120 kg/kW (200 lb/hp) truck has an E_T of 6, while a 180 kg/kW (300 lb/hp) truck has an E_T of 7. Their adjustment factors are 0.50 and 0.45, respectively.

Clearly, heavy trucks with high weight/power ratios are a major impediment on steep grades. To the extent that many of the heaviest current trucks are equipped to operate at 120 kg/kW (200 lb/hp), the corresponding adjustment factors are less obstructive on steep grades than they were 10 to 20 years ago. Nevertheless, transportation professionals concerned with trucking will want to examine these values critically in situations where the traffic flow is marginal compared to a desired set of targets for flow characteristics. Trucking professionals may want to conduct theoretical and experimental studies to verify whether these truck adjustment factors apply to their operations. Because of the investment in vehicles, wages, and just-in-time delivery, trucking organizations are likely to suffer greater economic penalties from congestion than passenger car drivers. Trucking firms have reason to examine the impact of these service flow rates critically.

The matter of traffic flow gets at the heart of operating the transportation system for both passenger cars and trucks. The understanding of traffic flow is important to the well-being of trucking and to the arranging of schedules and terminals to avoid congestion. With the integration of Intelligent Transportation Systems (ITS) technology (or advanced technology) into commercial vehicle operations, the trucking industry will learn much about traffic flow. This information will be very useful to the development of future versions of the HCM and to further development of the theory of traffic flow. Hopefully, the trucking industry will participate in developing new knowledge that will contribute to a theory of traffic flow that accounts for differences in vehicle lengths, acceleration characteristics, and driving behavior as well as the development of automatic or semi-automatic systems for controlling the headway range between vehicles.

In conjunction with ITS, researchers have been reexamining traffic flow from a control-system point of view. Among many things, they have been considering the use of intelligent cruise control systems in connection with an appropriate infrastructure designed to select and communicate the desired speed and headway for the current traffic situation (*66*). (Headway is defined here as the distance from the rear of a leading vehicle to the front of the following vehicle.) This work for ITS is leading to further examination of how drivers select and maintain headway distance. Since control ideas are involved, various relationships between flow rate, speed, and density are being examined as control algorithms. There are projections that simple headway control systems can smooth out traffic flow and even increase maximum flow rates beyond current levels.

The need for climbing lanes and the benefits they would provide is an example of the type of performance analysis that can be done. Although research and measurement efforts would be required, the benefits from having passing lanes added to two-lane rural roads with heavy-truck traffic could be handled within this framework. Passing is discussed further in the next subsection.

Future research and experience could lead to a more detailed treatment of trucks, especially with regard to the influence of truck lengths in situations where speeds under 56 or 64 km/hr (35 or 40 mph) are expected. Also, procedures for using the acceleration and deceleration characteristics of trucks versus cars and differences in driving techniques could be developed to provide a stronger foundation for the passenger-car equivalents concept. Computer simulation and modeling techniques now exist for treating different types of vehicles in a traffic stream or network (*20*).

PASSING SIGHT DISTANCE

The adequacy of passing zones depends on the risks involved and the obstructions to traffic flow created by slower-moving vehicles. Heavy trucks may be moving slower than passenger cars, particularly on roads with features that tend to slow traffic such as hills or the presence of other slowly moving vehicles. Climbing lanes are provided under certain conditions on mountainous roads, and sometimes on two-lane roads with high traffic volumes or few passing zones, to reduce delay to other vehicles. When possible, truck drivers tend to make flying passes, which means they do not slow down before passing. They simply go around traffic if the road is clear. Because trucks take very long distances to accelerate at highway speeds, the sight distances needed when trucks are passing, according to the method presented in this subsection, usually are excessively long, if acceleration is required.

There are several difficulties when the current AASHTO policy (*2*) is applied to cars passing trucks. The AASHTO policy does not include the lengths of the vehicles involved. A simple analysis (*67*) indicates that the overall length of a truck is an important factor in the sight distance needed to pass a long truck. Glennon and others (*68, 69*) have developed a passing sight distance (PSD) model that not only takes the lengths of the vehicles into account, but is based upon the concept of a point of no return or a decision point (somewhat like the ideas behind the last point of stopping used in Chapter 6). The idea is that there is a point where the driver must choose to either abort the pass attempt and fall in behind or continue with the passing maneuver around the vehicle ahead. This approach is less conservative than AASHTO policy and appears to be less conservative than approaches that satisfy some other researchers (*9*). In addition, the AASHTO policy for designing roads is different from the MUTCD (*3*) recommendations for marking no passing zones. The net conclusion is that there is a need to establish mechanisms for evaluating passing potential on road sections.

TABLE 19
RELATIONSHIPS: PASSING AT SPEEDS EXCEEDING 48 KM/HR (30 MPH)

$t_p = K(L_T + L_p + V_T t_{c1}) / (V_p - V_T)$

where

t_p = Time to pass = (relative distance/relative speed)
K = Unit consistency factor
L_T = Length of truck
L_p = Length of passing vehicle
V_p = Velocity of passing vehicle
V_T = Velocity of truck
t_{c1} = Clearance time or interval in front of truck
$PSD = V_p (2 t_p + t_{c2})$

where

PSD = Passing sight distance
t_{c2} = Clearance time with respect to the oncoming vehicle. (The oncoming vehicle is assumed to travel at the same speed as the passing vehicle in this relationship.)

Source: Baraket and Fancher (*9*).

The simplified relationships given in Table 19 pertain to one of several possible methods for determining PSD in a manner that takes into account the lengths of the passing and passed vehicles. In general, the differences in methods for evaluating the necessary passing time depend on when and where the decision to pass or not to pass is made.

Table 19 is based on the assumption that it is acceptable to provide the passing driver with enough sight distance for the driver to decide to pass another vehicle when the front of the passing vehicle is even with the rear of the vehicle to be passed. It is presumed that the driver will ordinarily abort the pass, if necessary, before this decision point is reached. Hence the time to pass is taken as the controlling factor. (This means that these relationships may not work very well at attempted passing speeds that are less than 48 km/hr (30 mph).) The relationships in Table 19 also assume that the relative speed between the two vehicles is constant, although in practice the passing vehicle may continue to accelerate, especially if hurried by oncoming traffic. Further, it is assumed that the oncoming vehicle has the same speed as the passing vehicle. These relationships need field evaluation before they can be considered for adoption as policy. Nevertheless, they provide an indication of the importance of various truck and road factors in passing situations.

The PSD is equal to the distance the passing vehicle will travel during the passing time (t_p), plus an equal distance that an oncoming vehicle will travel, plus a clearance distance. As an example of using these equations, let L_T = 29 m (65 ft), L_p = 5.8 m (19 ft), t_{c1} = 1 sec, t_{c2} = 1 sec, V_p = 48 km/hr (30 mph), and V_T = 32 km/hr (20 mph). Then t_p = 10.7 sec, and PSD = 48,000/3,600 * (21.4 + 1) = 300 m (990 ft). (If, in Table 19, t_p < 10 sec, set t_p = 10 sec. This allows the passing vehicle time to abort the pass when the front of the passing vehicle is even with the rear of the truck. For $V_p - V_T$ = 16 km/hr (10 mph), and with a deceleration rate of at least 0.1 g, the time required to abort the pass is less than 10 sec.)

Even though the relationships given in Table 19 do not exactly correspond to any currently used design practice, they contain the essential elements of situations involving one vehicle passing another. Hence these relationships can be examined to identify truck and road characteristics related to the risks of passing on particular road sections. Figure 29 presents a matrix of the influences of truck and road characteristics on PSD for cars passing trucks.

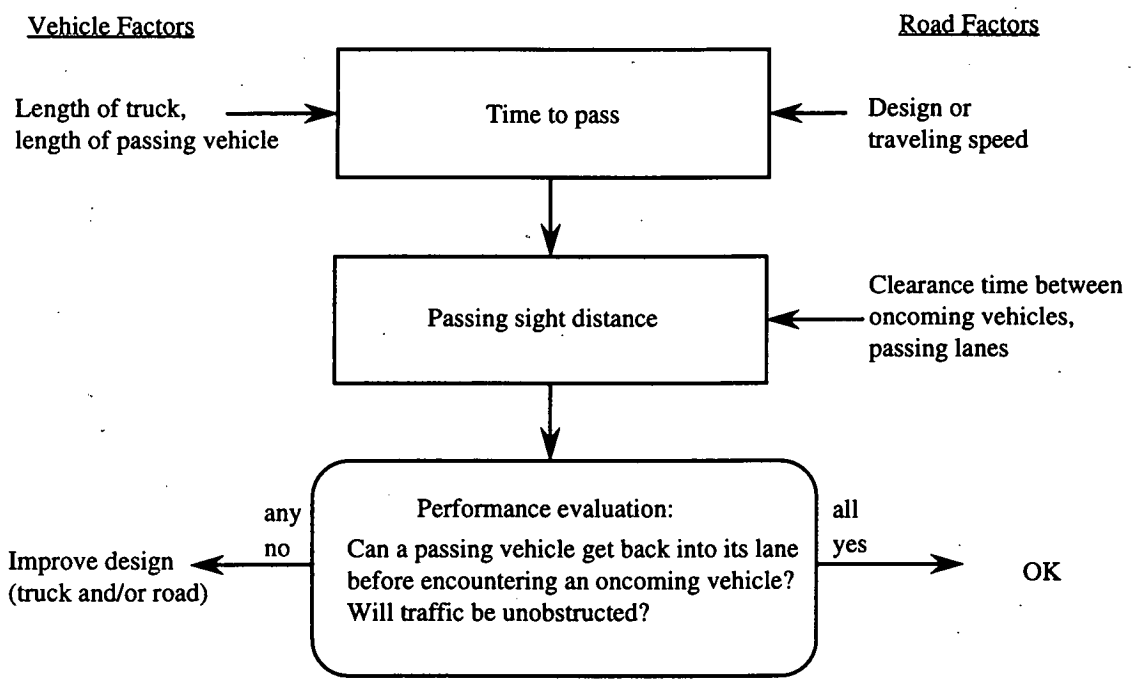


FIGURE 29 Cars passing trucks performance evaluation.

CHAPTER TEN

CONCLUSIONS

In the simplest terms, current practice is that heavy trucks are designed to serve diverse shippers' needs, within the constraint of laws intended to protect the highway infrastructure, public safety, and the environment. Highways are designed, in turn, to meet the requirements of heavy trucks carrying payloads. However, there is considerably more interaction of truck design and highway design decision making than this simplistic description implies. Further, truck designs evolve at a faster pace than highways, primarily because of the differences in service life of these two system components. As a result, older highways may impose unintended inefficiencies on current truck operations.

This synthesis of current practice found that designers of both highways and heavy trucks contend with broad diversity in design requirements and underlying market forces that influence these requirements. Despite the substantial influence of AASHTO policies on highway design, variations in geography, truck traffic composition, and truck designs have motivated some states to go beyond AASHTO policy, particularly regarding bridge life and intersection design, to fit local conditions. More significantly, current practice could better reflect the relationships between the truck/highway system's ability to deliver payload while minimizing such factors as pavement wear and bridge fatigue, vehicle wear and fuel usage, congestion, and noise, while optimizing traffic operations and safety. Better understanding of these relationships could lead to improved truck/highway performance.

Certain heavy truck designs, for example, are substantially less damaging to pavements and bridges than other designs. Axle loads (rather than gross weight), axle spacings, suspensions, and vehicle dynamics are particularly significant truck factors; pavement thickness and roughness are the most important highway factors. However, much more research is needed to better understand the mechanisms of pavement and bridge fatigue.

Highway ramp designs have substantial influence on truck control and operating safety, particularly with respect to rollover potential. Low-speed and high-speed offtracking are of importance here, also, but simple means to quantify them are not available. Intersection design is also important with regard to low-speed offtracking.

Accelerating and braking to attain and control speed are other aspects of truck operations that seem not to be well reflected in current highway design practice. Engine power needs to increase as weight increases to prevent acceleration performance from degrading in crossing intersections and railroad crossings, and climbing grades. Signal timing at intersections on routes with heavy truck traffic is an important factor to be considered with truck acceleration performance in mind. With aerodynamic improvements and other improvements in drag reduction, braking on downgrades places additional demands on truck service brakes. Regular reevaluation and wider use of grade severity rating systems could inform heavy truck designers and drivers of needs for change in braking requirements. Braking imbalances between axles also can create safety problems such as jackknifing and trailer swing. Antilock brake systems offer a great opportunity to eliminate these problems as well as reduce stopping distances.

Many differences pose safety or operational problems that could become even more significant under North American Free Trade Agreement provisions. Canadian and U.S. weight limits are not the same. The design target rollover threshold, as another example, warrants attention, as Canadian practice sets this parameter at 0.4 g's for heavy vehicles, while U.S. practice uses 0.35 g's.

The AASHTO policies themselves may warrant revision in their treatment of cars passing heavy trucks. The AASHTO policy does not include consideration of the length of the vehicles, which can become important in safe minimum passing sight distance determinations, particularly in areas where longer single and multiple trailers are permitted.

Truck designs are continually evolving due to market forces. Trucks are likely to become heavier and longer in the future. Longer and heavier trucks, especially if they use additional axles and two or more trailers, can reduce pavement and bridge fatigue, and provide less low-speed offtracking. Their major disadvantage is likely to be their greater propensity for rearward amplification, unless newer hitch designs are employed.

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GLOSSARY

A-Dolly—the simplest and most widely used dolly for converting semitrailers into full trailers. See "dolly."

Aerodynamic drag—the net force resisting vehicle forward motion created by the air flowing around the vehicle.

American Association of State Highway and Transportation Officials (AASHTO)—an organization that creates policies on highway and street design. See (*2*).

Antilock brakes—braking systems that automatically modulate the braking effort should a wheel begin to "lock up," providing better control of a vehicle undergoing heavy braking.

Articulation—the hitch connection between two units of a multi-unit truck that allows the trailing unit to rotate horizontally (yaw) relative to the leading unit.

Axle load—the vertical force imposed on the road by all the wheels on an axle. If the vehicle is stationary, the load is said to be the *static* axle load; if it is moving, the instantaneous force is known as the *dynamic* axle load.

Axle separation (axle spread)—the longitudinal distance between the centerlines of the wheels on two adjacent axles in a multiple-axle group.

Axle tramp—a form of wheel hop vibration in which wheels on the opposite ends of an axle bounce out of phase.

B-dolly—a type of dolly commonly used in Canada, but not in the United States, using double draw bars instead of the single draw bar of the A-dolly pintle-hook arrangement.

Bobtail—a truck tractor running with no trailer attached.

Bridge fatigue—a weakening of the structural elements of a bridge due to repeated application of loads.

Bridge Formula B—a standard formula used to define the allowable weight of any group of truck axles, based on their number and overall longitudinal spacing, to limit bridge fatigue.

Cab-over-engine—a type of tractor in which the driver compartment is located above the engine, producing a shorter tractor than one with a conventional cab.

Capacity (highway)—the maximum hourly rate at which vehicles can reasonably be expected to traverse a point or uniform section of a roadway.

Cargo body length—the external length of that portion of a truck or trailer body intended for carrying cargo.

Center of gravity (cg)—the point where the weight of the truck and/or body and payload appears to be concentrated. The longitudinal position of the cg determines the distribution of load between the front and rear axles. The height of the cg above the ground is important to rollover potential.

Class 7, Class 8—a means of classifying heavy trucks by their weight. Class 7 trucks have a GCW of 12 000 to 15 000 kg (26,000 to 33,000 lb), and Class 8 trucks have weights over 15 000 kg (33,000 lb), but generally not over 36 000 kg (80,000 lb).

Clear zone—the area alongside a roadway clear of trees and other obstacles that a vehicle might otherwise hit if it ran off the road.

Clearance interval—the "yellow" plus "all red" intervals that occur within the cycle of a traffic signal to provide for clearance of traffic in an intersection before conflicting traffic movements are released.

Conventional (cab)—a truck in which the engine compartment protrudes forward from the driver cab.

Cornering coefficient—tire cornering stiffness divided by its vertical load.

Cornering stiffness—the rate of buildup of lateral force per degree of slip on a tire.

Cubic capacity (cube)—the volume (cubic meters or feet) in the truck available for carrying cargo.

Density (cargo)—the weight of the cargo divided by its volume.

Density (traffic)—the number of vehicles on a roadway per unit length of the roadway.

Dolly—a component of a truck combination, containing one or more axles, a turntable or fifth wheel, and a pintle hook. Placed under the front of a semitrailer with compatible hardware, it converts the semitrailer to a full trailer.

Double—a truck combination consisting of a tractor and two trailers.

Drag—the forces acting on a vehicle that tend to slow it down. These include aerodynamic forces, rolling resistance of the tires, gravitational forces if operating on a grade, etc.

Driver eye height—the height of the eyes of the vehicle's driver, a function of the seating height, and important in stopping sight distance considerations.

Duals (or dual tires)—two tires on the same end of an axle, used to carry more load than a single tire could carry.

Dynamic load—see "axle load."

Effective mass—the combined equivalent mass of a vehicle resisting acceleration arising from its actual mass plus the inertia of its rotating components.

Engine retarders—devices on some truck engines enabling the driver to convert the engine's purpose from supplying power to absorbing power, used to assist in braking on downgrades.

Equivalent single axle load (ESAL)—the number of passes of a truck axle that causes the same fatigue or rutting wear to a pavement as is caused by a dual-tire axle loaded to 8000 kg (18,000 lb).

Fifth wheel—a type of hitch commonly used to connect a tractor and a semitrailer.

Flexible pavement—typically an asphaltic pavement, with wear characteristics that differ from rigid pavements.

Flow rate—the number of vehicles passing a point on a roadway per unit time. The roadway's "capacity" is the maximum flow rate reasonably achievable.

Foundation brakes (or service brakes)—the truck brakes normally used for stopping or controlling speed on downgrades.

Friction demand—the lateral force on an axle necessary to hold a vehicle on the road in a curve, normalized by its vertical load.

Grade—the slope of a road along the direction of travel, normally characterized by the vertical rise per unit of longitudinal distance.

Gross combination weight (GCW)—the actual weight of an entire combination of vehicle components (tractor, trailers, dollies), including all equipment, fuel, body, payload, driver, etc.

Gross vehicle weight (GVW)—the actual weight of a single vehicle unit, including all equipment, fuel, body, payload, driver, etc.

High-speed offtracking—offtracking at speeds sufficiently high that the rear axle(s) track to the outside of a turn or curve relative to the front axle.

***Highway Capacity Manual* (HCM)**—a highway design document written and periodically updated by the Transportation Research Board (*12*).

Hitch locations—the longitudinal and vertical positions of connections between the individual vehicle units making up a combination vehicle (e.g., the fifth-wheel connection between a tractor and a semitrailer).

Intersection sight distance—the distance along a crossroad needed for a driver to determine whether there is adequate time to accelerate from a stopped position across an intersection or onto the crossing roadway without conflicting with cross traffic.

Jackknifing—a condition in which a towing unit (truck or tractor) rotates out of alignment with a trailer in an uncontrolled manner. Jackknifing usually occurs when the rear wheels of the towing unit lose traction when braking, causing it to spin out on the road. It can also occur when maneuvering or backing in close quarters.

King pin—the pin protruding from the front of a trailer by which the trailer connects to the fifth wheel hitch on the tractor, allowing the towed unit to pivot. It is the point from which axle spacings are measured in offtracking calculations.

Lateral track width—the distance measured laterally between the centers of the tires or tire sets on an axle.

Level of service (LOS)—a qualitative measure used by traffic engineers that characterizes the operational conditions within a traffic stream, ranging from A (very light, free-flowing traffic) to F (congested, stop-and-go traffic).

Load enforcement—actions and practices of government agencies to prevent vehicles from operating in violation of load limits. This is often accomplished by installing weigh scales along the roadway to monitor truck weights, conducting unscheduled roadside inspections and weighings by Motor Carrier Enforcement Officers, and, more recently, placing "weigh-in-motion" equipment in the roadway to measure the weight of passing trucks.

Longer combination vehicles (LCVs)—heavy trucks with a variety of specific definitions, but generally referring to the vehicle combinations that are longer or heavier than those in common use across the country.

Low-speed offtracking—offtracking at very low speeds in which the rear axle(s) of a vehicle track to the inside of a turn or curve relative to the front axle.

***Manual on Uniform Traffic Control Devices* (MUTCD)**—a Federal Highway Administration document on signing and other traffic control devices used by traffic engineers (*3*).

Maximum offtracking—the maximum distance between the inside front tire and the inside rear tire as a vehicle traverses a specific turn or curve.

Maximum wheel cut—the maximum angle to which the front (steering) wheels of a vehicle can be steered.

Minimum turn radius—the minimum radius of the path of the outside front wheel of a vehicle, on which subsequent offtracking calculations are based.

North American Free Trade Agreement (NAFTA)—an agreement among Mexico, the United States, and Canada fostering free trade. It has heavy vehicle transportation implications for the future.

Offtracking—the phenomenon that the axles of turning vehicles, especially trucks, do not follow one another precisely; at low speeds the rear axles track inside of the front axles, but at high enough speeds the reverse can occur.

Overall height—the height from the road surface to the highest rigid part of a vehicle body or payload, excluding foldaway or flexible components such as antennas, etc.

Overall length—the longitudinal dimension from the front to the rear of a vehicle or a combination of connected vehicle units.

Overall width—the nominal design dimension of the widest part of the vehicle, exclusive of signal lamps, marker lamps, outside rearview mirrors, flexible fender extensions, and mud flaps, determined with doors and windows closed and the wheels in the straight-ahead position.

Passenger car equivalent (PCE)—the number of passenger cars to which a given truck is equivalent in determining capacity and level of service, as a function of grade and the percentage of trucks in the traffic flow.

Passing sight distance (PSD)—the distance a passing vehicle on a two lane road will travel during the time it is making a pass, plus an equal distance that an oncoming vehicle will travel during that time, plus a clearance distance or safety factor.

Pavement fatigue—a gradual deterioration of the road structure as a result of the repetitive stresses from vehicle passages, which eventually results in failure of the material (cracking).

Pavement rutting—depression in the wheel tracks of a road surface caused by compaction of the layers or creep flow of the materials under the loading of vehicle tires.

Pavement wear—the actions of passing vehicles that cause

deterioration of the road structure, principally resulting from contributions to the cumulative fatigue of the structure or to rutting of an asphalt surface.

Payload density—the average weight per unit volume of the payload on a vehicle.

Payload volume—the volume occupied by the payload of a commercial vehicle, or the volume available for payload.

Pintle hook—a type of hitch incorporating a draw bar and a hook-and-eye arrangement to couple a full trailer with a leading unit of a vehicle combination.

Rear overhang—the length of a vehicle body that extends behind the rearmost axle.

Rearward amplification—the phenomenon that the rear units of a combination vehicle respond with higher amplitudes of lateral motion than the steering inputs at the front of the vehicle.

Rigid pavement—a class of pavement in which the road is a "rigid" material (most frequently, portland cement concrete), as contrasted with "flexible pavements."

Road roughness—vertical deviations of the road surface from a flat surface that induce ride vibrations in vehicles.

Roll stiffness—the resistance to vehicle body roll provided by a suspension system.

Rollover threshold (RT)—the lateral acceleration level that will cause a vehicle to roll over.

Run-off (escape) ramps—ramps built alongside some highway downgrades for the purpose of stopping trucks that have lost their braking ability.

Rutting—see "pavement rutting."

Service brakes (foundation brakes)—the truck brakes normally used for stopping or controlling speed on downgrades.

Skid resistance—a standardized measure of the frictional properties of a road surface.

Slab length—the nominal length of rigid pavement slabs when originally constructed.

Slip angle—the difference between the direction a tire is pointed and the direction it travels when a vehicle is in a turn. Slip angles occur when a tire generates lateral force to counteract lateral accelerations in a turn.

Sprung mass—the portion of the weight of a vehicle that is supported by its suspension.

Steering ratio—the ratio of the steering wheel angle to the road wheel steer angle.

Stopping sight distance—the distance required to stop a vehicle from the time the driver sees an obstruction in the road ahead. Traditionally, the obstruction is taken as a 15-cm (6-in.)-high object on the roadway. The distance includes that traveled during the driver's perception/reaction time, typically about 2 sec.

Super-single—a wider than normal tire used by some segments of the trucking industry in place of a pair of dual tires, to improve productivity, safety, and fuel consumption, but at the possible cost of increased pavement wear.

Superelevation—the practice of elevating the roadway surface on the outside of a curve or turn, to improve the ability of vehicles to traverse the curve or turn at higher speeds. It is measured as the increase in vertical elevation divided by the width of the roadway.

Swept path—the maximum distance between the outside front tire and the inside rear tire as a vehicle traverses a specific turn or curve. It is approximately the sum of the maximum offtracking and the vehicle width.

Swing out—excursions of the extremities of a vehicle body beyond the path followed by its wheels in a turn.

Tandem—two closely spaced axles on a truck; they share the load placed on them and tend to function as a unit.

Tare weight—the weight of a container and the materials used for its packing. As applied to a loaded truck, it is the weight of the truck, exclusive of its contents.

Tire contact patch—the area enclosed by the outer boundary of contact between a loaded tire and the road.

Tire rolling resistance—the resistance to forward motion experienced by a freely rolling tire.

Tire width—tire *section* width is the maximum width of the cross section of the inflated tire; tire *tread* width is the nominal width of the tread that contacts the road.

Track width (tread)—the lateral distance between the centerlines of tires on opposite ends of an axle. When dual tires are present, it is the distance between the centerlines of the dual wheel assemblies.

Trailer swing—a condition in which a towed unit rotates out of alignment with the towing unit. Trailer swing usually occurs when the rear wheels of the towed unit lose traction when braking, causing it to swing out from the path of the tractor. Compared to jackknifing, trailer swing is potentially controllable.

Tridem—three closely spaced axles on a truck; they share the load placed on them and tend to function as a unit.

Triple—a truck combination consisting of a tractor and three trailers.

Turner truck—a truck concept that incorporates heavier weights but more axles, so the GCW is distributed in such a way as to cause less pavement and bridge wear (*10*).

Turntable—a type of hitch that is free to rotate in the horizontal plane (yaw) but is constrained from rotating in pitch or roll.

Twin—double van-type trailers, as opposed to tankers or other types of trailers.

Walking beam—a type of truck tandem suspension in which the two adjacent axles are attached at opposite ends of beams (left and right side) that support the vehicle frame through springs located at the central pivot of the beams. In the United States they are mainly used with off-road vehicles; when used on the highways, they are unusually damaging to pavements.

Wander—the variation in lateral position of trucks in a road lane, the result of which modifies the pavement damage estimates made without consideration of this phenomenon.

Weigh-in-motion—an instrument placed in the roadway to measure the load under the tires of a passing truck.

Weight-to-power ratio—the weight of the combination vehicle divided by its engine power, typically measured as kg per kW (lb per hp). It is the first-order determinant of the vehicle's capabilities for acceleration and speed maintenance on a grade.

Wheel hop—a bouncing motion of wheel and axle assemblies

caused by bumps in the road or triggered by application of the vehicle's service brakes.

Wide-base—a wider than normal tire used by some segments of the trucking industry in place of a pair of dual tires, to improve productivity, safety, and fuel consumption, but at the possible cost of increased pavement wear.

Survey Questionnaire Sent to Highway Agencies

NCHRP PROJECT 20-5
TOPIC 22-12

"TRUCK OPERATING CHARACTERISTICS"

Highway Design Related to Truck Characteristics

The objective of this survey is to obtain information concerning the state of the practice in addressing highway design, planning, operation and policy issues related to the characteristics of heavy trucks and buses. In order to assist in the review of the survey response, please indicate the person(s) who may be contacted for clarification or additional information:

AGENCY_____

NAME_____

TITLE_____

ADDRESS_____

_____

_____

TELEPHONE_____

FAX_____

The purpose of this survey is to obtain information that will be used to develop matrices of highway design parameters as related to truck characteristics. Within the AASHTO policies and guides and the MUTCD there are design elements that are based on, or consider, the characteristics of large trucks or buses, i.e., as a design vehicle. There are others that are not explicitly based on truck characteristics (performance, size, or weight), but perhaps should be. Using the AASHTO and MUTCD guides as a base condition, we would like to know if your agency has adopted a design or operation standard or procedure that is either different from or supplements the guidance in the AASHTO or MUTCD standards, and why a different standard or procedure was selected. For each of the areas listed below, please indicate if your policy differs and describe how it differs. Also, please provide a copy of the appropriate standard or procedure.

Topic 22-12 *Agency*_____

For which of the following design elements has your agency used design standards related to truck characteristics that differ from the AASHTO or MUTCD standards. Please provide a description of the differences. (Please use additional sheets if necessary.)

	ELEMENT DIFFERENCE?	NO	YES
1.	Pavement Life (fatigue, damage)	_____	_____
	*Description of difference and why it is used:*_____		
2.	Bridge Life (fatigue, damage)	_____	_____
	*Description of difference and why it is used:*_____		
3.	Sight Distance (stopping, passing, decision)	_____	_____
	*Description of difference and why it is used:*_____		
4.	Intersection Geometrics	_____	_____
	*Description of difference and why it is used:*_____		
5.	Lane width and pavement widening on curves	_____	_____
	*Description of difference and why it is used:*_____		
6.	Horizontal Curves (radius and superelevation)	_____	_____
	*Description of difference and why it is used:*_____		
7.	Run-Off Ramps, Speed Control on Grades	_____	_____
	*Description of difference and why it is used:*_____		

*Agency*_____

	ELEMENT DIFFERENCE	NO	YES
8.	Climbing Lanes (critical length of grade)	_____	_____
	*Description of difference and why it is used:*_____		
9.	Entrance/Exit Ramps (length, grade, curve)	_____	_____
	*Description of difference and why it is used:*_____		
10.	Interchange Ramps (curvature, superelevation)	_____	_____
	*Description of difference and why it is used:*_____		
11.	Sign Placement	_____	_____
	*Description of difference and why it is used:*_____		
12.	Signal Timing	_____	_____
	*Description of difference and why it is used:*_____		
13.	Other Element_____	_____	_____
	*Description of difference and why it is used:*_____		
14.	Other Element_____	_____	_____
	*Description of difference and why it is used:*_____		

THANKS FOR HELPING
Please send your responses to:
Paul S. Fancher, Jr.
University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, Michigan 48109-2150
Telephone: (313) 936-1059
Fax: (313) 936-1081

Questionnaire Sent to Truck Manufacturers and Designers

NCHRP PROJECT 20-5
TOPIC 22-12

"TRUCK OPERATING CHARACTERISTICS"

Truck Characteristics Related to Highway Design

The objective of this survey is to obtain information concerning the characteristics of heavy trucks that influence the design and operating features of highways. It may be necessary for several people to review this questionnaire within the agency in order to address the complete range of topics covered. To assist in the review of the response, please indicate the person(s) who may be contacted for clarification or additional information.

AGENCY_____

NAME_____

TITLE_____

ADDRESS_____

_____

_____

TELEPHONE_____

FAX_____

The purpose of this questionnaire is to identify where and how specific truck characteristics influence the development of the roadway system. We are seeking information on the design practice currently used by your organization to address potential highway problems associated with the mechanical properties of large trucks. This will be used to develop a matrix of truck characteristics as related to highway design parameters.

Topic 22-12 *Agency*_____

For each of the following truck characteristics, please indicate if the characteristic influences highway design or operating considerations, and if so, how it influences these decisions.

CATEGORY: SIZE, WEIGHT, AND CONFIGURATION

Overall Length—*Is it used?*_____ *How?*_____

_____

Overall Width—*Is it used?*_____ *How?*_____

_____

Overall Height—*Is it used?*_____ *How?*_____

_____

Axle Locations—*Are they used?*_____ *How?*_____

_____

Hitch (King Pin) Locations, or alternatively, King Pin to Rear Axle Dimension—*Are they used?*_____ *How?*_____

_____

Number of Trailers—*Is it used?*_____ *How?*_____

_____

Length of Individual Trailer—*Is it used?*_____ *How?*_____

_____

Tractor Wheelbase Length—*Is it used?*_____ *How?*_____

_____

Type of Tractor (conventional, cab-over, set back front axle, etc.)—*Is it used?*_____

*How?*_____

_____

Type of Trailer (van, tank, flatbed, etc.)—*Is it used?*_____ *How?*_____

Number of Tires (on an axle)—*Is it used?*_____ *How?*_____

Type of Dolly (A-dolly, double drawbar, etc.)—*Is it used?*_____ *How?*_____

Gross Combination Weight—*Is it used?*_____ *How?*_____

Axle Loads—*Are they used?*_____ *How?*_____

Hitch Loads—*Are they used?*_____ *How?*_____

Center of Gravity Height—*Is it used?*_____ *How?*_____

Driver Seat Height—*Is it used?*_____ *How?*_____

"Hump" Clearances (approach, departure, and break-over angles)—*Are they used?*_____ *How?*_____

CATEGORY: COMPONENT FACTORS

Brake Type (S-cam, wedge, disk)—*Is it used?*_____ *How?*_____

Size of Brakes—*Is it used?*_____ *How?*_____

Air Chamber Sizes and Slack Adjuster Length—*Are they used?*_____ *How?*_____

Brake Adjustment—*Is it used?*_____ *How?*_____

Effectiveness of the Brakes—*Is it used?*_____ *How?*_____

Tire Sizes—*Are they used?*_____ *How?*_____

Tire Construction Type—*Is it used?*_____ *How?*_____

Tire Inflation Pressures—*Are they used?*_____ *How?*_____

Tire Wear (tread depth)—*Is it used?*_____ *How?*_____

Suspension Type (air, 4-spring, walking beam)—*Is it used?*_____ *How?*_____

Engine Power—*Is it used?*_____ *How?*_____

Transmission Information (gear ratios, drive axle ratio)—*Is it used?*_____ *How?*_____

Topic 22-12 *Agency*_____

CATEGORY: VEHICLE PERFORMANCE CAPABILITIES

Braking Distances
(braking distance versus initial velocity)

(effectiveness of the braking system under different loading states and at various levels of tire road friction)—*Is it used?*_____*How?*_____

_____

Hill Climbing
(speed loss versus distance for various grades)—*Is it used?*_____*How?*_____

_____

Acceleration from a Stop
(distance versus time from a standing start)—*Is it used?*_____*How?*_____

_____

Acceleration at Speed
(velocity versus distance for various initial velocities)—*Is it used?*_____*How?*_____

_____

Offtracking, Swept Path
(turning templates)—*Is it used?*_____*How?*_____

_____

Rollover Threshold
(level of lateral acceleration at which the vehicle will rollover)—*Is it used?*_____*How?*_____

_____

Braking Efficiency
(deceleration divided by friction utilization at wheel lock)—*Is it used?*_____*How?*_____

_____

Topic 22-12 *Agency*_____

Obstacle Evasion Capability
(rearward amplification of lateral acceleration from the power unit to the last trailer)—*Is it used?*_____*How?*_____

_____

Handling Qualities
(steady turning path curvature gain and articulation angle gain)
(transient response times, damping, overshoot, settling time)—*Is it used?*_____*How?*_____

_____

To conclude the questionnaire, please list truck information that is needed, but for which satisfactory information is difficult to obtain. Or, what truck properties would you use if you knew representative values. (Attach extra sheets if needed.)

_____
_____
_____
_____
_____
_____
_____
_____
_____
_____
_____

THANKS FOR HELPING
Please send your responses to:
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