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

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DISCLAIMER

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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*). Ninety percent of all goods moving, 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, higher crashes would be expected. However, Texas exceeds the next two highest states, California by 30 percent and Florida by 60 percent.

PURPOSE OF THE GUIDE

The purpose of this guide is to identify the potential factors that could impact truck use of toll roads and managed lanes. The guide summarizes 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).

CHAPTER 2: GEOMETRIC DESIGN FACTORS

The Texas geometric design guide is TxDOT's Roadway Design Manual (*4*). The national guide is the American Association of State Highway and Transportation Officials (AASHTO) Green Book (*5*). 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 U.S. found nearly two-thirds of the projects (i.e., those coded with red squares in Figure 1) use some form of reduced design values (*6*).

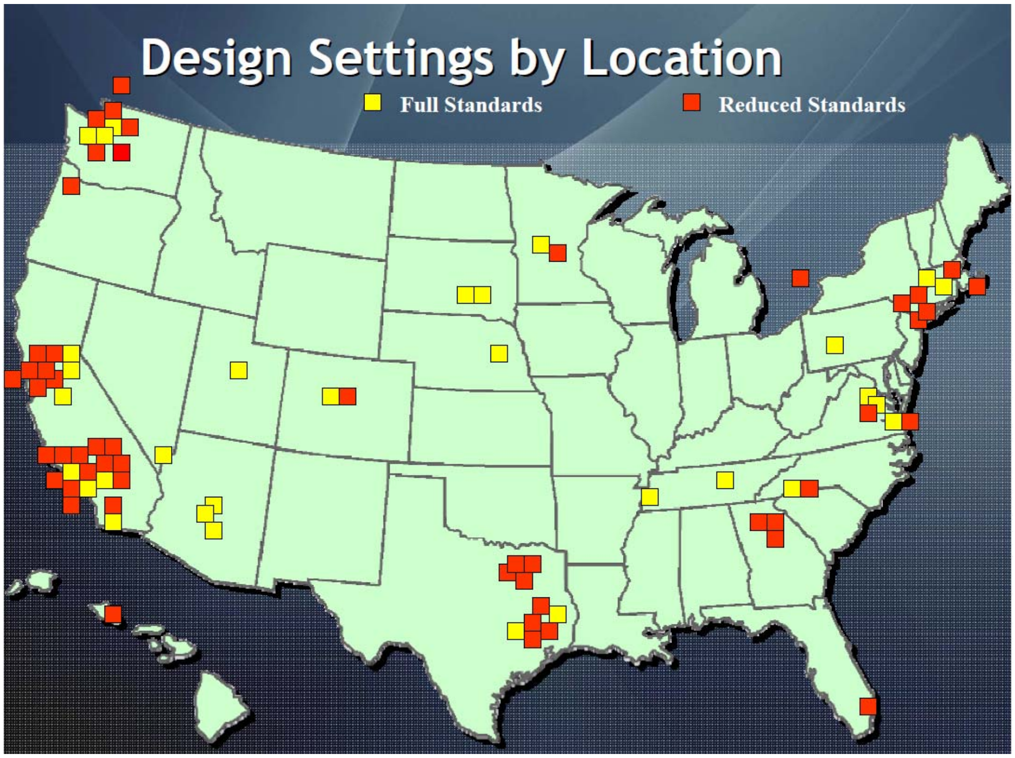


Figure 1. HOV/Managed Lane Projects Using Reduced Design Values (*6*).

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 TxDOT Roadway Design Manual was developed by the Department "to provide guidance in the geometric design of roadway facilities. The Roadway Design Manual represents a synthesis of current information and operating practices related to the geometric design of roadway facilities" (*4*). There are two sections that specifically address the type of facility with which toll roads would be most associated. Those sections are the freeway section of Chapter 3 and Chapter 8 on mobility corridors.

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 are a relatively new section of the TxDOT 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 guideline for roadway geometric design is the AASHTO "A Policy on Geometric Design of Highways and Streets" (referred to as the Green Book) (*5*). 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" (*5*). 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 (*7*). 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 classes include 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 wheelbase)
- Triple-trailer combination – WB-100T (100-ft wheelbase), and
- Turnpike-double combination – WB-109 (109-ft wheelbase).

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 shows an example of the design vehicle characteristics for the truck class of Interstate semitrailer WB-67.

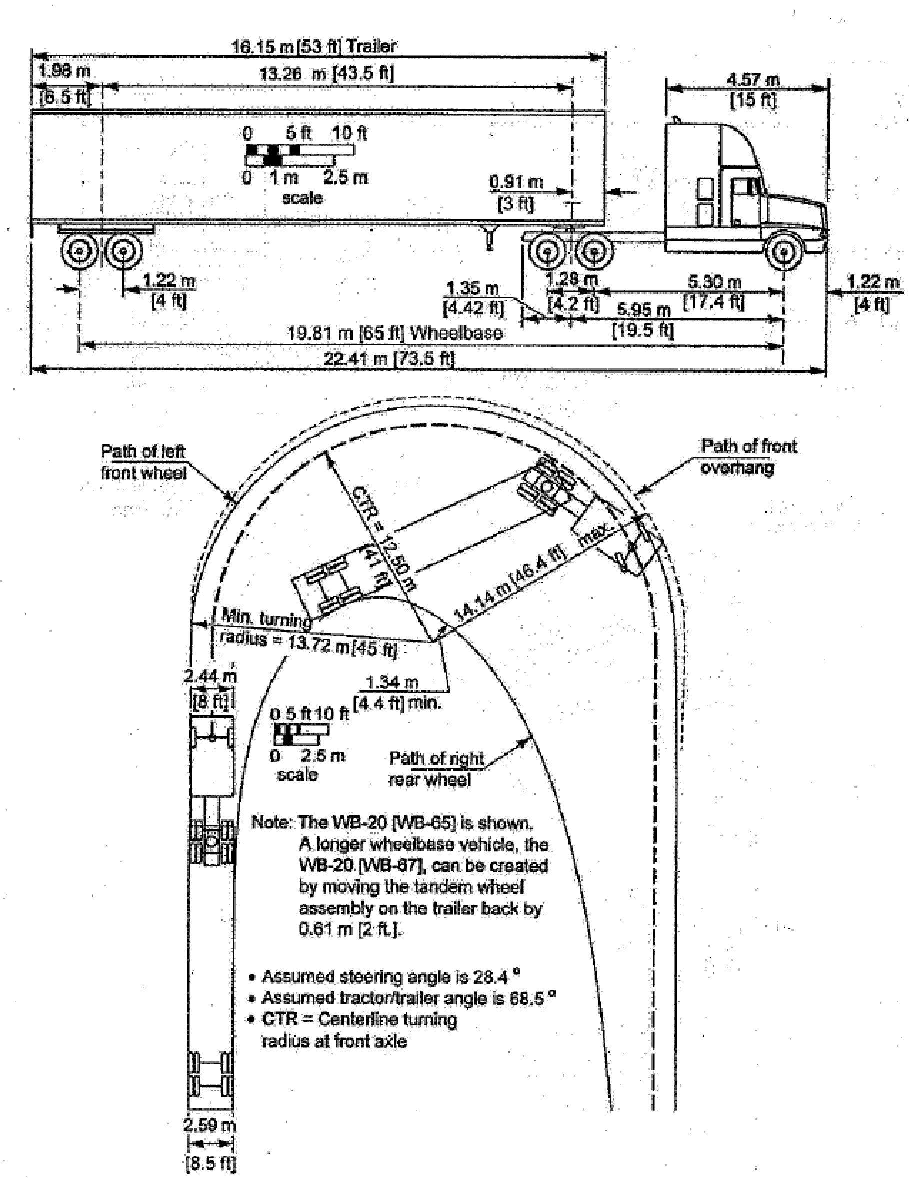


Figure 2. Minimum Turning Path for Interstate Semitrailer – WB-67 (5).

Stopping Sight Distance

Stopping sight distance in the Green Book is based on 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 (*8, 9*) discuss additional braking distances for trucks. Truck braking distance should consider both the best- and worst-case drivers. Table 1 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 (*10*). The braking distances for worst performing truck drivers, best performing truck drivers, and anti-lock brake systems are also presented in Table 1.

Table 1. 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 down grades. 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 2 shows the stopping sight distance needed on downgrades from the Green Book.

Table 2. Stopping Sight Distance on Grades (*5*).

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 et al. (*11*) 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 3 presents the recommended traveled way widening from the Green Book.

Reverse Curve Design

When designing reverse curves (*7*), 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 makes 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:
  - tangent lengths in excess of 1,150 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. The impact of 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 (*4*):

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

Table 3. Traveled Way Widening on Horizontal Curves (adapted from 5).

Design Values for Pavement Widening on Highway Curves (ft)														
Curve Radius (ft)	24 ft				22 ft				20 ft				Adj for WB-100T	Adj for WB-109D
	Design Speed (mph)				Design Speed (mph)				Design Speed (mph)					
	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

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. The speed-distance curves from the AASHTO Green Book are presented in Figures 3 and 4 (*5*). These curves can be used to calculate the expected speed changes for different grades over varying length of grade.

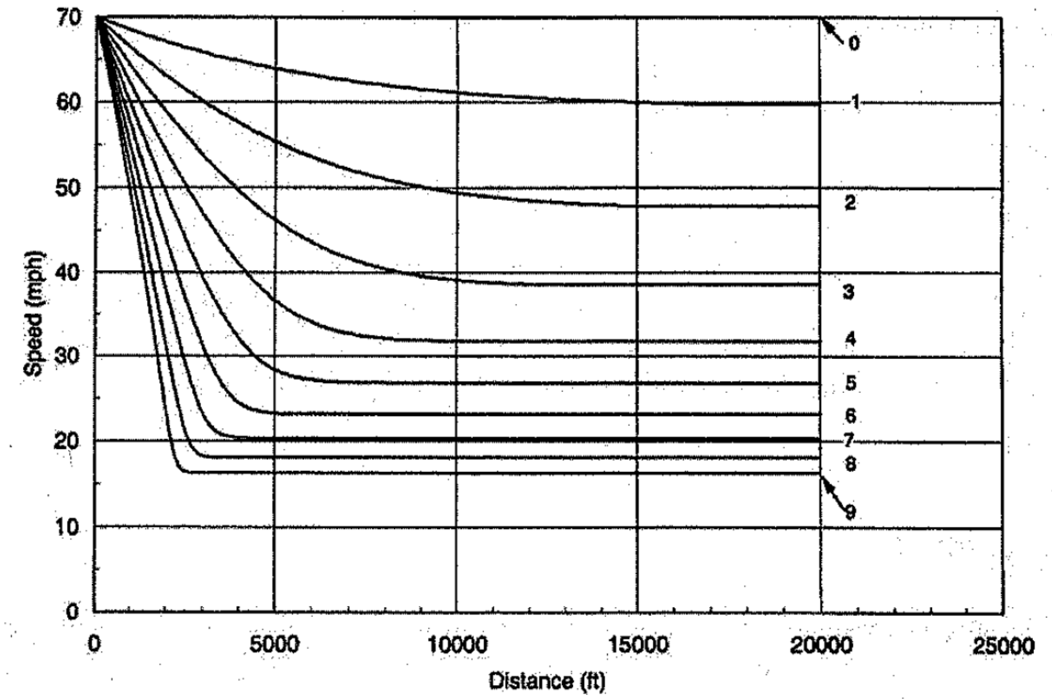


Figure 3. Speed-Distance Curves for Heavy Truck on Upgrades (200 lb/hp) (*5*).

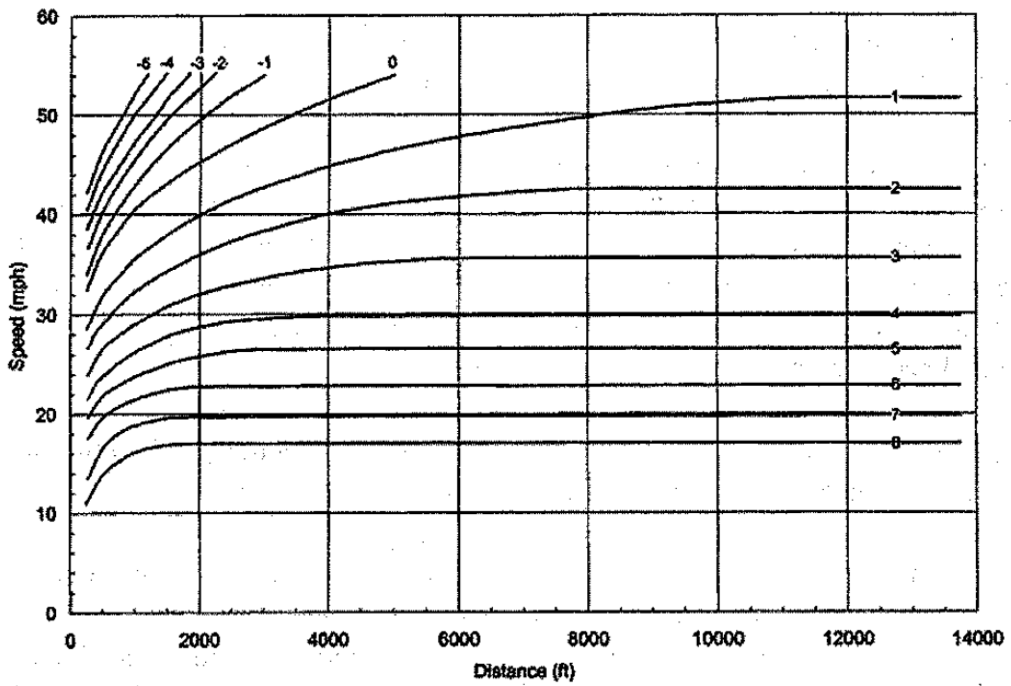


Figure 4. Speed-Distance Curves for Heavy Truck on Downgrades (200 lb/hp) (*5*).

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 4 provides minimum crest and sag vertical curve lengths based on research examining anti-lock brakes and less efficient driver/braking combinations (*12*).

Table 4. 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
Anti-lock 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
Anti-lock 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 truck driver 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 (*5*). 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 (*13*). 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 TxDOT Roadside 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. 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 (*14*) investigated several expressway ramps with high tractor-semitrailer accident experience. They 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 (*4*).

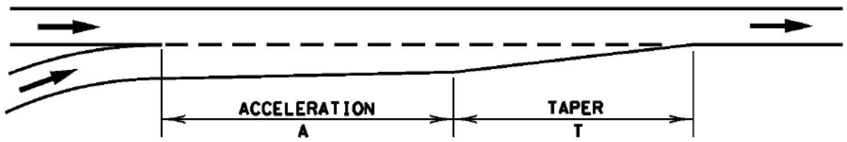
Entrance Ramps near Upgrades

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 (*15*).

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 (*16*):

- 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.



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 (*4*).

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 as shown in Table 5.

Table 5. Recommended Length and Spacing for Passing Lanes for Rural Toll Roads (*16*).

ADT (vehicles per day)		Recommended Passing Lane Length (mi)	Recommended Distance between Passing Lanes (mi)
Level Terrain	Rolling Terrain		
≤1,950	≤1,650	0.8 – 1.1	9.0 – 11.0
2,800	2,350	0.8 – 1.1	4.0 – 5.0
3,150	2,650	1.2 – 1.5	3.8 – 4.5
3,550	3,000	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 ramps 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 arterials 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. (*17*) 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. The gap times necessary to calculate the legs of the intersection sight triangle are provided in Tables 6 and 7. 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 (*9*). These times and sight triangle legs may even be greater than those resulting from the gap times in Tables 6 and 7. The gap time needed to make a left turn maneuver is slightly longer than the right turn maneuver or the crossing maneuver.

Table 6. Recommended Gap Times for Intersection Sight Distance – Right Turn and Crossing Major Road from Stop Control (Case B2 and B3) (*5*).

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	

Table 7. Recommended Gap Times for Intersection Sight Distance – Turning Left from Stop Control (Case B1) (*5*).

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 (*18*). 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.

Parking on shoulders or ramps for trucks 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 3: 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 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 (*5*). 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 (*5*).

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 responses to a survey in Virginia, a study (*19*) noted that the state's installation of continuous shoulder rumple 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 1,750 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 (*20*) has guidance on the use of continuous rumble strips. 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.

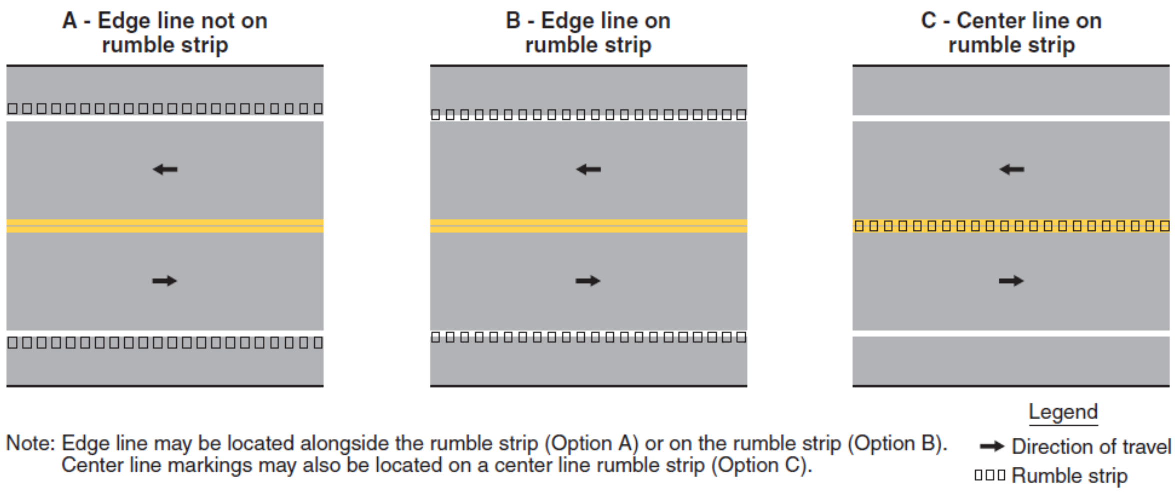


Figure 9. Example of Longitudinal Rumble Strips (*20*).

Another delineation treatment to help with curve warning is lighted barrier delineation. Figure 10 shows a use of this 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 4: 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 in the U.S., but not in Texas, is the PrePass (*21*). Figure 11 shows a truck using an AVI lane. By using a 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 (*21*).

INTELLIGENT TRANSPORTATION SYSTEMS

Intelligent transportation systems (ITS) offer improved truck operation through transportation management strategies. ITS offers the collection of real-time data and communication of 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. An example of this type of system is shown in Figure 12 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 of 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 (*22*). 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 (*23*) 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.
- 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 definitions of active traffic management are evolving, the fundamental concept is to use technology and transportation operational tools to pro-actively manage a corridor. Some of the early active traffic management systems have been deployed in Europe, but there are several pilot projects being developed in the U.S. Some of the key elements of active traffic management are described in the following sections.

Active traffic management can consist of a number of different strategies, used individually or in combination. Some of the strategies that will assist in keeping traffic flows stable and are as follows:

- **Speed Harmonization/Speed Management.** 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 (*24*).
- **Queue Warning.** A major addition to the speed harmonization system is the queue warning system. 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 (*25*).
- **Temporary Shoulder Use with 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. Also known as the plus lane, a narrowed extra lane provided by reconstructing the existing roadway while keeping the hard shoulder is opened for travel use when traffic volumes reach levels that indicate congestion is growing (*25*).
- **Dynamic Lane Assignment.** This 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 (*26*).

CHAPTER 5: 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;
- the 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 decreasing 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.
- 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.
- 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.
- Use ITS technologies to manage traffic flow and communicate unexpected delays to all users of a facility.

CHAPTER 6: REFERENCES

1. *Strategies for Managing Increasing Truck Traffic*, NCHRP Synthesis 314, Transportation Research Board, Washington, D.C., 2003.
2. Poole, R.W., "It's Time for a Goods-Movement Interstate System," The Reason Foundation, Los Angeles, CA, 2006.
3. Federal Motor Carrier Safety Administration, *"Large Truck and Bus Crash Facts 2007,"* U.S. Department of Transportation, January 2009.
4. *"Texas Roadway Design Manual,"* Texas Department of Transportation, Austin, Texas, 2009.
5. American Association of State Highway and Transportation Officials (AASHTO) *"A Policy on Geometric Design of Highways and Streets,"* Fifth Edition, Washington, D.C., 2004.
6. Fuhs, Charles, presentation from the 89th Annual Transportation Research Board Meeting, Washington, D.C. 2010.
7. Harwood, D.W. and J.M. Mason, *"Horizontal Curve Design for Passenger Cars and Trucks,"* Transportation Research Record 1385, Transportation Research Board, Washington, D.C., 1994.
8. Fambro, D.B., K. Fitzpatrick, and R.J. Koppa, *"Determination of Stopping Sight Distances,"* NCHRP 400, Transportation Research Board, National Research Council, Washington, D.C., 2000.
9. Donnell, E.T., M.L. Adolini, D.T. Torbic, J.M. Mason, and L. Elefteriadou, *"Truck Safety Considerations for Geometric Design and Traffic Operations,"* Proceedings from ITE Annual Meeting, Institute of Transportation Engineers, 2001.
10. Van Order, D. D. Skorupski, R. Stinebiser, R. Kreeb, "*Fleet Study of Brake Performance and Tire Pressure,"* Federal Motor Carrier Safety Administration, Washington, D.C., 2009.
11. Easa, S. and A. Abd El Halim, "Radius Requirements for Trucks on Three-Dimensional Reverse Horizontal Curves with Intermediate Tangents," 85th Annual Transportation Research Board Meeting Conference Proceedings, Washington, D.C., 2006.
12. Harwood, D.W., J.M. Mason, W.D. Glauz, B.T. Kulakowski, and K. Fitzpatrick, "Truck Characteristics for Use in Highway Design and Operation," Reports FHWA-RD-89-226 and FHWA-RD-89-227, FHWA, U.S. Department of Transportation, 1990.
13. Mason, J.M., L. Griffin, N. Straub, and C. Molina *"Annotated Bibliography of Research on Operational Characteristics and Geometric Implication of Longer and Wider Trucks,"* Research Report 397-1, Texas Transportation Institute, College Station, TX, 1986.
14. Ervin, R.D. *"Effects of Expressway Ramps on Control of Tractor-Semitrailers." UMTRI Research Review*, Vol. 16, No. 4, January 1986, pp. 1–15. University of Michigan Transportation Research Institute, Ann Arbor, MI, 1986.
15. Middleton, D. and S. Venglar, *"Operational Aspects of Exclusive Truck Roadways,"* 85th Annual Transportation Research Board Meeting Conference Proceedings, Washington, D.C., 2006.
16. Wooldridge, M.D., C.J. Messer, B.D. Heard, S. Raghupathy, A.H. Parham, M.A. Brewer, and S. Lee, "Design Guidelines for Passing Lanes on Two-Lane Roadways (Super 2)," Report 4064-1, Texas Transportation Institute, College Station, Texas, 2001.

17. Mason, J.M., K. Fitzpatrick, D.W. Harwood, and J. True, *"Intersection Design Considerations to Accommodate Large Trucks,"* Transportation Research Record 1385, Transportation Research Board, Washington, D.C., 1993.
18. Prozzi, J., R. Harrison, and J.A. Prozzi, *"Defining and Measuring Rural Truck Traffic Needs in Texas,"* Report Number 0-4169-2, Center for Transportation Research, University of Texas, Austin, Texas, 2006.
19. Fontaine, M.D., "*Engineering and Technology Measures to Improve Large Truck Safety: State of the Practice in Virginia,"* Technical Assistance Report, Virginia Transportation Research Council, Charlottesville, Virginia, 2003.
20. Manual on Uniform Traffic Control Devices, Federal Highway Administration, U.S. Department of Transportation, 2009.
21. PrePass website. http://www.prepass.com/services/prepass/Pages/WhatIsPrepass.aspx. Accessed January 28, 2010.
22. Giles, T. *"Under Observation,"* Traffic Technology International, Surrey, United Kingdom, 2006.
23. Ballard, A., *"Incident Management for Managed Lanes,"* Report Number 0-4160-17, Texas Transportation Institute, College Station, Texas, 2004.
24. *Traffic Control Hessen.* Hessen Road and Traffic Authority, Weisbaden, Germany, 2006.
25. F. Middelham. "Dynamic Traffic Management." Ministry of Transport, Public Works, and Water Management, Directorate-General of Public Works and Water Management, AVV Transport Research Centre, Rotterdam, Netherlands, Presentation to PCM Scan Team, June 2006.
26. S. Tignor, L. Brown, J. Butner, R. Cunard, S. Davis, H. Hawkins, E. Fischer, M. Kehrli, P. Rusche, and W. Wainwright. *Innovative Traffic Control Technology and Practice in Europe.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., August 1999.