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16. Abstract

This purpose of this project was to identify the potential factors that could impact truck use of toll roads or managed lanes. The researchers outlined the trucking and freight industry needs through synthesis of existing literature. Identification of geometric and operating factors that are important to truck drivers and operators in terms of safety and efficiency will better characterize what makes toll roads attractive to those users. The factors are organized around industry needs (e.g., safety, travel reliability), facility design characteristics (e.g., access, ramp design, system connectivity), operating characteristics (e.g., signing and pavement markings), and corridor operating characteristics (e.g., traffic, congestion). The research resulted in published guidelines to help transportation planners, highway designers, and transportation operations professionals determine the geometric design and operational factors important to attract the trucking and freight industry to toll roads. The research was done through known relationships of design, safety, and operations.

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GEOMETRIC DESIGN AND OPERATIONAL FACTORS THAT IMPACT TRUCK USE OF TOLL ROADS

by

Christopher Poe, PhD, P.E.
Senior Research Engineer
Texas Transportation Institute

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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Christopher Poe, PhD, P.E. #70345.

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Program Coordinator

Bob Daigh, P.E., Austin District, TxDOT

Project Director

Bubba Needham, P.E., Austin District, TxDOT

Technical Panel

Ron Fagan, Central Texas Regional Mobility Authority

Clayton Howe, North Texas Tollway Authority

Catherine Sanchez, Texas Turnpike Authority Division, TxDOT

Wade Odell, P.E., Research and Technology Implementation Office, TxDOT

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CHAPTER 1: INTRODUCTION

PROBLEM DESCRIPTION

Texas has approximately 300 miles of toll roads, predominantly in the three largest and most congested urban areas of Austin, Dallas, and Houston. The Texas Turnpike Authority (TTA) Division of the Texas Department of Transportation (TxDOT) and the Central Texas Regional Mobility Authority are developing a substantial toll road network in the Austin area. The North Texas Tollway Authority and the Harris County Toll Road Authority are responsible for the toll road systems in the Dallas/Fort Worth and Houston areas. Both of these agencies have new expansion projects under development in their areas. TTA also operates a toll road on SH 49 in Tyler, Texas, in a more rural environment of east Texas. Additional toll road and managed lane projects are in development by TxDOT through comprehensive development agreements in the Dallas/Fort Worth and Austin/San Antonio areas.

At the same time, the freight and trucking industry are growing at an increasing rate. The vehicle miles of truck travel have increased 216 percent since 1970, whereas overall vehicle miles of travel have only increased 137 percent in the same time (*1*). Of all goods moving, 90 percent measured by value are moved by truck (*2*). Truck safety is also a concern. According to 2007 data from the Federal Motor Carrier Safety Administration, Texas leads the nation in the number of fatal crashes involving large trucks with 421 crashes (large trucks defined as gross vehicle weight exceeding 10,000 lb) (*3*). Because of Texas' size and significant trucking industry, a higher number of crashes would be expected. However, Texas exceeds the next two highest states, California, by 30 percent and Florida, by 60 percent.

There are several managed lane projects in Texas with a pricing component to assist in managing traffic demand. As these second generation managed lanes are developing in Texas, there are more multi-lane facilities with physical barriers separating managed lanes from general purpose lanes. The positive physical separation makes these facilities candidates for truck use. Some of these managed lanes are expecting as much as 10 percent of their annual toll revenue to be from truck traffic. Decisions related to the geometric design and operation of these facilities directly influence the likelihood of truck use.

From a transportation system management perspective, increasing truck and traffic volumes strain both the transportation agency's ability to manage congestion and provide sufficient capacity as well as the trucking industry's ability to operate safely and efficiently on the highway network. As more toll road infrastructure is built in Texas, it will be important to understand how the freight and trucking industry can make effective use of these facilities.

PURPOSE OF RESEARCH

The purpose of this project was to identify the potential factors that could impact truck use of toll roads and managed lanes. The researchers summarized the trucking and freight industry needs through synthesis of existing literature. Geometric design and roadway operational factors that are important to truck drivers and freight operators were identified for inclusion in new toll road design in hopes of building facilities that are more attractive to those users in terms of safety and efficiency. The factors are organized around facility geometric design characteristics (e.g., horizontal alignment, vertical alignment, cross section, ramp design), operating characteristics (e.g., signing and pavement markings), industry needs (e.g., safety, travel reliability), and corridor operational strategies (e.g., transportation management, intelligent transportation systems).

RESEARCH METHODOLOGY

The research methodology primarily focused on extracting findings from past research, existing guidelines, and published industry surveys. The scope of the research was kept to full access-controlled facilities that represent toll roads and most managed lanes. The research did not investigate pavement design needed for trucks and heavy vehicles. In addition, the scope of the research was not to address impact pricing might have on trucks use of toll roads. The approach was to be "pricing-neutral." That is, the researchers investigated the design and operational factors that may increase safety and operational efficiency. The rationale was that if a facility could be built with the design and operational features that are more attractive to truck drivers and freight operators, then there is a greater chance for use by the trucking industry. If a facility is perceived or found to be more efficient and safe, truck drivers may be more likely to use the facility assuming it is fairly priced.

The research resulted in published guidelines to help transportation planners, highway designers, and transportation operations professionals determine the geometric design and operational factors important to attract the trucking and freight industry to toll roads. The research was done through past researched relationships of design, safety, and operations.

CHAPTER 2: LITERATURE REVIEW

Existing toll facilities in the United States represent a wide range of conditions (i.e., urban to rural) and have diverse toll structures (i.e., multi-tier price structures with frequent user, carpool, and time of day discounts to simple structures with number of axles per vehicle differentiation). Existing managed lane facilities are equally diverse in their operational characteristics. Few studies have attempted to directly define the facility geometric design and operational characteristics that lead to successful utilization of existing toll or managed lane facilities by trucks. The literature review is divided into three major sections: facility geometric design characteristics, facility operational characteristics, and trucking industry characteristics.

FACILITY GEOMETRIC DESIGN CHARACTERISTICS

A number of previous studies have examined the adequacy of highway geometric design policy for trucks of various size and weight. These articles commonly reference various editions of the American Association of Highway Transportations Officials (AAHSTO) "A Policy on Geometric Design of Highways and Streets." This chapter discusses many of the studies that focused on controlled-access facilities.

Harkey et al. (*4*) examined the operational characteristics of longer-combination vehicles (LCVs) as they relate to geometric design. The common LCVs examined were the Rocky Mountain Double, the Triple, and the Turnpike Double. The researchers concluded that if LCVs are to operate on roadways with moderate to severe curvature, the lane widths on horizontal curves should be significantly increased to prevent encroachments into an adjacent lane or edge drop-off. Specifically, the Rocky Mountain Double and Turnpike Double exhibit low-speed offtracking worse than a standard tractor semitrailer. A Triple combination trailer was found to have the worst performance for high-speed offtracking.

Harwood et al. (*5*) subsequently examined the limitations imposed by existing roadway geometrics on the ability of the roadway system to accommodate potential larger and heavier trucks. The study acknowledges that a tractor-semitrailer combination with a 48-ft long semi-trailer is a baseline vehicle currently operating in all states (equivalent to an intermediate semitrailer with a wheelbase of 62 ft). The study focused on 12 truck sizes that exceeded this baseline tractor-semitrailer. Horizontal curves on mainline roadways and horizontal curves on freeway on- and off-ramps were two of the geometric elements identified as being in need of improvement. Horizontal curves, either on mainline roadways or ramps, require greater lane width to accommodate the swept-path width of these trucks. Geometric design guidelines typically call for a lane width in these horizontal curves of 14 to 15 ft. The 12 trucks sizes examined would all require a lane width in excess of 15 ft. Without these geometric improvements, trucks would encroach on other lanes or shoulders and potentially create a safety hazard.

Glines (*6*) summarized a research project to determine the impact of specific geometric features on truck operations and safety at expressway interchanges. The article summarized several conclusions; the ones related to design practices are listed below:

- Jackknife accidents are found ahead of curves that appear to pose a threat of rollover to vehicles traveling near or above the advisory speed. Truck drivers apply excessive braking in an attempt to reduce speed before entering the curve, suffering wheel lock-up conditions causing a jackknife before the curve is reached.
- AASHTO's policy for geometric curve design provides for virtually no margin of safety against rollover for certain trucks.
- Deceleration lanes that realistically reflect the braking constraints of trucks should be 30–50 percent longer than AASHTO guidelines suggest.
- The mismatch between the provided lengths of acceleration lanes and the acceleration length demands of loaded trucks may be prompting truck drivers to speed in the later portions of many interchange ramps to mitigate the inevitable conflicts associated with merging.
- AASHTO's policy of accepting ramp downgrades as high as 8 percent may be ill-advised at sites on which a relatively sharp curve remains to be negotiated toward the bottom of the grade.
- Curve warning signs were observed to be improperly selected or placed an insufficient distance ahead of the curve.
- State transportation departments should review ramps that have a history of accidents involving heavy-duty trucks. The use of improved warning and advisory speed signs, or removing curbs, may offer effective short-term countermeasures.
- Assurance of adequate pavement friction levels for safe operation of trucks calls for new research in truck tire traction.

Tom and Fong (*7*) summarized the activities of an evaluation of truck merging operations at a selection of four California freeway on-ramp locations with significant truck volumes. The 50th percentile merge location for truck combinations was approximately 1072 ft, compared to 498 ft for cars, 489 ft for recreational vehicles, and 565 ft for all vehicles. Researchers found that as more length was provided to accelerate and merge, more length was used by drivers. At each site, more than half of the merging maneuvers took place in the latter half of the length provided.

Ervin (*8*) summarized a research study to establish how particular expressway ramps cause drivers of tractor-semitrailers to lose control of their vehicles. The most basic conclusion of the study was that highway design in the United States does not sufficiently account for the special maneuvering limitations of heavy trucks. Ervin's study recommended that all AASHTO policies relating to the geometric design of highway ramps and other curved roadways be examined from the viewpoint of the maneuvering requirements of heavy trucks.

The author selected several sites to be illustrative of the range of ramp design problems identified by the computer simulations. The sites illustrated the more significant aspects of geometric design that limited margins of safety for heavy trucks operating on freeway connectors and ramps. Both the physical size of trucks and limitations in their physical performance caused problems when negotiating connector roadways. Several of the sites illustrated the major problems identified by crash records and by computer simulation.

- Site 1 – Tight curve with insufficient superelevation;
- Site 2 – Hazardous sequence of curves (flatter curves approaching tighter curves leading to errors in driver expectations);
- Site 3 – Short deceleration lane leading to tight-radius curve (deceleration lane lengths are deficient for trucks, resulting in excessive speeds at the entrance of sharply curved ramps);
- Site 6 – Poor pavement friction on high-speed curve (lightly loaded truck tires are sensitive to pavement texture in avoiding hydroplaning on high-speed ramps);

- Site 13 – Curb placed along the outside of curve (curbs placed on the outer side of curved ramps pose a peculiar obstacle that may trip and overturn articulated truck combinations); and
- Site 8 – Ramp downgrade leading to a tight curve (an exit ramp leading to a downward slope followed by a tight curve may result in truck drivers exceeding the safe speed).

Perera et al. (*9*) focused on the task of determining the critical speed of a ramp for heavy vehicles, then translating that into a safe operating speed. Through the use of computer simulation models and input of geometric design elements from an example ramp, researchers determined critical speed and safe operating speed for a baseline vehicle and a vehicle with a high center of gravity. The critical speed was the lowest speed at which the wheels of the subject vehicle would either begin to lift off of the ramp surface (rollover) or run off the ramp (offtracking). The safe operating speed was determined by dividing the critical speed by a factor of safety, assumed to be 2.0 for this test. For both vehicles (baseline and high center of gravity), the safe operating speed was determined to be 13 to 18 mph lower than the corresponding AASHTO design speed, based on the equations developed through the model.

Accommodating Trucks on Highways: State Department of Transportation Reviews

In response to increased truck traffic and experience with truck safety, several states have done reviews of how trucks are being accommodated on the highways in their state. The following highlights reports from Texas, Virginia, and Kentucky.

The Research and Technology Implementation Office of TxDOT did a survey of their districts in 2001 to determine what actions were being undertaken to accommodate the higher truck traffic being experienced in Texas (*10*). The survey consisted to two parts: what the districts were doing and suggested actions from district staff. At the time, the districts were undertaking a number of activities in the geometric design and traffic operations area:

- design: lane and shoulder widening project, providing passing lanes and providing climbing lanes, construction of additional rest stops, and construction of additional parking areas; and
- traffic: truck tipping hazard signs at selected interchanges, variable transverse striping at interchanges, and speed marking at interchanges.

The survey also suggested geometric and traffic operations measures to be undertaken. Specific recommendations made by district personnel were:

- reduce design criteria for maximum percent grade to result in a speed reduction of only 5 mph, rather than 10 mph allowed under current guidelines;
- provide wider shoulders along controlled-access facilities;
- adopt the Texas Super 2 guidelines for primary two-lane roads with high truck traffic; and
- use truck-oriented dynamic message sign displays.

Fontaine performed a state-of-the-practice review for the Virginia Department of Transportation (DOT) on engineering and technology measures to improve truck safety (*11*). The study used both a literature review and a survey of Virginia DOT personnel. The study found support for the following measures:

- design: climbing lanes, truck escape ramps, improved ramp geometry, improved geometric design of interchanges, and improved design of parking facilities;
- traffic: rumble strips; and
- intelligent transportation systems (ITS): ITS speed advisory systems, automatic truck rollover warning systems, and improved traveler information.

The study also mentioned that there was no consensus on the use of truck lane restrictions and differential speed limits for trucks. The Kentucky Transportation Center also conducted a study on impacts of large trucks on highway safety (*12*). Similarly, this study recommended countermeasures related to design, traffic engineering, and ITS:

- design: construct climbing lanes, emphasize truck needs in work zones, increased use of concrete median barriers, and provide additional parking facilities;
- traffic: include audible rumble strips on shoulders; and
- ITS: provide real-time congestion/incident information, provide real-time weather information, and use speed monitoring equipment in advance of ramps with low design speeds.

In summary, facility geometric design characteristics that may affect truck use of toll roads and managed lanes include:

- general design characteristics including design speed, horizontal and vertical clearance, stopping sight distance, superelevation, cross slope, minimum turning radius, horizontal and vertical curvature and gradient, lane and shoulder width, and the number of lanes set aside as tolled or managed lanes;

- ramp junctions, including within or entering or exiting from the tolled/managed lane facility;
- direct connect ramps and ramp configurations; and
- system connectivity.

CORRIDOR OPERATIONAL CHARACTERISTICS

A number of study efforts have attempted to define the corridor operational characteristics that would lead to successful operation of trucks on highways, most commonly, studies on exclusive truck facilities. A study done for the Federal Highway Administration (FHWA) (*13*) developed a method and computer program called Exclusive Vehicle Facilities Software (EVFS) to help determine the economic feasibility of separating light and heavy vehicles on interstate and other controlled-access highways. EVFS calculates the net present worth, benefit-cost ratio, and other corridor performance measures for various lane configurations that designate existing lanes or provide additional lanes exclusively for trucks or passenger vehicles. Cost components include engineering and construction, right-of-way acquisition and demolition, and periodic pavement resurfacing.

Most recently, Samuel et al. (*14*) considered the feasibility of truck tollways. In doing so, they developed an analysis methodology consisting of three main components: pavement design, productivity analysis, and feasibility analysis. The pavement design examined various scenarios of truck usage, enabling realistic estimation of initial investment, and providing input to pavement deterioration models. The productivity analysis quantified the impact that the truck tollway system would have upon the productivity of truck fleets, measured by the resulting changes in operating costs. Results provide information about the range of tolls that could be levied from trucks using the truck tollway system (*14*). The feasibility analysis estimated the likely feasibility of the proposed toll truck tollway concept using modeled pavement deterioration and corresponding estimated road user costs. The feasibility analysis considers two major facets: the overall economic feasibility of the project from the system-wide point of view and the private (financial) feasibility of the project from the standpoint of a private truck tollway developer/operator.

Utilizing this same analysis procedure and building upon the earlier work of Samuel et al. (*14*), Holguin-Veras et al. (*15*) considered the effects of exclusive truck lanes in combination with high gross weight limits and sizes for trucks using the system, actual tolls levied on trucks using the system, and providing gas tax rebates for exclusive lane-miles traveled. The feasibility study, complemented by a sensitivity analysis on key variables, strongly suggests that at relatively low traffic levels (20,000 vehicles per day) exclusive lane implementation has a beneficial economic effect. As traffic increases, so does the benefit. As determined by the balance between revenue stream and the annualized exclusive lane building and operating costs, the financial feasibility analysis indicates that tolls between $0.25 and $0.50 per kilometer ($0.40 and $0.80 per mile) yield a rate of return higher than the opportunity cost of the capital (estimated at 6 percent).

Middleton and Venglar (*16*) conducted VISSIM microsimulation analysis on generic rural highway sections to examine the capacity of truck roadways under varying geometric design elements. The geometric design variables they looked at were vertical grade, longitudinal coverage of grade, and interchange spacing. The researchers also varied the percent of entering and exiting truck traffic at the ramp junctions. The simulation results indicated that truck facilities capacities could range from 1025 to 1475 trucks per hour per lane depending on the grade and interchange spacing.

In practice, exclusive lanes for trucks are infrequent. According to *NCHRP Synthesis 314, Strategies for Managing Increasing Truck Traffic* (*1*), only one state of 25 reports approval of a dedicated road for trucks; the New York State DOT (NYSDOT) has allocated $11 million for a new truck-only route along Edgewater Road between the southbound Sheridan Expressway and the Hunts Point Market. Because of limited implementation, the majority of site-specific studies conducted (i.e., Washington, California, Florida, Georgia, and the I-35 multi-state corridor) have considered the feasibility of exclusive truck lanes and simulated impacts; no implementations have provided observed evaluation results.

Washington

A simulation study conducted in Washington (*17*) considered the effects of both exclusive truck lanes and the use of existing high-occupancy vehicle (HOV) lanes by trucks along several routes in the greater Seattle area. The study considered operational impacts, economic impacts, safety impacts, and pavement deterioration rates, as well as public opinion.

The study found that "reserved capacity" strategies for trucks would offer nearly $10 million in annual travel-time savings for the trucking industry in the Seattle region. The impact on individual trips would be small, about 2.5 minutes saved per average trip (less than 8 percent savings in trip travel time). The biggest impact of truck reserved capacity strategies is in the travel-time savings they would create for single-occupant vehicles, almost $30 million per year. This travel-time savings would be an artifact of the current underutilization of HOV lanes in the Seattle area and not necessarily a virtue of reserved-capacity strategies. The difference in travel times between the reserved capacity strategy that adds trucks to the existing HOV lanes and the one that adds an exclusive truck lane are insignificant, providing little justification for construction of an exclusive lane.

California

Similarly, Taylor (*18*) completed a feasibility study on exclusive lanes for commercial trucks along State Route 60 (SR-60), from I-710 to I-15, a distance of approximately 38 miles. This freeway, serving intermodal freight yards and bridging between the Ports of Long Beach/Los Angeles and inland areas, currently carries a daily truck volume of more than 20,000 in some locations, projected to more than double by 2020. SR-60 is identified in the Southern California Association of Government's (SCAG) adopted 2001 Regional Transportation Plan as one of four highways planned to include exclusive truck lanes by 2025. In the current Regional Transportation Plan for Southern California, the SCAG identifies dedicated truck lanes as a means to more efficiently keep goods movement flowing smoothly, improve overall mobility along the freeway, and improve traffic safety and air quality.

Three main strategies were considered: 1) allowing trucks to share the HOV lanes during limited time periods, 2) adding truck lanes to the freeway at grade, and 3) adding lanes above the freeway grade. The shared HOV option was dropped due to a number of barriers including legal and funding obstacles. The study recommended combining the two remaining strategies, with at-grade truck lanes built where feasible and above-grade mixed-flow lanes (trucks would operate at grade for safety) built where right-of-way acquisition would be difficult. Above-grade lane sections should be kept to a minimum due to safety and operational consideration, as well as higher construction costs.

Florida

With a directed focus on areas where trucks have a significantly negative impact on safety and congestion, Reich et al. (*19*) considered the feasibility of separating large trucks from the traffic mix. Researchers constructed several geographic information system (GIS) models to identify "hot spots" based on truck crashes, truck volume and percent, and level of service. Both rural and urban locations were considered, as each scenario presented a different set of challenges. Lastly, researchers assessed the feasibility of countermeasures for each site. Researchers determined that most of Florida's interstate system was suitable for exclusive truck facilities, with the most appropriate areas having sufficient available right of way.

Georgia

Most recently, Parsons, Brinkerhoff, Quade, and Douglas (*20*) completed a feasibility study in Atlanta that considers HOV, high-occupancy toll (HOT), and truck-only toll (TOT) lanes. With respect to TOT lanes, the stated facility objectives are to: 1) improve safety – the inherent safety problem created by the size disparity between trucks and other automobiles and danger of traveling side by side at high speeds and in congested areas is avoided; 2) improve efficiency – freight could travel more efficiently without placing a strain on the already limited federal, state, and local highway funds; and 3) generate revenue – tolls provide an additional source of revenue to pay for transportation improvements. The overall goal is to manage heavy-duty vehicle flow in transportation corridors by maximizing the utilization of transportation infrastructure in order to improve productivity and enhance safety.

The project study area included all limited-access facilities in the 13-county Atlanta region. This study examined three TOT lane alternative concepts (scenarios):

- **A1 Major Truck Corridors.** Along two of the most promising corridors in the region, two TOT lanes would be constructed in each direction, in addition to HOV lanes, with access provided to the local road network at appropriate locations.
- **A2 Service to Deliveries.** Assuming that the TOT lanes of A1 are in place, the current HOV lanes inside I-285 would additionally be reserved for light-duty commercial vehicles willing to pay a fee during the midday.

- **A3 Regional TOT Network.** All existing and proposed HOV lanes would be converted into TOT lanes (except inside I-285, where the current prohibition for through truck trips is maintained), with no need to construct separate TOT lanes.

Measures of the long-term performance of each scenario were developed to determine if any fatal flaws exist in the TOT concept. The study found that under any of the three scenarios: 1) total vehicle hours traveled are reduced with a negligible change in vehicle miles traveled; 2) trucks can save a significant amount of time; 3) congestion in general-purpose lanes is significantly improved; and 4) respectable amounts of revenue can be generated to cover operating and maintenance costs.

In summary, the operational characteristics that may affect truck use of toll roads and managed lanes include:

- overall congestion levels (peak period and other) on the facility, including tolled or managed lanes and general purpose lanes;
- percentage of trucks in the general traffic stream;
- entrance and exit activity for trucks (local vs. long-haul, industry centers, etc.);
- allowable speed limits on the facility, including tolled or managed lanes and general purpose lanes;
- speed differentials within the toll/managed lane facility and between the tolled/managed lane facility and the general purpose facility;
- availability of and traffic and geometric conditions on potential alternate routes;
- tolled/managed lane accessibility, including the type and degree of separation from the general purpose facility and the number and frequency of ingress/egress points;
- tolled/managed lane hours of operation (i.e., continuous, extended hours, or peak travel periods only);
- tolled/managed lane eligibility criteria, including vehicle types, vehicle occupancies, toll structures, etc.;
- tolled/managed lane enforcement strategies; and
- freight movement incentives, including allowable use of longer combination vehicles, higher gross vehicle and axle weight limits, etc.

INDUSTRY CHARACTERISTICS

Perhaps the most important factor influencing truck and freight use of toll roads or managed lanes are the industry's own needs and business processes. Surprisingly, few of the studies that have considered the feasibility or impact of trucks in tolled or managed roadways have also considered the trucking industry perspective to any great extent. Several factors may offer explanation:

- The trucking industry is diverse, comprising local and long-haul carriers, less-than-truckload carriers, interstate and intrastate carriers, common and private carriers, small carriers with a single truck to carriers managing fleets of several thousand, etc. Each has distinctive administrative and operational practices and philosophies.
- Because of the competitive nature of the industry, the information to support an investigation of the administrative and operational practices and philosophies is not readily accessible.
- Administrative and operational philosophies are determined by numerous factors including local, state, and federal regulation related to noise ordinances, driver hours, shipper and receiver constraints and logistics, commodity types and delivery windows, load/unload times, etc.
- The trucking industry is dynamic, constantly changing to improve efficiency and reduce delays.

Bill Webb, President of the Texas Motor Transportation Association, spoke to the Trans-Texas Corridor Advisory Committee in September 2005 (*21*). His comments reflect many published comments of the trucking and freight industry. The trucking industry in Texas is large and diverse. There are 43,000 trucking companies registered to operate in the state. The top 100 carriers represent 60 percent of the industry, with the average being a 12-truck, family owned operation. Some of his observations of what the industry may support include:

- tolls on new capacity, not on existing facilities;
- toll in corridors where a "free" alternative is available;
- tolled facilities that allow for increased speed, size, and weight;
- tolled facilities that are managed to control consistency of speed;
- interoperability of tag/transponder technology; and
- tax relief where tolls are levied.

The underlying question for this research project is: do the potential benefits provided by a toll road or managed lane (i.e., reduced delay, improved reliability, enhanced safety, etc.) offer something of value to the trucking industry that outweighs the potential costs (i.e., increased operating costs attributable to tolls, negative public reaction, etc.)? To answer this question, one must have a clear understanding of how congestion-related delays and unpredictability in travel times truly affect the overall delivery process (i.e., how do congestion delays rank in comparison to other delays caused by limits on driver's hours, double handling of the product, wait time for connections or access, rough pavement, company-imposed maximum speed restrictions, etc.) and the range of alternative solutions (to avoid paying a toll) that the trucking industry can draw from (i.e., changing hours of operation to avoid peak travel periods, changing travel routes to avoid congested segments of the roadway, etc.).

For example, using traffic simulation of the Seattle-area roadways, Trowbridge et al. (*17*) estimated an annual savings in truck travel time of 395.8 vehicle hours during the peak morning hour or $9,786,551 per year (assuming an average of $15.85 per hour for truck drivers) if they were allowed to use the HOV lanes. While this seems significant, the actual per-trip savings for trucks is small, only about 2.5 minutes per trip. Whether these savings could be translated into improved productivity is questionable; 2.5 minutes is too small a time increment to be used productively by manufacturing inventory control and dispatching. An exclusive lane shows somewhat smaller benefits of saving 7.8 truck hours during the morning peak period. These small improvements reflect the relatively small number of heavy trucks. A reduction in variance was considered but not quantified as part of this study. The study did suggest, however, that since much of a truck's total trip takes place on non-exclusive or reserved facilities, that the change in variance attributable to truck only lanes would be small.

As part of this same study (*17*), several attitudinal surveys were conducted to gauge the reaction to both exclusive truck lanes and the use of existing HOV lanes by trucks along several routes in the greater Seattle area. Researchers solicited opinions from: 1) the trucking industry, 2) truck drivers (local and long-haul), 3) motorists who do and do not use the existing HOV lane, and 4) law enforcement officers. To capture the broader trucking industry perspective: 1) mail-back surveys were handed out at truck stops, 2) two large companies were contacted and had their drivers participate, and 3) the state trucking association distributed surveys to their members. The following description summarizes the findings from those surveys.

Truck Company Survey

The key findings from the trucking industry surveys are as follows:

- Routes of choice for truck drivers are not regulated by companies according to 65 percent of respondents.
- Only 8 percent of companies regulate travel times of urban highways to avoid general peak commute times.
- Most companies, 87 percent, regulate the speed of their trucks on the highways with the most common allowable maximum speed being 60 mph or below.
- A majority of respondents felt that separating trucks would improve both safety and congestion.
- Strong disagreement was reported by 69 percent of respondents that large trucks should pay a special usage fee for using a reserved or shared lane.

General Public Survey

The key findings from the survey of the general public are as follows:

- Loaded trucks will cause problems for empty trucks on uphill grades, such as speed differential within the lane.
- Survey respondents do not want trucks impeding faster moving HOV or toll traffic.
- Traffic backups cost money that cannot easily be charged back to customers.
- Overcoming "left-lane restriction" mentality, most trucks are used to being restricted to the right-hand lanes, traveling in left lanes may be uncommon.
- Time sensitivities of materials hauled (i.e., concrete, etc.).
- Lane widths should be wider than normal to accommodate oversize/overweight loads.
- Do not want trucks speeding.
- Pay trucks by the hour instead of by the mile to increase safety.
- Differences between long-haul passing through and local requiring access.
- Much of the industry requests and encourages greater enforcement of existing restrictions—level playing field.

Truck Driver Survey – Long Haul

The key findings from the long haul truck drivers are as follows:

- Changing their hours of operation to account for congestion was reported by 76 percent of truck drivers.
- Changing their route to account for congestion was reported by 81 percent of truck drivers.
- 65 percent disagree strongly that large trucks should pay a special usage fee for using a reserved or shared lane.

Truck Driver Survey – Local

The key findings from the local truck drivers are as follows:

- Changing their hours of operation to account for congestion was reported by 22 percent of the truck drivers.
- Changing their route to account for congestion was reported by 69 percent of truck drivers.
- Pay a special usage fee for using a reserved or shared lane was strongly disagreed to by 73 percent of the respondents.

General Overall Survey Findings:

The key overall survey findings are as follows:

- Consistency in lane "rules" is important to both general public and trucking industry.
- Trucks impact other lane users by increased delay, decreased safety, and decreased visibility.
- Speed differentials are caused by trucks within the lane and between the lanes; large trucks cannot maintain a constant speed.
- Speed differentials are caused when entering and exiting the lane.
- Some delay is incurred at the warehouses due to loading/unloading.
- Consideration should be given on how trucks using this lane preserve intended use of the lane. For example, HOV lanes are intended to encourage carpooling, reduce fuel consumption, and reduce pollution; however it is not clear how trucks impact these intended uses.

- Increased merging maneuvers can result depending on the lane location. Cars will often not allow trucks to merge in congested conditions.
- The trucking industry is sensitive to increased fees due to already increased fuel taxes, license fees, etc.

Despite 82 percent of the general public agreeing that large trucks are important to our nation's economy, only 28 percent of the general public thought that trucks should have the same travel benefits as public transit and HOV. Seventy-eight percent of truckers thought they should share these benefits. Only 2 percent of truckers agreed that trucks should pay a special usage fee to use a reserved lane or existing HOV lane, compared to 35 percent of the general public. The general public expressed concerns related to speed differential, poor visibility, safety, diesel smell, intimidation, congestion in preferential lane, etc.

Researchers with the Texas Transportation Institute (TTI) have contacted and worked extensively with various elements of the motor carrier community for many years. These contacts include contacts of individual carriers in a variety of states, state level organizations of motor carriers, and the American Trucking Associations (ATA) Foundation (now American Trucking Research Institute). In one recent federally funded research project, TTI worked directly with the ATA Foundation interviewing a wide range of motor carrier representatives. TTI has become very familiar with the Texas Motor Transport Association (TMTA) through involving their staff and members in a variety of research projects, mostly sponsored by TxDOT.

In the federal research mentioned above, TTI contacted and interviewed a large body of industry representatives, including motor carriers and their drivers. Table 1 summarizes some aspects of these interviews to give an indication of their breadth. The research included interviews with a full spectrum of private and for-hire carriers. These included the large for-hire carriers operating over 2000 units down through smaller regional and commodity-specific carriers, including some owner-operators operating one to 10 units. Large fleets included large less-than-truckload (LTL) carriers using van-type cargo trailers, mid-size and small fleets included tanker operations, and material haulers. The subject of the interviews was the feasibility of using on-board diagnostics to enhance roadside safety inspections. Clearly, most drivers and some management personnel anticipated that the introduction of any means of monitoring the vehicle could also monitor their behavior and were very skeptical. However, the TTI interviews were structured to capture the appropriate information while allaying fears of privacy intrusion.

Table 1. Summary Profile of Motor Carriers Interviewed.

Category	No. of Carriers	No. of Tractors
Owner Operator	8	19
For Hire	33	86,282
Private	9	4,738

SUMMARY

There has been considerable research in the past on trucks' impact on the design and operation of highway facilities. This information can be effectively synthesized to create guidelines on which corridors may have operational and design characteristics suitable for truck use of toll roads or lanes or, conversely, what characteristics are needed to attract truck use to a facility. The subsequent chapters use the information available to craft these guidelines to be most effective for use by highway engineers designing toll road and managed lane facilities.

CHAPTER 3: SURVEYS OF TRUCKING INDUSTRY

A survey on opinion of geometric design elements was prepared to solicit input from truck drivers and the trucking industry. The Appendix presents the survey questions. In an effort to reduce research costs, the survey was to be combined with another TxDOT project on value pricing and truck drivers' understanding of toll roads *(22)*. Once the surveys were compiled, the researchers felt that the length of the combined survey would deter responses due to the time to complete the survey, ultimately not serving either project. The value pricing project survey was administered, and this chapter summarizes the findings. To gather input on the trucking industry needs related to geometric design and operational factors, the project made use of other relevant published surveys.

The TxDOT value pricing project conducted surveys in the I-35 area around Austin, Texas, to better understand truckers' use of toll roads. Trucker responses to incentives were classified as follows:

- Lower fuel prices were the biggest motivation for using the toll roads.
- Other responses were: no congestion, dining facilities with better parking lots for trucks, and wide shoulders for emergencies all received an above average score.
- Smaller trucking companies (owner-operator) clearly preferred the non-toll route, citing the fact that tolls come directly out of their expenses and it is difficult to pass these costs on to their customers.
- Larger companies were more likely to carefully weigh the benefits and costs of using the toll route when making their decision rather than avoiding toll roads in general.

The American Transportation Research Institute (ATRI) conducted a survey on behalf of the Georgia State Road and Tollway Authority. The survey asked opinions of motor carriers on potential TOT lanes in the Atlanta area. Responses were received from 71 Georgia-based trucking firms, mostly for-hire carriers and private fleet operators. The key findings from this survey were:

- Georgia carriers were willing to use optional TOT lanes when no costs exist and a pricing mechanism could successfully keep TOT lanes at free-flow levels.
- Congestion was thought to lead to the use of alternate routes by 49 percent of the respondents.

- Use of alternate routes in anticipation of congestion was reported by 42 percent of the respondents.
- Only 3 percent said delivery time was flexible.
- Highways congested and traffic accidents were the two greatest reasons for using TOT lanes.

Darrin Roth, speaking to the International Symposium on Road Pricing, made the following statements concerning the trucking industries views on use of pricing and tolls (*23*):

- A recent study found significant diversion from Ohio Turnpike following an 82 percent toll rate hike.
- Vehicles are using congested alternate routes instead of free-flowing turnpikes.
- 70 percent of trucks on one arterial are using the road solely to avoid a toll.
- Facilities that are supported by the trucking industry include:
    - Reason Foundation truck lanes,
    - Trans-Texas Corridor,
    - Southern California truck lane proposal,
    - Electronic toll collection lanes (e.g., FAST lanes), and
    - HOT lanes on existing HOV lanes.

Wolshon and Ciprian (*24*) conducted a study on trucker perceptions of lane restriction and differential speed limit policy on freeways in Louisiana. A total of 159 responses were received from trucking companies. Overall, truckers were not in favor of the restrictions imposed on their driving, and the truck drivers did not perceive a significant safety benefit. Other findings from the survey were:

- 83–85 percent of respondents said information on lane restrictions are effectively communicated and clearly understood by truckers.
- 57 percent of respondents expressed that the existing speed deferential policies worked to diminish safety.
- The most common complaint was that the reduced speed policy resulted in long queues of trucks in the right lane, which in turn led to reductions in sight distance.
- Lower speeds resulted in reductions in levels of driver alertness.
- The most common reasons for lane changing into the restricted lane were to avoid breakdowns and slower moving vehicles.

Ko et al. (*25*) conducted a survey to understand the trucking industry's perceived factors affecting level-of-service on freeways. Approximately 500 surveys were received from Florida truck drivers and truck company mangers (459 truck drivers and 38 truck company managers). The following findings were developed:

- The top two most important factors, ranked by both truck drivers and truck company managers, were passenger car drivers' knowledge about truck driving characteristics and passenger car drivers' road etiquette.
- The top five geometric design factors felt to influence level-of-service, ranked by truck drivers, were: availability and condition of signage, lane width, road striping, shoulder width, and length of merge/diverge lanes. (The signing factor was not specific to location of the sign.)
- Truck company mangers gave more importance to timing of construction activities—availability of alternate routes—and tended to be more concerned about the overall travel time as opposed to the truckers concern for drive quality and consistency of travel during the trip.

The survey also presented some proposed performance measures and asked which should be used as a performance measure for freeways. The top ranked performance measures by truck drivers were good ride quality (i.e., enhanced ride comfort and minimize impact on truck equipment and goods being transported) and ease of maintaining a consistent speed (i.e., enhanced driving safety and minimize the need for acceleration and deceleration).

Adelakun and Cherry (*26*) explored truck driver perceptions of urban congestion and safety and gauged their interests in potential geometric or operational solutions. The researchers conducted an intercept survey at truck stops along I-75 and I-40 in Knoxville, Tennessee. One question specifically asked drivers about the interactions with passenger vehicles on roadways. Truck drivers were asked to pick two factors from a list as to which most significantly reduced their efficiency and safety.

- Two of the top five answers were vehicles exiting off-ramps and vehicles entering on-ramps.
- The other three responses in the top five were aggressive drivers, lane changing, and fast trucks.

The American Trucking Associations Federation for several years has commissioned the ATRI to conduct an annual survey on critical issues facing the trucking industry (*27*). Congestion continued to rise in priority of responses from the ATRI survey. Congestion was ranked 4th place in 2007, up from 5th place in 2006 and 8th place in 2005. Possible solutions were noted as:

- Identify tools and strategies for expanding roadway capacity with an emphasis on infrastructure maintenance and expansion for the highest congested corridors. Fifty-six percent of the respondents ranked this the number one strategy.
- Examine the potential for truck-only lanes/corridors/networks. Responses focused on the voluntary use, reasonable tolls, adequate entrance and exit points, and assurances that passenger vehicles would be prohibited from use.

SUMMARY

While many of the surveys conducted with truck drivers and trucking companies had different focuses, there were some consistent answers on what geometric design elements are important to truck drivers. Lane width, shoulder width, signing, pavement markings, ramp and interchange design, and supporting parking facilities were mentioned as important factors to trucking operations.

The top concerns of truck drivers and trucking managers in several of the surveys were passenger car drivers' lack of knowledge on truck driving and passenger car driver behavior in the traffic stream on roadways. Truck drivers also gave consistent answers on their frustration with congestion, speed differentials, and lane restrictions. Truck drivers may support truck only facilities, but their preference is for these facilities to exclude passenger cars, charge reasonable or no tolls, and remain congestion free.

CHAPTER 4: GEOMETRIC DESIGN FACTORS

The Texas geometric design guide is TxDOT's Roadway Design Manual (*28*). The national guide is the AASHTO Green Book (*29*). Both of these design guidelines incorporate trucks and heavy vehicles into their procedures. This chapter looks at the horizontal alignment, vertical alignment, and cross section geometric elements that could be considered in designing toll roads and managed lanes to increase truck driver comfort to improve driving efficiency and safety. In general, these recommendations reinforce or exceed the criteria in the state and national geometric design guides.

These design factors are important, as there is increasing pressure in developing projects in developed corridors to use minimum or reduced design values. A recent review of high-occupancy and managed lane projects in the United States found nearly two-thirds of the projects (i.e., those coded with red squares) use some form of reduced design values (*30*).

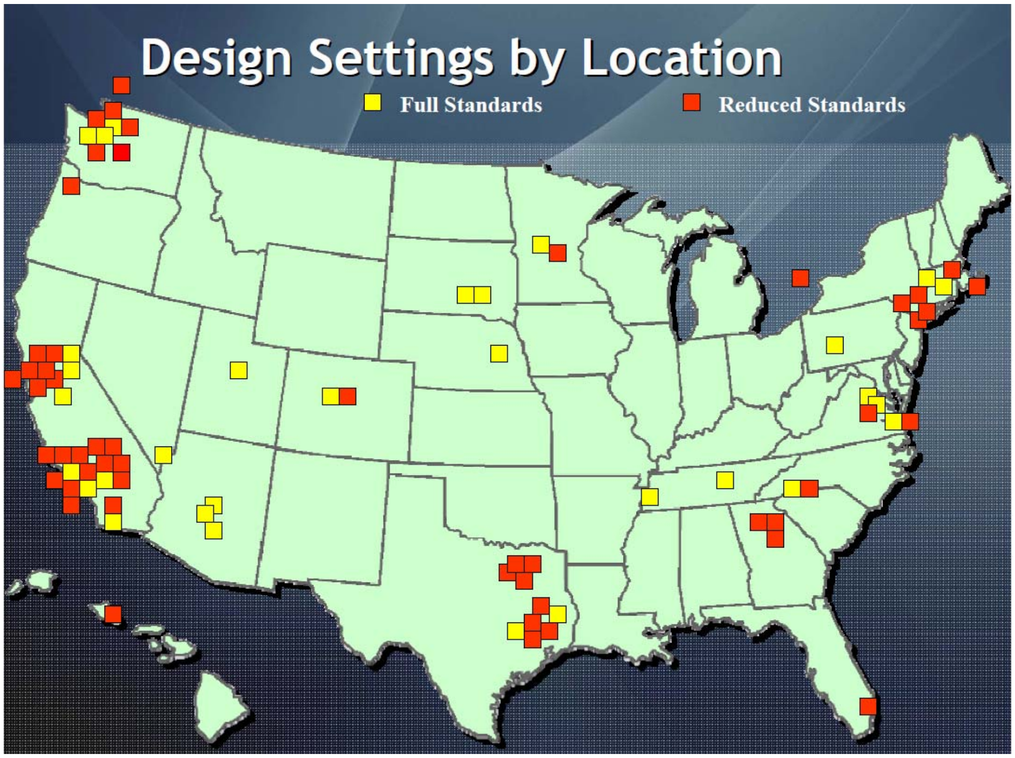


Figure 1. HOV/Managed Lane Projects Using Reduced Design Values (*30*).

While many of these projects may be termed interim projects, the findings show a trend of what may be the difficulty in constructing new facilities in developed corridors. Highway designers must make design trade-off decisions routinely on projects as they are developed within the context of the surrounding environment. However, designers must recognize that these decisions may have a negative impact on the willingness of truck drivers to use these facilities.

TXDOT ROADWAY DESIGN MANUAL

The Texas *Roadway Design Manual* was developed by the Department "to provide guidance in the geometric design of roadway facilities. The manual represents a synthesis of current information and operating practices related to the geometric design of roadway facilities" (*28*). There are two sections that specifically address the type of facility with which toll roads would be most associated. Section 6 of Chapter 3 presents the freeway guidelines and Chapter 8 presents the mobility corridors guidance.

Freeways

Freeways are typically the highest functional classification of facility. Access is fully controlled to provide the highest level of mobility. Section 6 discusses freeway design criteria within Chapter 3 on new location and reconstruction (4R) design criteria. The freeway design criteria includes: basic design criteria, access control, mainlanes, vertical and horizontal clearance at structures, frontage roads, and interchanges.

Mobility Corridors

Mobility corridors is a relatively new section of the Texas *Roadway Design Manual*. Mobility corridors are focused on mobility and thus have full control of access to these facilities. One of the characteristics that separate these facilities is the high range of design speeds between 85 mph and 100 mph.

AASHTO POLICY ON GEOMETRIC DESIGN OF HIGHWAYS AND STREETS

The national guidelines for roadway geometric design are the American Association of State Highway and Transportation Officials (AASHTO) *A Policy on Geometric Design of Highways and Streets* (referred to as the Green Book) (*29*). Throughout the Green Book, there is guidance on roadway design for trucks. Specifically, the Green Book addresses the following design elements:

- design vehicle characteristics:
  - length, width, and height,
  - combinations,
  - minimum turning radius,
  - off-tracking,
  - weight-to-power ratio;
- driver characteristics:
  - driver eye height;
- design for operational analysis;
- braking capability and stopping sight distance;
- control grades and critical length of grades:
  - operating characteristics on grades,
  - deceleration on grades,
  - acceleration on grades; and
- climbing lanes.

BASIC DESIGN CRITERIA

The following section identifies the basic design criteria related to designing toll roads and managed lanes for increased attractiveness to truck drivers. If a design element is not addressed, it should be assumed that there is no additional information beyond what is currently presented in the Texas *Roadway Design Manual*.

Design Speed

Design speed "is a selected speed used to determine the various geometric design features of the roadway" *(29)*.

- For toll roads and managed lanes, a design speed of 70 mph should be considered, regardless of urban or rural environment. Higher design speeds should be considered in relationship to the mobility corridor criteria.

Selection of a realistic design speed is critical to safety for trucks (*31*). When trucks exceed the design speed, the likelihood of skidding or rolling over is higher for trucks due to having different vehicle characteristics from passenger vehicles (e.g., higher center of gravity). The most unstable trucks can roll over when traveling as little as 5 to 10 mph over the design speed. Special care should be taken when selecting design speeds less than 30 mph to confirm that these design speeds will not be exceeded by trucks.

Design Vehicles

Trucks generally require more generous geometric designs than do passenger vehicles. This is attributed to trucks having longer wheel bases and greater minimum turning radii. Trucks are one of four general classes of design vehicles described in the Green Book. The truck class includes eight different design vehicles as follows:

- single-unit truck,
- intermediate semitrailer – WB-40 (40-ft wheel base),
- intermediate semitrailer – WB-50 (50-ft wheel base),
- interstate semitrailer – WB-62 (62-ft wheel base),
- interstate semitrailer – WB-67 (67-ft wheel base),
- double-trailer combination – WB-67D (67-ft wheel base),
- triple-trailer combination – WB-100T (100-ft wheel base), and
- turnpike-double combination – WB-109 (109-ft wheel base).

The Green Book states that the interstate semitrailer WB-67 should generally be the minimum size design vehicle for consideration for freeway ramp terminals intersection with frontage roads or arterials streets on routes that provide access for trucks. Figure 2, from the Green Book, shows an example of the design vehicle characteristics for the truck class of Interstate semitrailer WB-67 (*29*).

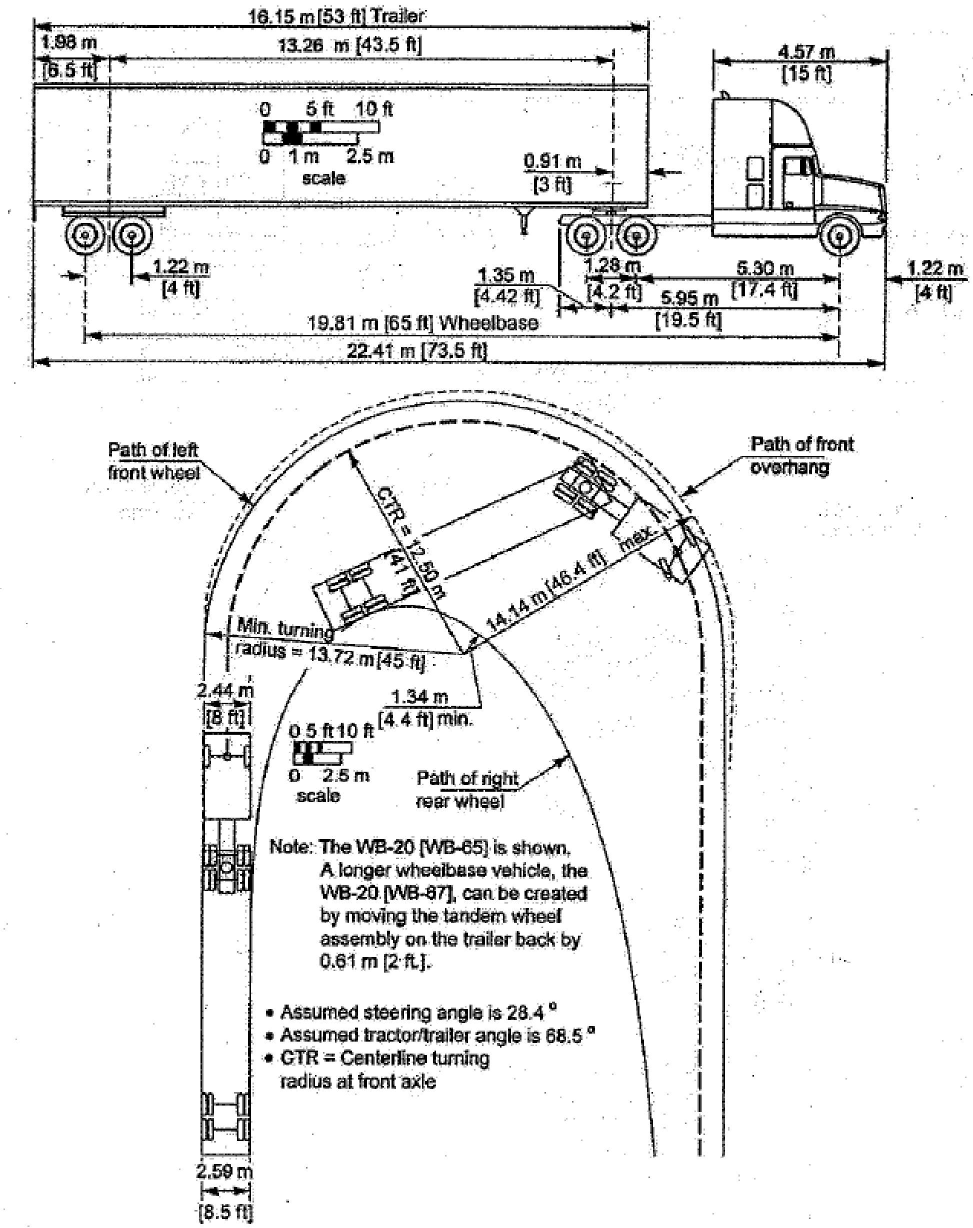


Figure 2. Minimum Turning Path for Interstate Semitrailer – WB-67 (*29*).

Stopping Sight Distance

Stopping sight distance in the Green Book is based on the passenger car as the design vehicle and is based on the driver perception reaction time and the driver comfortable deceleration rate. It is generally considered that the additional stopping sight distance a truck may need for slower deceleration rates is offset by the increased driver eye height. The driver eye height for a truck driver ranges from 5.9 to 7.9 ft. The Green Book recommends a value of truck driver eye height for design of 7.6 ft. Comparatively, the driver eye height for a passenger vehicle is assumed to be 3.5 ft.

Braking distance is one of the components of stopping sight distance. Two studies (*32, 33*) discuss additional braking distances for trucks. Truck braking distance should consider both the best- and worst-case drivers. Table 2 shows the braking distances for passenger cars from the AASHTO Green Book. Anti-lock brake systems are not required on most trucks; however, there is still a significant percentage of the truck traffic population with improper performing brakes (*34*). Table 2 also shows the braking distances for worst performing truck drivers, best performing truck drivers, and trucks with anti-lock brake systems.

Table 2. Truck Braking Distance on Wet Pavement.

Design Speed (mph)	AASHTO Criteria for Passenger Cars (ft)	Braking Distance for Trucks (ft)		
		Worst-Performance Driver	Best-Performance Driver	Anti-lock Brake System
20	38	77	48	37
30	86	186	115	88
40	154	344	213	172
50	240	538	333	267
60	345	744	462	375
70	470	1013	628	510

One situation the Green Book does call out for additional stopping sight distance for trucks is on downgrades. The Green Book states "Although the average truck driver tends to be more experienced than the average passenger car driver … it is desirable under such conditions to provide stopping sight distances that exceed the values [in Table 2]." Table 3 shows the stopping sight distance needed on downgrades from the AASHTO Green Book.

Table 3. Stopping Sight Distance on Grades (*29*).

Metric							US Customary						
Design speed (km/h)	Stopping sight distance (m)						Design speed (mph)	Stopping sight distance (ft)					
	Downgrades			Upgrades				Downgrades			Upgrades		
	3 %	6 %	9 %	3 %	6 %	9 %		3 %	6 %	9 %	3 %	6 %	9 %
20	20	20	20	19	18	18	15	80	82	85	75	74	73
30	32	35	35	31	30	29	20	116	120	126	109	107	104
40	50	50	53	45	44	43	25	158	165	173	147	143	140
50	66	70	74	61	59	58	30	205	215	227	200	184	179
60	87	92	97	80	77	75	35	257	271	287	237	229	222
70	110	116	124	100	97	93	40	315	333	354	289	278	269
80	136	144	154	123	118	114	45	378	400	427	344	331	320
90	164	174	187	148	141	136	50	446	474	507	405	388	375
100	194	207	223	174	167	160	55	520	553	593	469	450	433
110	227	243	262	203	194	186	60	598	638	686	538	515	495
120	263	281	304	234	223	214	65	682	728	785	612	584	561
130	302	323	350	267	254	243	70	771	825	891	690	658	631
							75	866	927	1003	772	736	704
							80	965	1035	1121	859	817	782

HORIZONTAL ALIGNMENT

Easa and El Halim (*35*) highlight that many geometric elements, such as horizontal and vertical curve design, in the AASHTO Green Book are based on the point-mass model. The point-mass model, while simplifying implementation, has shortcomings because it does not address different vehicle characteristics (i.e., cars versus trucks) or roadway characteristics (simple, compound, or reverse curve). The researchers point out that trucks have significantly different forces acting on the vehicle due to differences in height, weight, length, number of tires, and suspension. They further argue that tractor-trailer trucks have a higher center of gravity, which results in less margin of safety when trucks deviate from the design speed of a roadway.

Curve Widening in Horizontal Curve Design

Offtracking is when a vehicle's rear wheels may track inside or outside of the front wheels. This characteristic is more pronounced for trucks. The amount of offtracking is dependent on the curve radii, vehicle speed, superelevation, and size of vehicle. Table 4 presents the recommended traveled way widening for trucks from the AASHTO Green Book.

Table 4. Traveled Way Widening on Horizontal Curves (adapted from *29*).

Design Values for Pavement Widening on Highway Curves (ft)														
Curve Radius (ft)	24 ft Design Speed (mph)				22 ft Design Speed (mph)				20 ft Design Speed (mph)				Adj for WB-100T	Adj for WB-109D
	30	40	50	60	30	40	50	60	30	40	50	60		
7000														
6500												2.0	0.1	0.3
6000												2.0	0.1	0.3
5500												2.1	0.1	0.4
5000											2.0	2.1	0.1	0.4
4500											2.1	2.2	0.1	0.5
4000										2.0	2.2	2.3	0.1	0.5
3500										2.1	2.3	2.4	0.1	0.6
3000									2.0	2.2	2.4	2.6	0.1	0.7
2500									2.2	2.4	2.6	2.8	0.1	0.8
2000								2.1	2.4	2.6	2.8	3.1	0.2	1.0
1800							2.0	2.2	2.5	2.8	3.0	3.2	0.2	1.1
1600							2.2	2.4	2.7	2.9	3.2	3.4	0.2	1.3
1400						2.1	2.4	2.6	2.8	3.1	3.4	3.6	0.2	1.5
1200					2.1	2.4	2.7	2.9	3.1	3.4	3.7	3.9	0.3	1.7
1000			2.0	2.4	2.4	2.7	3.0	3.4	3.4	3.7	4.0	4.4	0.3	2.0
900		2.0	2.3		2.6	3.0	3.3		3.6	4.0	4.3		0.4	2.3
800		2.2	2.6		2.9	3.2	3.6		3.9	4.2	4.6		0.4	2.6
700	2.2	2.6	3.0		3.2	3.6	4.0		4.2	4.6	5.0		0.5	2.9
600	2.7	3.1	3.5		3.7	4.1	4.5		4.7	5.1	5.5		0.6	3.4
500	3.3	3.7			4.3	4.7			5.3	5.7			0.7	4.1
450	3.7	4.1			4.7	5.1			5.7	6.1			0.7	4.6
400	4.2	4.7			5.2	5.7			6.2	6.7			0.8	5.1
350	4.8	5.3			5.8	6.3			6.8	7.3			1.0	5.9
300	5.6				6.6				7.6				1.1	6.9
250	6.8				7.8				8.8				1.4	8.3
200	8.5				9.5				10.5				1.7	10.5

Notes: Values shown are for WB-50 design vehicle; last two columns are adjustments beyond values
Values less than 2.0 ft may be disregarded
For 3-lane roadways, multiply above values by 1.5; for 4-lane roadways, multiply by 2.0

Reverse Curve Design

When designing reverse curves (*31*), consideration should be given to increasing the minimum radii for curves and for inclusion of a tangent section between curves to accommodate trucks. The vehicle dynamics of trucks make it more difficult to negotiate reverse curves. Increasing the curve radius or inclusion of a tangent section between reverse curves accommodates the lateral acceleration experienced by trucks. Consideration should be given as follows:

- increase of minimum radius of 5 percent to 25 percent:
    - higher values should be associated with higher design speeds, higher curve ratios, and smaller tangent lengths between curves; and
- increase in tangent length between reverse curves:
    - tangents lengths in excess of 1150 ft were found to eliminate the need for increased radii in reverse curves.

VERTICAL ALIGNMENT

Vertical alignment is important to truck operation because of the truck operating characteristics. Vertical alignment is more impactful to truck speeds than passenger car speeds. Vertical alignment can cause speed differentials between trucks and passenger cars as well as between trucks and the desired operating speed of the facility.

Grades

Grades above 2 percent may affect truck traffic depending on the length of grade. The following recommendations are offered for consideration when designing vertical grades on toll roads for trucks to be consistent with TxDOT mobility corridors (*28*):

- maximum grade for level terrain: 2–3 percent and
- maximum grade for rolling terrain: 4 percent.

These modest grades can still have an impact on truck operating speed. Attempts should be made to minimize the impact of grade and length of grade on truck operating speed. Figures 3 and 4 present the speed-distance curves from the AASHTO Green Book (*29*). These curves can be used to calculate the expected speed changes for different grades over varying length of grade.

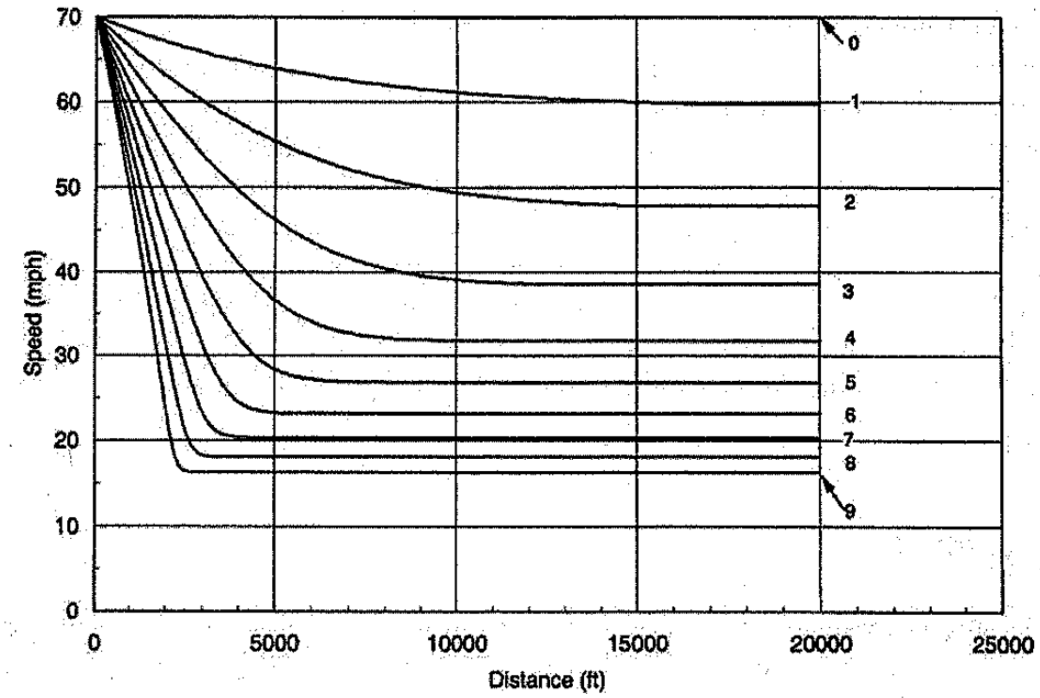


Figure 3. Speed-Distance Curves for Heavy Truck on Upgrades (200 lb/hp) (*29*).

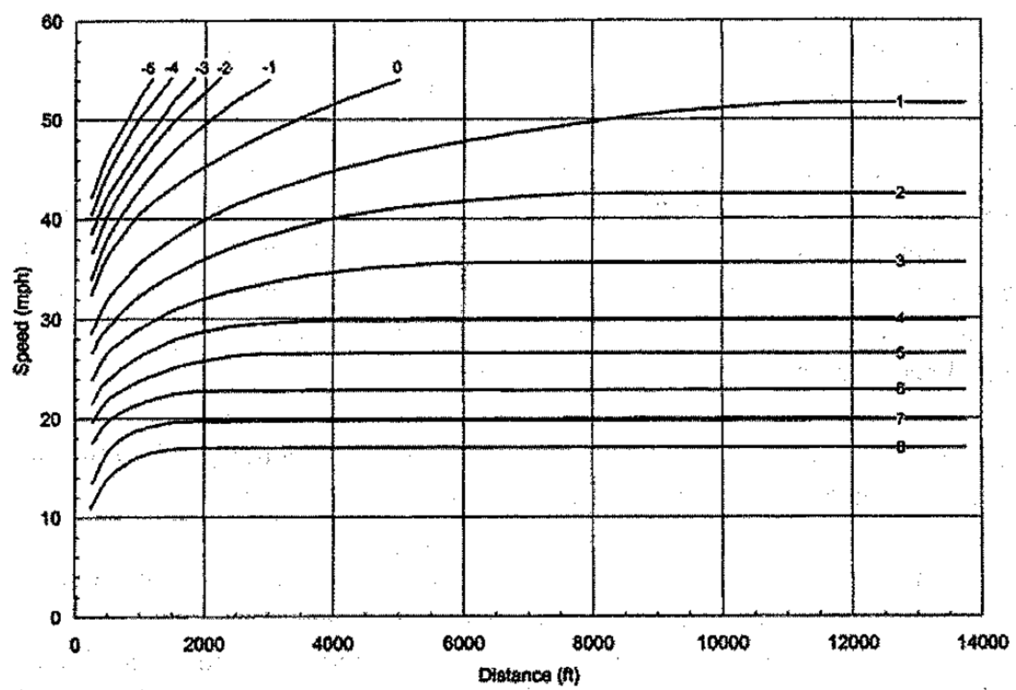


Figure 4. Speed-Distance Curves for Heavy Truck on Downgrades (200 lb/hp) (*29*).

Vertical Curve Design

The primary design control in vertical curve design is stopping sight distance. Because of the concerns with truck braking distances, it is recommended to consider longer crest and sag vertical curves to provide additional sight distance for trucks, as they need more time and distance to stop. Table 5 provides minimum crest and sag vertical curve lengths based on research examining anti-lock brakes and less efficient driver/braking combinations (*36*).

Table 5. Minimum Crest and Sag Vertical Curve Lengths.

Algebraic Difference in Grades (%)	Design Speed (mph)					
	20	30	40	50	60	70
Conventional Brake System with 70% Driver Control Efficiency (Crest Curves, ft)						
2	60	90	170	360	550	1100
4	60	130	300	720	1270	2190
6	60	150	510	1080	1910	3290
8	70	250	670	1430	2550	4380
10	90	310	840	1790	3180	5470
Antilock Brake System (Crest Curves, ft)						
2	60	90	120	190	320	390
4	60	90	190	340	640	1060
6	60	110	260	560	960	1590
8	60	120	370	740	1270	2120
10	60	180	920	920	1590	2650
Conventional Brake System with 70% Driver Control Efficiency System (Sag Curves, ft)						
2	40	90	190	290	410	570
4	70	180	370	580	830	1130
6	110	260	560	870	1240	1690
8	140	350	740	1160	1650	2260
10	170	430	920	1450	2060	2820
Antilock Brake System (Sag Curves, ft)						
2	30	60	110	190	250	340
4	60	110	220	370	500	690
6	80	160	330	560	750	1030
8	110	220	440	740	1000	1380
10	130	270	550	920	1250	1720

CROSS SECTION

The cross section of a toll road or managed lane includes the traveled way, shoulders, and roadside. The traveled way is the portion of the highway, toll road, or managed lane for the movement of vehicles, exclusive of the shoulders. The roadway is the portion of a highway, toll road, or managed lane, including shoulders, for vehicular use. The U.S. Department of Transportation defines a toll road or managed lane positively separated from another highway (i.e., concrete barrier or pylons) as a separate facility. Each facility should be designed to meet design guidance on its own accordingly.

Lane Widths

Lane widths are critical for trucks driver's comfort in operating larger vehicles. The following recommendations are offered for consideration when designing mainlanes on toll roads and managed lanes for comfortable truck operation: the minimum and usual mainlane width should be 12 ft.

Shoulder Widths

Shoulders allow for emergency parking and disabled vehicles. Shoulder widths of 12 ft should be used for facilities with high truck traffic demand (*29*). A common problem for trucks operating on urban freeways is inadequate left shoulder widths for emergency stops. Trucks are unable to completely clear the lane when inadequate shoulders are present, which requires parking on the median or encroaching on the adjacent travel lane (*37*). The following recommendations are offered for consideration when designing mainlanes on toll roads and managed lanes for comfortable truck operation:

- The minimum inside shoulder widths should be 12 ft.
- The minimum outside shoulder widths should be 12 ft.
- Shoulders should be continuous and uniform.

RAMPS AND INTERCHANGES

A complete ramp system consists of the three interrelated parts: the ramp terminal with the highway, the ramp proper, and the ramp terminal with the intersecting cross street or frontage road. The Texas *Roadway Design Manual* states "there should be a definite relationship between the design speed on a ramp or direct connection and the design speed on the intersecting highway or frontage road." This is applicable to toll roads and managed lane ramp design too. The ramp design speed applies to the sharpest or controlling ramp element and should not be lower than the design speed of either connecting facility.

Additionally, in making ramps and interchange direct connections easier for trucks to navigate, attention should focus on keeping the ramp design speed similar to the highway design speed. The survey responses of truck drivers in Chapter 3 consistently cited the speed differentials created at ramp junctions and interchanges as a problem for truck operations. Both the *Roadside Design Manual* and the AASHTO Green Book provide guidance for selecting lower design speeds on the ramp than on the highway. For ramp design on toll roads and managed lanes to be favorable to truck operations, lower ramp design speeds should be discouraged at the ramp terminal at the toll road or managed lane. Trucks prefer to enter the ramp system without having to make speed adjustments. Poorly designed ramps and acceleration lanes, particularly those located just prior to an upgrade, present special geometric and operational problems for trucks.

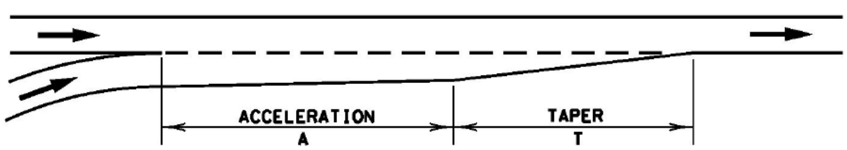
A study by the University of Michigan investigated several expressway ramps with high tractor-semitrailer accident experience (*8*). The researchers used simulation to examine the design deficiencies of the ramp interchanges. Some of the corrective actions they determined would be effective in reducing crashes were: increasing superelevation on ramp curves, redesigning of compound/multi-radius curves, lengthening deceleration lanes, resurfacing with high-friction overlays, and adding curve warning signing.

Figures 5 and 6 present the minimum deceleration and acceleration lengths for ramp terminals with highways. The following recommendation is suggested to reduce impact on truck operations at ramp terminals: select ramp design speeds close to toll road or managed lane design speeds to reduce the acceleration and deceleration needing to take place on the mainlanes.

HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	DECELERATION LENGTH, D (ft) FOR ENTRANCE CURVE DESIGN SPEED (mph)								
		STOP CONDITION	15	20	25	30	35	40	45	50
		AND INITIAL SPEED (mph)								
		0	14	18	22	26	30	36	40	44
30	150	235	200	170	140	-	-	-	-	-
35	165	280	250	210	185	150	-	-	-	-
40	180	320	295	265	235	185	155	-	-	-
45	200	385	350	325	295	250	220	-	-	-
50	230	435	405	385	355	315	285	225	175	-
55	250	480	455	440	410	380	350	285	235	-
60	265	530	500	480	460	430	405	350	300	240
65	285	570	540	520	500	470	440	390	340	280
70	300	615	590	570	550	520	490	440	390	340
75	330	660	635	620	600	575	535	490	440	390

Note: Where providing desirable deceleration length is impractical, it is acceptable to allow for a moderate amount of deceleration (10 mph) within the through lanes and to consider the taper as part of the deceleration length.

Figure 5. Minimum Deceleration Lengths for Exit Terminals (*28*).



HIGHWAY DESIGN SPEED (mph)	MINIMUM LENGTH OF TAPER T (ft)	ACCELERATION LENGTH, A (ft) FOR ENTRANCE CURVE DESIGN SPEED (mph)								
		STOP CONDITION	15	20	25	30	35	40	45	50
		AND INITIAL SPEED (mph)								
		0	14	18	22	26	30	36	40	44
30	150	180	140	-	-	-	-	-	-	-
35	165	280	220	160	-	-	-	-	-	-
40	180	360	300	270	210	120	-	-	-	-
45	200	560	490	440	380	280	160	-	-	-
50	230	720	660	610	550	450	350	130	-	-
55	250	960	900	810	780	670	550	320	150	-
60	265	1200	1140	1100	1020	910	800	550	420	180
65	285	1410	1350	1310	1220	1120	1000	770	600	370
70	300	1620	1560	1520	1420	1350	1230	1000	820	580
75	330	1790	1730	1630	1580	1510	1420	1160	1040	780

Note: Uniform 50:1 to 70:1 tapers are recommended where lengths of acceleration lanes exceed 1,300 ft.

Figure 6. Minimum Acceleration Lengths for Entrance Terminals (*28*).

Entrance Ramps near Upgrades

Slowly accelerating vehicles often cause undesirable operations, possibly resulting in a breakdown of the traffic flow. The following recommendations are offered for consideration when designing an entrance ramp near vertical upgrades on toll roads: a ½-mile or more separation is recommended between an entrance ramp and an upgrade hill (*16*).

RURAL TOLL ROADS

A two-lane rural toll road on SH 49 was constructed in 2007 in the TxDOT Tyler District. This is the first segment of an "hour glass" loop that would surround the cities of Tyler and Longview. For a facility such as SH 49, design considerations associated with a "Super 2 Highway" may be appropriate to improve capacity as traffic and truck demand increase. Some of the key characteristics of a Super 2 Highway are (*38*):

- added passing lanes in one or both directions of travel to facilitate passing maneuvers,
- increased lane and shoulder widths to give motorists more space to recover from driver error, and
- improved signing and marking to enhance the safety and efficiency of the roadway.

In the survey findings from Chapter 3, truck drivers wanted consistent operation and traffic flow over the length of a facility. Two-lane rural toll roads can potentially experience delays as traffic volumes increase and faster moving vehicles encounter slower moving vehicles. To prevent congestion and delay on rural toll roads, passing lane length and frequency are recommended from the "Super 2" design guidelines for two-lane roadways.

Table 6. Recommended Length and Spacing for Passing Lanes for Rural Toll Roads (*38*).

ADT (vehicles per day)		Recommended Passing Lane Length (mi)	Recommended Distance between Passing Lanes (mi)
Level Terrain	Rolling Terrain		
≤1950	≤1650	0.8 – 1.1	9.0 – 11.0
2800	2350	0.8 – 1.1	4.0 – 5.0
3150	2650	1.2 – 1.5	3.8 – 4.5
3550	3000	1.5 – 2.0	3.5 – 4.0

CONNECTING FACILITIES

There are a couple of connecting facilities that support truck use of toll roads that when designed for truck operations will create a more truck-friendly environment for the overall corridor.

Intersections

The ramp systems off of toll roads and managed lanes typically lead to arterial streets. The toll roads and managed lanes will be more attractive to truck drivers if those connections to arterial street systems are designed for truck operations. The literature on truck operations at intersections highlights the need to accommodate trucks at intersections. Mason et al. (*39*) identify a number of key design considerations to accommodate large trucks at intersections. Roadway design speed, turn radii, turn angle, and trailer length all affect the offtracking through an intersection. Lane width, channelization, and intersection geometrics can all be adjusted to accommodate the offtracking experienced by trucks moving through an intersection.

In addition, providing proper sight distance at intersections with stop control or signalized intersections that allow for right turn on red will better accommodate truck drivers. Tables 7 and 8 provide the gap times necessary to calculate the legs of the intersection sight triangle. The additional gap time for combination trucks is shown in both tables. Special consideration should be given to intersection sight distance for trucks, especially on grades where trucks may require longer gap times due to the higher weight-to-horsepower ratios (*33*). These times and sight triangle legs may even be greater than those resulting from the gap times in Tables 7 and 8.

Table 7. Recommended Gap Times for Intersection Sight Distance – Right Turn and Crossing Major Road from Stop Control (Case B2 and B3) (*29*).

Vehicle Type	Time Gap (sec) at Design Speed of Major Road
Passenger Car	6.5
Single-Unit Truck	8.5
Combination Truck	10.5
Note: Add 0.5 sec for passenger cars and 0.7 sec for trucks for each additional lane to be crossed	
Note: Add 0.1 sec for each grade percent greater than 3 percent	

The gap time needed to make a left turn maneuver is slightly longer than the right turn maneuver or the crossing maneuver.

Table 8. Recommended Gap Times for Intersection Sight Distance – Turning Left from Stop Control (Case B1) (*29*).

Vehicle Type	Time Gap (sec) at Design Speed of Major Road
Passenger Car	7.5
Single-Unit Truck	9.5
Combination Truck	11.5
Note: Add 0.5 sec for passenger cars and 0.7 sec for trucks for each additional lane to be crossed	
Note: Add 0.2 sec for each grade percent greater than 3 percent	

Rest Area Parking

A study in Texas found that rural areas through the state had inadequate capacity to accommodate all trucks seeking night parking (*40*). As a result, truck drivers often park on the entrances, exit ramps, and sometimes on the edge of roadways. The report offered that a potential solution is to have a rural travel information system that provides availability of parking spaces as well as information on public rest areas, fueling, and food services.

Truck parking on shoulders or ramps is not recommended. Having sufficient truck parking at rest areas or at adjoining lane uses near interchanges with a toll road or managed lane is preferred. The connecting roadways to these supporting parking facilities should be designed to accommodate truck movements trying to reach these parking locations.

CHAPTER 5: TRAFFIC OPERATIONS/ENGINEERING FACTORS

Traffic operations and traffic engineering techniques that can improve traffic flow and safety are potential factors that can increase the attractiveness of toll roads or managed lanes to truck drivers. This chapter highlights some of the current design practice and some emerging practices that will improve truck operations on toll roads and managed lanes.

DESIGN FOR OPERATIONAL ANALYSIS

For operational analysis of uninterrupted flow on highways, toll roads, and managed lanes, vehicles are classified as passenger cars and trucks. Trucks are commonly defined as all buses, single-unit trucks, combination trucks, and recreational vehicles. For traffic-classification purposes, trucks are normally defined as those vehicles having manufacturer's gross vehicle weight ratings of 9000 lb or more and having dual tires on at least one rear axle. Designing for trucks should not be oversimplified to one truck classification. With increased truck volumes and larger combination vehicles, it is important to examine the full range of vehicle characteristics for the trucks expected on a facility.

For the purpose of design, the percentage of trucks in the traffic stream during the peak hours should be used in the operational analysis. The percentage of trucks may vary considerably during a particular hour of the day (*29*). It is advisable, therefore, to count trucks for several peak hours that are considered representative of the design hour. At intersections, the truck percentage during the morning peak period may be considerably different than the truck percentage during the evening peak period (*29*).

SIGNING

Truck drivers repeatedly mentioned the importance of signing and sign condition in good highway design. In addition to proper guide and regulatory signing, proper warning signing is recommended to alert truck drivers of situations needing their attention. Because of the issues raised with truck difficulty in negotiating curves and ramp systems, dual curve warning signing may be a positive treatment. Examples of dual speed warning signs for trucks are shown in Figures 7 and 8. Figure 7 provides an example of a gantry mounted sign with good visibility from all lanes of traffic. Figure 8 shows an example of a ground mounted sign on the edge of an elevated section of roadway.

Figure 7. Dual Speed Warning Sign for Trucks – Gantry Mounted.
(Photo courtesy of TTI)

Figure 8. Dual Speed Warning Signs for Trucks – Ground Mounted.
(Photo courtesy of TTI)

ROADWAY DELINEATION

Roadway delineation was identified by truck drivers as important for truck operations on highways. In addition to the pavement markings on highways, toll roads, and managed lanes, two other treatments are recommended on facilities to make them more attractive to trucks.

Rumble Strips

Continuous rumble strips can be used along the edge line or along the centerline of a roadway. Because most toll roads and managed lanes have physically separated directions of travel, edge line rumble strips are recommended. In response to a survey in Virginia, a study (*11*) noted that the state's installation of continuous shoulder rumble strips was "one of the most effective measures that could be implemented to improve safety." The study notes that the Virginia Department of Transportation has installed more than 1750 miles of shoulder rumble strips. This treatment has been reported to reduce run-off-the-road crashes by more than 50 percent.

The 2009 Manual on Traffic Control Devices has guidance on the use of continuous rumble strips (*41*). Figure 9 shows an example of continuous, longitudinal rumble strips. TxDOT standard sheet RS1-06 shows the details on depressed shoulder markings for use on highways.

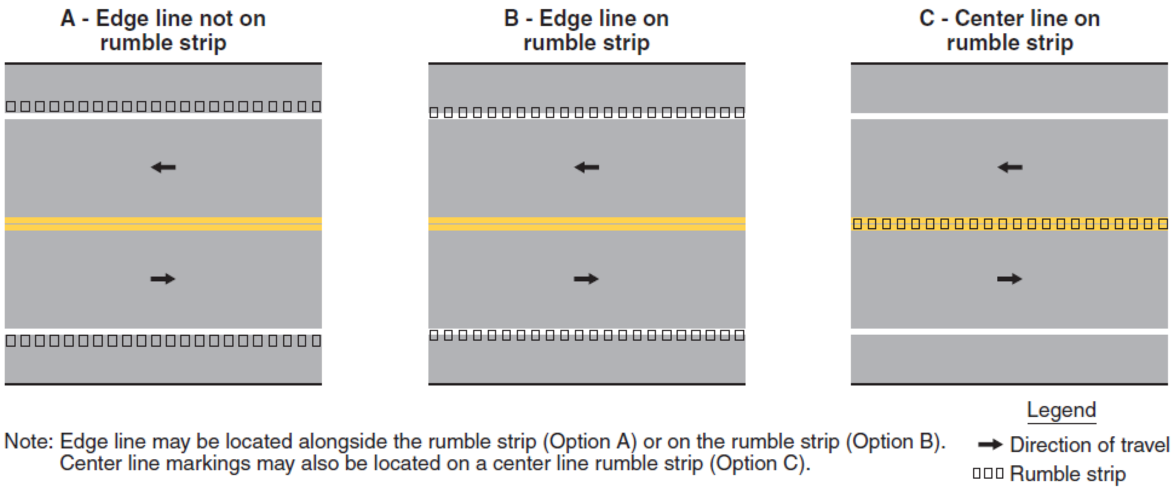


Figure 9. Example of Longitudinal Rumble Strips (*41*).

Another delineation treatment to help with curve warning is lighted barrier delineation. Figure 10 shows a use of this treatment in Texarkana in the TxDOT Atlanta District. Again, truck drivers responded that improvements in curves and ramps assist with truck operations and safety. This delineation treatment is especially helpful at night to guide truckers though an interchange or ramp connection.

Figure 10. Curve Warning Barrier Markings.
(Photo courtesy of TTI)

CHAPTER 6: CORRIDOR OPERATION FACTORS

Surveys of the trucking industry repeatedly indicated that consistency of flow was very important to truck drivers. There are a number of intelligent transportation system technologies and corridor operational techniques that would assist in improving efficiency, improving safety, and stabilizing traffic flow. These techniques range from localized applications to corridor applications.

AUTOMATIC VEHICLE IDENTIFICATION

Automatic vehicle identification (AVI) is a method for trucks to clear weigh stations, border crossings, and ports of entry to individual states. As tolling across the country becomes more interoperable, these systems will also allow for toll payment with the same toll tag transponders. Account management with AVI through trucking companies allows toll authorities a method of billing a trucking company for the amount of use a certain truck makes on their toll road.

One similar electronic pass already in use is the PrePass (*42*). PrePass is an AVI system that allows vehicles with proper clearance and information to avoid the queuing at weigh stations and border crossings. This clearance is done by communicating truck information to the agency conducting the screening. The system determines if the information presented is clear and valid. If the information passes, the truck can bypass the station on the facility. If the information does not clear, the truck must make a stop at the station and go through the normal station procedures. Twenty-five states already use this technology, but Texas is not one of the PrePass states.

By using an AVI system similar to PrePass on toll facilities, trucker drivers and trucking companies would increase their ability to move along the facility without stops and delays. This improvement in travel time has the potential to attract more truck drivers to a toll road or managed lane facility.

Figure 11. Example of Automatic Vehicle Identification (*42*).

INTELLIGENT TRANSPORTATION SYSTEMS

Intelligent transportation systems offer improved truck operation through transportation management strategies. ITS offers the collection of real-time data and communication of that information to operating agencies and users of the system.

Active Curve Warning System for Trucks

An example of an application applied to trucks at interchanges and ramp junctions is active curve warning signs. The active aspect of this application is the use of real-time speed and vehicle classification data approaching a curve. The safe speed for different vehicles is known by the system. If the system detects a vehicle, for example a truck, approach the curve too fast, it can set off the warning lights to alert the driver. This type of application is more effective because the warning is targeted at only the drivers that are entering a potentially hazardous situation. Figure 12 shows an example of this type of system in Houston, Texas.

Figure 12. Active Curve Warning System.
(Photo courtesy of TTI)

Incident Management

A strong incident management program may attract truck drivers because of the operating agencies commitment to keeping traffic flowing and returning traffic to normal conditions as soon as possible following an incident.

The key elements of incident management are detection, verification, response, clearance, and traveler information. Detection is often accomplished through sensors in the roadway, motorist calls, or from surveillance cameras. Verification can be done by camera systems or by field personnel. The North Texas Tollway Authority has a unique automated incident detection system called the NICE system (*43*). This system uses high-end digital cameras and machine vision analytics to detect incidents. Not only is the NICE system analyzing what is happening on the roadway, it is also analyzing what is not happening. The machine vision analytics searches for elements in the field of view that do not move. In a high-speed roadway environment, this identified stalled vehicles, debris in the roadway, and other potential incidents.

Ballard (*44*) researched incident management for managed lanes under a previous TxDOT research project. Many of the recommendations from that study are applicable for developing an incident management program to support toll roads. The key recommendations to establishing an effective incident management program are as follows:

- Use well coordinated, multi-response teams that combine traffic management, fire, emergency response, and police enforcement;
- Stage proper equipment for responding to truck incidents; this includes proper tow trucks on-site or nearby that can handle the truck size and combinations using the toll road or managed lane;
- Create a safe work area at the incident scene;
- Provide response vehicle access, including median openings and breaks in barriers separating toll roads or managed lanes from general purpose facilities;
- Plan for diversions to connection facilities, including crossovers or truck turnarounds if trucks need to be routed onto opposing lanes to return an interchange to access the highway network; and
- Provide good traveler information, including adequate advance notification to prevent drivers from encountering unexpected congestion as well as timely information on when an incident is cleared and roadway conditions have returned to normal.

ACTIVE TRAFFIC MANAGEMENT

Active traffic management is the latest evolution of managing corridors to improve operational efficiency and safety. While the exact definition of active traffic management is evolving, the fundamental concept is to use technology and transportation operational tools to pro-actively manage a corridor. Some early active traffic management systems have been deployed in Europe, but there are several pilot projects being developed in the United States. Some of the key elements of active traffic management are described in the following sections.

Speed Harmonization/Speed Management

Speed harmonization or management has been in use in Germany since the 1970s and is geared toward improving traffic flow based on prevailing conditions. Similar installations are in operation in The Netherlands and England on various roadway sections with high traffic volumes. A typical installation of speed harmonization monitors traffic volumes and weather conditions along the roadway. If sudden disturbances occur in the traffic flow—such as with an incident or building congestion—the system modifies the speed limits accordingly, providing users with the quickest possible warning that roadway conditions are changing (*45*). The deployment of the speed harmonization is automatic and begins immediately upstream of the congestion point. The system incrementally decreases speeds upstream in a cascading manner to smooth the deceleration of the traffic and help ensure more uniform behavior. Potential benefits of speed harmonization include:

- an increase in throughput,
- a decrease in primary incidents,
- a decrease in incident severity,
- more uniform speeds,
- a decrease in headways,
- more uniform driver behavior,
- an increase in trip reliability,
- a delay in the onset of freeway breakdown,
- a reduction in traffic noise,
- a reduction in emissions, and
- a reduction in fuel consumption (*46*).

Queue Warning

A major addition to the speed harmonization system is the queue warning system, which is in operation in Germany and The Netherlands. Integrated with the speed harmonization gantries, this system involves displaying a congestion pictograph on each side of the speed harmonization gantry indicating congestion ahead. In other installations, this congestion pictograph may be displayed on an overhead dynamic message sign or drivers may be alerted with flashing lights displayed with the speed limit signs. This warning system is intended to help reduce the occurrence of secondary incidents caused by either recurrent or nonrecurring congestion. It is typically deployed to indicate lane closures near incidents and work zones and to provide queue tail warning and protection in known bottleneck locations (*47*). The system typically begins reducing speeds between three and four gantries before an incident (*48*). Potential benefits of a queue warning system include:

- a decrease in primary incidents,
- a decrease in secondary incidents,
- a decrease in incident severity,
- more uniform speeds,
- a decrease in headways,
- more uniform driver behavior,
- an increase in trip reliability,
- a reduction in traffic noise,
- a reduction in emissions, and
- a reduction in fuel consumption (*46*).

Temporary Shoulder Use and Speed Harmonization

Temporary shoulder use is a congestion management strategy typically deployed in conjunction with speed harmonization to address capacity bottlenecks on the freeway network. The strategy—known in Germany as temporary hard shoulder use and known in The Netherlands as hard shoulder running or the rush hour lane—provides additional capacity during times of congestion and reduced travel speeds. The use of the right shoulder during peak travel periods has been used in Germany since the 1990s (*49*). When travel speeds are reduced, signs indicate that travel on the shoulder is permitted. A complete series of traffic signs indicates operations related to temporary shoulder use, including one with a supplemental speed limit indication (used when overhead gantries are not present). These signs and the overhead lane messages are blank when travel on the shoulder is not permitted. Temporary shoulder use is permitted only when speed harmonization is active and speed limits are reduced. In addition to allowing temporary use of the right shoulder, the Dutch also deploy the use of traveling on a dynamic lane on the median side of the roadway. Also known as the plus lane, a narrow extra lane provided by reconstructing the existing roadway while keeping the hard shoulder open for travel use when traffic volumes reach levels that indicate congestion is growing (*47*).

Generally, implementation of temporary shoulder use is at the discretion of the traffic management center operator, although traffic volumes help determine the need for the strategy.

A typical installation in Europe incorporates a number of unique roadway features, which can include:

- lightweight gantries,
- lane control signals,
- dynamic speed limit signals,
- dynamic message signs,
- digital enforcement technology,
- closed-circuit television cameras,
- enhanced lighting,
- roadway sensors,
- emergency roadside telephones,
- hard shoulder running, and
- emergency refuge (*50*).

Operation of the system is handled by the regional control center, with operators on hand to monitor the system and initiate the modified operations as necessary. Specifically, operators use closed-circuit televisions (CCTVs) mounted on light sign gantries or separately to check for incidents and stalled vehicles in the shoulder before activating the system. Potential benefits of a queue warning system include:

- an increase in throughput,
- an increase in capacity,
- an increase in trip reliability, and
- a delay in the onset of freeway breakdown (*46*).

Dynamic Lane Assignment

A variation of the temporary shoulder use—known as junction control in Germany—is a form of dynamic lane assignment (*51*). Typically, the concept is applied at entrance ramps or merge points where the number of downstream lanes is fewer than upstream lanes. The typical U.S. application to this geometric condition would be a lane drop for one of the outside lanes or a merge of two inside lanes, both of which are static treatments (*52*). The German dynamic solution is to install lane control signals over both upstream approaches before the merge, provide priority to the facility with the higher volume, and give a lane drop to the lesser volume roadway or approach (*52*). This is particularly effective when implemented with temporary shoulder use at on-ramp locations where bottlenecks frequently form. Potential benefits of dynamic lane assignment as it relates to merge points include:

- an increase in throughput,
- an increase in capacity,
- a decrease in primary incidents,
- more uniform speeds,
- more uniform driver behavior,
- an increase in trip reliability,
- a delay in the onset of freeway breakdown,
- a reduction in traffic noise,
- a reduction in emissions, and
- a reduction in fuel consumption (*46*).

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Truck use of toll roads and managed lanes may be important in many transportation networks to separate vehicle movements and increase the overall mobility of a corridor. If toll roads and managed lanes can be constructed to better serve truck operations and increase safety for truck drivers, then these facilities will be more attractive to the trucking industry. Truck use of toll roads or managed lanes could also result in a number of benefits for both the trucking industry and the motoring public. Some of the benefits that may be realized are:

- a reduction in truck travel times, improving freight movement efficiency;
- more predictable travel times, allowing expansion of just-in-time delivery options;
- an improvement in domestic and international competitiveness;
- maintenance of consumer goods pricing;
- a reduction in truck idle time due to congestion, which would reduce fuel consumption and improve air quality;
- an improvement in facility capacity by removing many trucks from the general purpose lanes and making better use of toll or managed lanes;
- a reduction in incident impacts (fewer lanes blocked, easier to access and clear) by concentrating trucks to a designated lane;
- a reduction in pavement rehabilitation costs by concentrating heavy loads in a single lane (i.e., only a single lane would have to be rehabilitated and this lane could eventually be reconstructed for additional strength); and
- a more comfortable driving environment for those intimidated by driving near trucks.

Based on a review of existing research and project implementations, there are several design, operation, and technology improvements that can be incorporated into the design of toll roads and managed lanes that would improve truck operation and safety. The following recommendations are made for consideration by engineers designing toll road or managed lane facilities.

GEOMETRIC DESIGN RECOMMENDATIONS

The following geometric design recommendations are made for consideration by highway designers focused on the design of toll roads and managed lanes to accommodate trucks:

- Thoughtfully select design speed for mainlane roadways, ramps, and interchanges;
- Use low maximum grades on vertical alignment;
- Include climbing lanes to minimize truck loss of speed and potential speed differentials;
- Avoid use of long downgrades;
- Increase the lengths of vertical curves to increase sight distance for truck drivers;
- Lengthen acceleration lanes from entrance ramps to provide trucks adequate space to reach mainline design speeds;
- Lengthen deceleration lanes to exit ramps to allow trucks to fully exit before decrease speeds from mainline design speeds;
- Use larger radii on curves in ramp systems to better account for vehicle dynamics of trucks negotiating multi-curve ramp systems;
- Consistently provide full 12-ft travel lanes;
- Use adequate lane widening in horizontal curves;
- Consistently provide full 12-ft shoulders for truck use;
- Provide adequate parking at rest areas and connecting facilities; and
- Provide adequate curve radii, curb return radii, and storage for left-turn and right-turn lanes at intersections at the end of ramps from toll roads or managed lanes.

TRAFFIC OPERATION RECOMMENDATIONS

The following traffic engineering and transportation operational recommendations are made for consideration by highway designers focused on the design of toll roads and managed lanes:

- Give proper consideration of the truck demand and truck classes expected to use a toll road or managed lane;
- Use static dual speed curve warning signs to alert truck drivers to the appropriate speed in negotiating ramps and direction connections;

- Provide informational signing and variable message signing in proper placement for better visibility for large trucks;
- Use continuous, longitudinal rumble strips to assist in alerting truck drivers to the edge lines of traveled ways; and
- Use barrier curve delineation systems on curves needing special attention from truck drivers to negotiating ramps and direct connections.

SYSTEM AND ITS RECOMMENDATIONS

The following corridor management and intelligent transportation system recommendations are made for consideration by highway designers focused on the design of toll roads and managed lanes:

- Explore automatic vehicle identification technology for trucks in Texas to be interoperable with other systems in North America;
- Install active curve warning systems for truck drivers to warn of approach speeds exceeding the design speed of ramps and direct connections;
- Provide a comprehensive, coordinated incident management program that can respond to truck incidents and can minimize the impact of incidents on traffic flow;
- Consider active traffic management techniques to proactively manage traffic flow on corridors for more stable and reliable operation; and
- Use ITS technologies to manage traffic flow and communicate unexpected delays to all users of a facility.

FURTHER RESEARCH NEEDS

This project has identified a number of research studies that have examined geometric design and traffic operations related to truck characteristics. A valuable effort going forward would be a synthesis of which research findings have been incorporated into the national and Texas geometric design guides. Some of the research dating back 10 to 20 years can now be found in the 2004 edition of the AASHTO Green Book and the 2006 edition of the Texas Roadway Design Guide. However, some research findings have not been incorporated and newer research is now emerging that should be considered in future editions.

This project did not administer the survey included in the appendix. There would be value in specifically asking truck drivers and truck company owners and operators about the geometric design and traffic engineering factors that impact their operation. Few past studies set out to measure the trucking industry's attitudes on geometric design and traffic operations.

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APPENDIX: SUGGESTED TRUCK SURVEY ON GEOMETRIC DESIGN FACTORS

Design Speed

1. If a toll road had a speed limit of 80 mph (for cars and trucks), would you be more likely to use the road?
   - ☐ Yes
   - ☐ No (Please indicate why)
     - ☐ Current speed limits are acceptable
     - ☐ Not allowed to drive near 80 mph

General Safety

2. If a toll road was known to have a better safety record (i.e., fewer crashes), would you be more likely to use the road?
   - ☐ Yes
   - ☐ No

Cross Section

3. How would each of the following roadway design features influence your use of a toll road?

   Wide travel lanes

   ☐ Not important ☐ Some importance ☐ Very important

   Wide shoulders for stopping, breakdowns, or emergencies

   ☐ Not important ☐ Some importance ☐ Very important

   Wide medians separating opposing traffic

   ☐ Not important ☐ Some importance ☐ Very important

   Concrete barriers separating opposing traffic designed for large truck impacts

   ☐ Not important ☐ Some importance ☐ Very important

   Other: ___________________________________

Vertical Alignment

4. How would each of the following roadway design features influence your use of a toll road?

   Flat roadway grades (up grades or downgrades less than 3%)

   ☐ Not important ☐ Some importance ☐ Very important

   Climbing lanes for roads with steep grades (upgrades greater than 6%)

   ☐ Not important ☐ Some importance ☐ Very important

   High clearance to over passes

   ☐ Not important ☐ Some importance ☐ Very important

   Other: ___________________________________

Ramps and Interchanges

5. How would each of the following ramp designs influence your use of a toll road?
   No sharp curves on the ramps
   ☐ Not important ☐ Some importance ☐ Very important
   Exit ramps that have an upgrade (uphill to help slow down and stop)
   ☐ Not important ☐ Some importance ☐ Very important
   Entrance ramps that have a downgrade (down hill to help speed up)
   ☐ Not important ☐ Some importance ☐ Very important
   Long acceleration and deceleration lanes
   ☐ Not important ☐ Some importance ☐ Very important
   Other: ________________________________

General Roadway Operations

6. How would each of the following operational factors influence your use of a toll road?
   Higher Speed Limits
   ☐ Not important ☐ Some importance ☐ Very important
   Congestion on the roadway
   ☐ Not important ☐ Some importance ☐ Very important
   Separating lanes for cars and trucks
   ☐ Not important ☐ Some importance ☐ Very important
   Other: ________________________________

Intelligent Transportation Systems

7. How would each of the following influence your use of a toll road?
   Electronic signs that warned of congestion ahead
   ☐ Not important ☐ Some importance ☐ Very important
   Electronic signs that warned of congestion on roads connecting to the toll road
   ☐ Not important ☐ Some importance ☐ Very important
   Electronic signs that warned of crash ahead
   ☐ Not important ☐ Some importance ☐ Very important
   Electronic signs with travel times to next major interchange
   ☐ Not important ☐ Some importance ☐ Very important
   Electronic signs with weather information
   ☐ Not important ☐ Some importance ☐ Very important
   Good response by police and fire departments to crashes
   ☐ Not important ☐ Some importance ☐ Very important
   Other: ________________________________

General Traffic Engineering

8. How would each of the following roadway features influence your use of a toll road?
   Good lighting of the roadway
   ☐ Not important ☐ Some importance ☐ Very important
   Good stripes and markings on the roadway
   ☐ Not important ☐ Some importance ☐ Very important
   Good signing
   ☐ Not important ☐ Some importance ☐ Very important
   Good water drainage (so water does not puddle on roadway during rain storms)
   ☐ Not important ☐ Some importance ☐ Very important

Rest Stops

9. How would the following services influence your use of a toll road?
   Having frequent rest stops along the toll road
   ☐ Not important ☐ Some importance ☐ Very important
   Having restaurants at the rest stops
   ☐ Not important ☐ Some importance ☐ Very important
   Having internet access at the rest stops
   ☐ Not important ☐ Some importance ☐ Very important
   Having overnight parking at the rest stops
   ☐ Not important ☐ Some importance ☐ Very important
   Having power at the rest stops to allow trucks to be turned off
   ☐ Not important ☐ Some importance ☐ Very important
   Other: ___________________________________

Method of Payment

10. How would each method of toll payment influence your use of a toll road?
    Ability to use a toll tag or transponder
    ☐ Not important ☐ Some importance ☐ Very important
    Ability to pay by mail (toll road recognizes your license plate)
    ☐ Not important ☐ Some importance ☐ Very important
    Ability to pay by text messaging or SMS messaging
    ☐ Not important ☐ Some importance ☐ Very important
    Ability to pre-pay a toll from a web site
    ☐ Not important ☐ Some importance ☐ Very important
    Ability to pre-pay a toll by calling in
    ☐ Not important ☐ Some importance ☐ Very important

Open Ended Question

11. Is there something about how a highway or toll road is designed or operated that you really do not like?