Chapter 1
INTRODUCTION

Background

General guidance for the geometric features of single-lane free-flow entrance ramps are given in the primary roadway geometric design guide for the United States which is “A Policy on Geometric Design of Highways and Streets”, 2004 (hereafter referred to as the Green Book)(1). For convenience of reference, the five-page segment of the guidebook from page 845 through 849 is included on the next few pages.

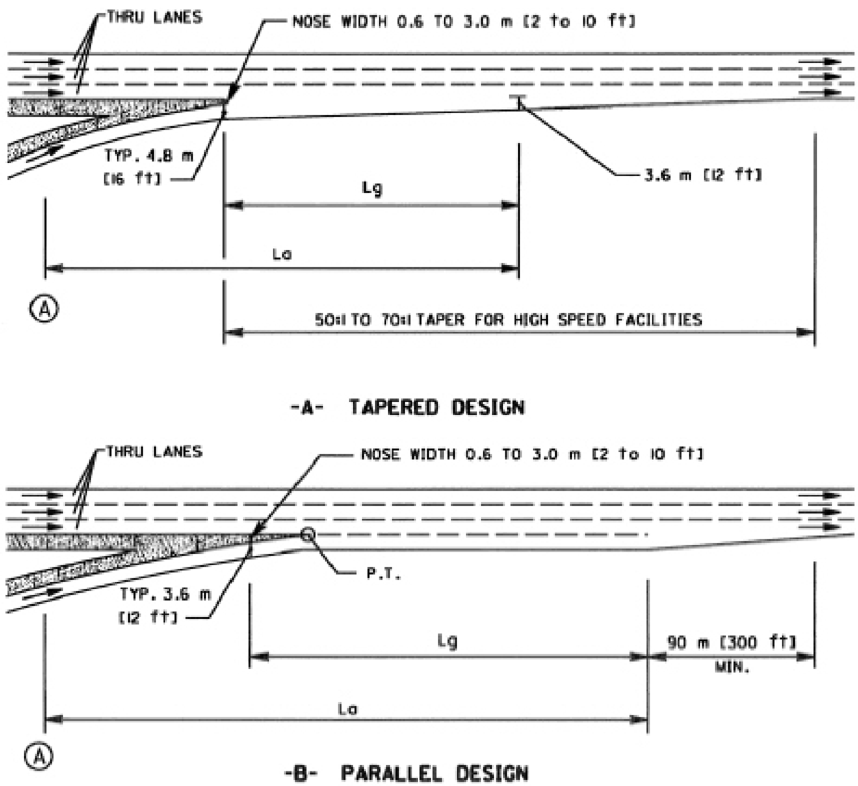
The direction given by these pages are the foundation of the designs of acceleration ramps on countless high-speed limited-access roadway systems in the US. There is no doubt that the consistency of the existing geometric features of long-lived acceleration ramps based on these guidelines have shaped driver behavior over the years to promote expectations for desirable design features that encourage successful outcomes for traversing acceleration lanes and accomplishing smooth merges into high-speed through traffic.

It is critical to understand the intent of the Green Book passages to properly use the advice. Since these guidelines have evolved from concepts and vehicle characteristics in the 1930s, the exhibits and content are not easily interpreted.

Over the past few years, there has been much focus on this particular subject, generating many different types of research projects to both determine if the 2004 guidelines are still relevant and also how to adapt them to larger vehicles in the surface transportation network such as tractor-trailer trucks.

Single-Lane Free-Flow Terminals, Entrances

Taper-type entrance. When properly designed, the taper-type entrance usually operates smoothly at all volumes up to and including the design capacity of merging areas. By relatively minor speed adjustment, the entering driver can see and use an available gap in the through-traffic stream. A typical single-lane, taper-type entrance terminal is shown in Exhibit 10-69A.



NOTES:

1. La IS THE REQUIRED ACCELERATION LENGTH AS SHOWN IN EXHIBIT 10-70 OR AS ADJUSTED BY EXHIBIT 10-71.
2. POINT (A) CONTROLS SPEED ON THE RAMP. La SHOULD NOT START BACK ON THE CURVATURE OF THE RAMP UNLESS THE RADIUS EQUALS 300 m [1000 ft] OR MORE.
3. Lg IS REQUIRED GAP ACCEPTANCE LENGTH. Lg SHOULD BE A MINIMUM OF 90 TO 150 m [300 to 500 ft] DEPENDING ON THE NOSE WIDTH.
4. THE VALUE OF La OR Lg, WHICHEVER PRODUCES THE GREATER DISTANCE DOWNSTREAM FROM WHERE THE NOSE EQUAL 0.6 m [2 ft], IS SUGGESTED FOR USE IN THE DESIGN OF THE RAMP ENTRANCE.

Exhibit 10-69. Typical Single-Lane Entrance Ramps

FIGURE 1 Portion of Page 845 in the 2004 Green Book Referring to Acceleration Lane Design (1)

The entrance is merged into the freeway with a long, uniform taper. Operational studies show a desirable rate of taper of about 50:1 to 70:1 (longitudinal to lateral) between the outer edge of the acceleration lane and the edge of the through-traffic lane. The gap acceptance length, L_g is also a consideration in the design of taper-type entrances, as illustrated in Exhibit 10-69A.

The geometrics of the ramp proper should be such that motorists may attain a speed that is within 10 km/h [5 mph] of the operating speed of the freeway by the time they reach the point where the left edge of the ramp joins the traveled way of the freeway. For consistency of application, this point of convergence of the left edge of the ramp and the right edge of the through lane may be assumed to occur where the right edge of the ramp traveled way is 3.6 m [12 ft] from the right edge of the through lane of the freeway.

The distance needed for acceleration in advance of this point of convergence is governed by the speed differential between the operating speed on the entrance curve of the ramp and the operating speed of the highway. Exhibit 10-70 shows minimum lengths of acceleration distances for entrance terminals. Exhibit 10-69 shows the minimum lengths for gap acceptance. Referring to Exhibit 10-69, the larger value of the acceleration length (L_a) or the gap acceptance (L_g) length is suggested for use in the design of the ramp entrance. Where the minimum values for nose width (0.6 m [2 ft]), lane width 4.8 m [16 ft]), and taper rate (50:1) are used with high traffic volumes, taper lengths longer than the larger of L_a or L_g may be needed to avoid inferior operation and to reduce fairly sharp moves into the mainline traffic stream. Where grades are present on ramps, speed-change lengths should be adjusted in accordance with Exhibit 10-71.

Parallel-type entrances. The parallel-type entrance provides an added lane of sufficient length to enable a vehicle to accelerate to near-freeway speed prior to merging. A taper is provided at the end of the added lane. The process of entering the freeway is similar to a lane change to the left. The driver is able to use the side-view and rear-view mirrors to monitor surrounding traffic.

A typical design of a parallel-type entrance is shown in Exhibit 10-69B. Desirably, a curve with a radius of 300 m [1,000 ft] or more and a length of at least 60 m [200 ft] should be provided in advance of the added lane. If this curve has a short radius, motorists tend to drive directly onto the freeway without using the acceleration lane. This behavior results in undesirable merging operations.

The taper at the downstream end of a parallel-type acceleration lane should be a suitable length to guide the vehicle gradually onto the through lane of the freeway. A taper length of approximately 90 m [300 ft] is suitable for design speeds up to 110 km/h [70 mph].

The length of a parallel-type acceleration lane is generally measured from the point where the left edge of the traveled way of the ramp joins the traveled way of the freeway to the beginning of the downstream taper. Whereas, in the case of the taper type entrance, acceleration is accomplished on the ramp upstream of the point of convergence of the two roadways, acceleration usually takes place downstream from this point in the case of the parallel type. However, a part of the ramp proper may also be considered in the acceleration length, provided the curve approaching the acceleration lane has a long radius of approximately 300 m [1,000 ft]

FIGURE 2 Page 846, Reproduced from the 2004 Green Book (1)

or more, and the motorist on the ramp has an unobstructed view of traffic on the freeway to his or her left. The minimum acceleration lengths for entrance terminals are given in Exhibit 10-70, and the adjustments for grades are given in Exhibit 10-71.

Metric

Highway		Stop condition	20	30	40	50	60	70	80
		Acceleration length, L (m) for entrance curve design speed (km/h) and initial speed, V'_a (km/h)							
Design speed, V (km/h)	Speed reached, V_a (km/h)	0	20	28	35	42	51	63	70
50	37	60	50	30	—	—	—	—	—
60	45	95	80	65	45	—	—	—	—
70	53	150	130	110	90	65	—	—	—
80	60	200	180	165	145	115	65	—	—
90	67	260	245	225	205	175	125	35	—
100	74	345	325	305	285	255	205	110	40
110	81	430	410	390	370	340	290	200	125
120	88	545	530	515	490	460	410	325	245

Note: Uniform 50:1 to 70:1 tapers are recommended where lengths of acceleration lanes exceed 400 m.

US Customary

Highway		Stop condition	15	20	25	30	35	40	45	50
		Acceleration length, L (ft) for entrance curve design speed (mph) and initial speed, V'_a (mph)								
Design speed, V (mph)	Speed reached, V_a (mph)	0	14	18	22	26	30	36	40	44
30	23	180	140	—	—	—	—	—	—	—
35	27	280	220	160	—	—	—	—	—	—
40	31	360	300	270	210	120	—	—	—	—
45	35	560	490	440	380	280	160	—	—	—
50	39	720	660	610	550	450	350	130	—	—
55	43	960	900	810	780	670	550	320	150	—
60	47	1200	1140	1100	1020	910	800	550	420	180
65	50	1410	1350	1310	1220	1120	1000	770	600	370
70	53	1620	1560	1520	1420	1350	1230	1000	820	580
75	55	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.

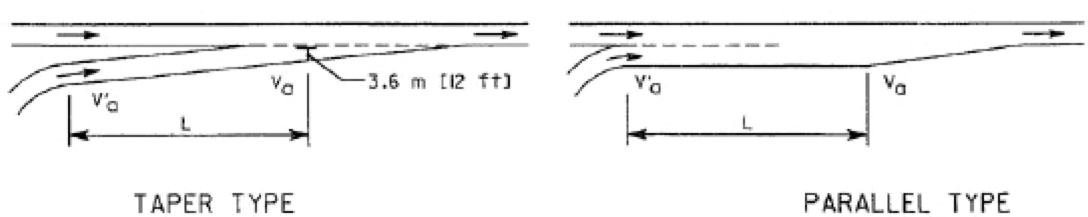


Exhibit 10-70. Minimum Acceleration Lengths for Entrance Terminals with Flat Grades of Two Percent or Less

FIGURE 3 Page 847, Reproduced from the 2004 Green Book (1)

Metric

Design speed of highway (km/h)	Deceleration lanes: Ratio of length on grade to length on level for design speed of turning curve (km/h)[a]					
All speeds	3 to 4% upgrade 0.9					3 to 4% downgrade 1.2
All speeds	5 to 6% upgrade 0.8					5 to 6% downgrade 1.35

Design speed of highway (km/h)	Acceleration lanes: Ratio of length on grade to length of level for design speed of turning curve (km/h)[a]					
	40	50	60	70	80	All speeds
			3 to 4% upgrade			3 to 4% downgrade
60	1.3	1.4	1.4	—	—	0.7
70	1.3	1.4	1.4	1.5	—	0.65
80	1.4	1.5	1.5	1.5	1.6	0.65
90	1.4	1.5	1.5	1.5	1.6	0.6
100	1.5	1.6	1.7	1.7	1.8	0.6
110	1.5	1.6	1.7	1.7	1.8	0.6
120	1.5	1.6	1.7	1.7	1.8	0.6
			5 to 6% upgrade			5 to 6% downgrade
60	1.5	1.5	—	—	—	0.6
70	1.5	1.6	1.7	—	—	0.6
80	1.5	1.7	1.9	1.8	—	0.55
90	1.6	1.8	2.0	2.1	2.2	0.55
100	1.7	1.9	2.2	2.4	2.5	0.5
110	2.0	2.2	2.6	2.8	3.0	0.5
120	2.3	2.5	3.0	3.2	3.5	0.5

US Customary

Design speed of highway (mph)	Deceleration lanes: Ratio of length on grade to length on level for design speed of turning curve (mph)[a]				
All speeds	3 to 4% upgrade 0.9				3 to 4% downgrade 1.2
All speeds	5 to 6% upgrade 0.8				5 to 6% downgrade 1.35

Design speed of highway (mph)	Acceleration lanes: Ratio of length on grade to length of level for design speed of turning curve (mph)[a]				
	20	30	40	50	All speeds
		3 to 4% upgrade			3 to 4% downgrade
40	1.3	1.3	—	—	0.7
45	1.3	1.35	—	—	0.675
50	1.3	1.4	1.4	—	0.65
55	1.35	1.45	1.45	—	0.625
60	1.4	1.5	1.5	1.6	0.6
65	1.45	1.55	1.6	1.7	0.6
70	1.5	1.6	1.7	1.8	0.6
		5 to 6% upgrade			5 to 6% downgrade
40	1.5	1.5	—	—	0.6
45	1.5	1.6	—	—	0.575
50	1.5	1.7	1.9	—	0.55
55	1.6	1.8	2.05	—	0.525
60	1.7	1.9	2.2	2.5	0.5
65	1.85	2.05	2.4	2.75	0.5
70	2.0	2.2	2.6	3.0	0.5

[a] Ratio from this table multiplied by the length in Exhibit 10-70 or Exhibit 10-73 gives length of speed change lane on grade.

Exhibit 10-71. Speed Change Lane Adjustment Factors as a Function of Grade

The operational and safety benefits of long acceleration lanes provided by parallel type entrances are well recognized. A long acceleration lane provides more time for the merging vehicles to find an opening in the through-traffic stream. An acceleration lane length of at least 360 m [1,200 ft], plus the taper, is desirable wherever it is anticipated that the ramp and freeway will frequently carry traffic volumes approximately equal to the design capacity of the merging area.

FIGURE 4 Page 847 and Portion of Page 848, Reproduced from the 2004 Green Book (1)

A Closer Look at Exhibit 10-69

The figures and text in Exhibit 10-69 are difficult to understand with respect to the taper-type design. A schematic of the information in Exhibit 10-69 is shown in FIGURE 5 to fully grasp what the guidelines are intending to convey. A longitudinal to lateral "50:1 to 70:1 taper for high speed facilities" is recommended on the diagram. "High speed" is inferred in the Green Book in Chapter 3 with reference to horizontal curvature design criteria and is considered to be a design speed of 50 mph or greater (1). There is also a notation under the acceleration length table in Exhibit 10-70 that indicates a 50:1 to 70:1 taper is recommended for lengths of acceleration lanes greater than 1300 ft.

Entrance ramps serve two purposes: 1) they allow entering vehicle drivers to attain a speed near that of the through traffic on a free-flow through facility, and 2) they allow time for a driver to observe an acceptable gap in through traffic in the nearest lane into which the driver can merge safely.

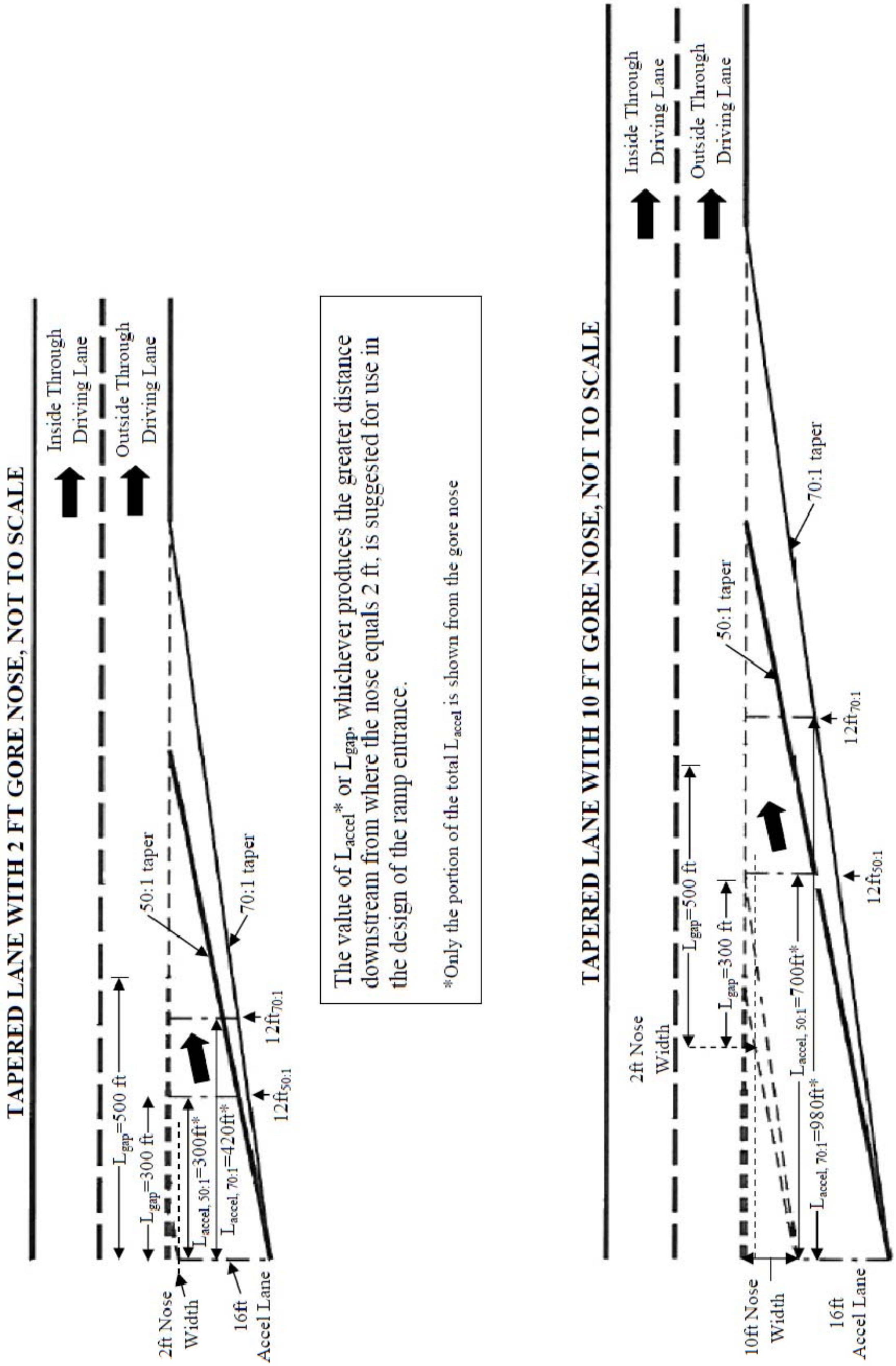


FIGURE 5 Schematic Details of Intent of Exhibit 10-69 in 2004 Green Book (1)

Therefore, the geometric attributes of the merging lane should allow enough length to accomplish both purposes. Since the 50 to 70:1 taper rate is specified, the portions of the acceleration length given a 2 ft to 10 ft gore width are shown on the schematic in FIGURE 5 which would be a part of satisfying Criterion 1. The current guidelines describe a longitudinal distance range (300 to 500 ft) from the location at which the gore nose width is 2 ft to allow enough time for gap acceptance which would satisfy Criterion 2. Using Exhibit 10-70 to determine the minimum acceleration length for a given design speed, the position of the end of the length required for acceleration can be compared to the 300 to 500 ft distance from the location where the gore nose is 2 ft and the option that is furthest from the gore nose may be selected for further geometric refinement. FIGURE 6 adds explanations of portions of Exhibit 10-70 for insight to the origins of the speed variables V, Va, and V′a, which are the through roadway design speed, the estimated running speed of drivers on the through roadway, and a close proximity to the estimated running speed of drivers at the end of the controlling curve on the merging ramp, respectively. Exhibit 3-14 from page 143 of the 2004 Green Book is reproduced in FIGURE 7 which shows the comparison between design speed and running speed. Running speed is oftentimes estimated by the arithmetic mean of the speeds of all traffic as measured at a specified point on the roadway (page 67, 1).

Low/high design speed boundary, as defined by Chapter 3 of Green Book

Average running speed of ramp based on given design speed (refer to page 143 of Green Book) shown for reference purposes

Average running speed (which is commonly estimated by mean speed) of through traffic based on given design speed (refer to page 143 of Green Book) minus 5 mph

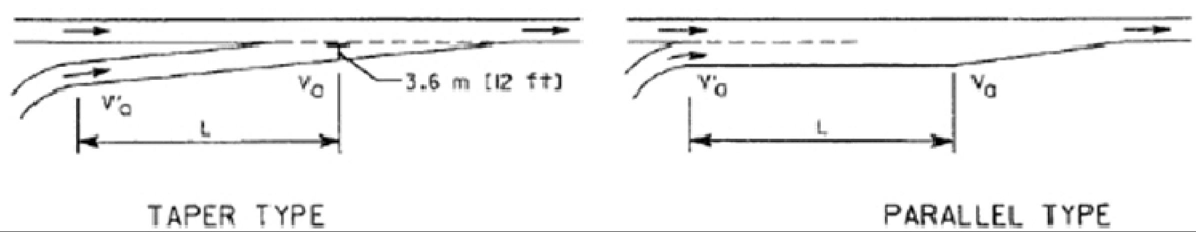
NOTE: Text recommends that drivers should reach a speed within 5 mph of **operating speed** (generally estimated as 85th-percentile speed)

US Customary

Highway		Acceleration length, L (ft) for entrance curve design speed (mph)								
		Stop condition	15	20	25	30	35	40	45	50
Design speed, V (mph)	Speed reached V_a (mph)	and initial speed, V'_a (mph)								
		0	**15**	**20**	**24**	**28**	**32**	**36**	**40**	**44**
		0	14	18	22	26	30	36	40	44
30	23	180	140	—	—	—	—	—	—	—
35	27	280	220	160	—	—	—	—	—	—
40	31	360	300	270	210	120	—	—	—	—
45	35	560	490	440	380	280	160	—	—	—
50	39	720	660	610	550	450	350	130	—	—
55	43	960	900	810	780	670	550	320	150	—
60	47	1200	1140	1100	1020	910	800	550	420	180
65	50	1410	1350	1310	1220	1120	1000	770	600	370
70	53	1620	1560	1520	1420	1350	1230	1000	820	580
75	55	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.

The text recommends this as a desirable taper rate range regardless of acceleration lane lengths.



General Assumptions:

- Values are minimums originally developed for passenger car acceleration
- Values are strictly based on acceleration and not on gap acceptance
- Ramp must be long enough in advance of the PT of its controlling curve to allow the average speed of passenger cars to accelerate to $V'a$
- Ramp controlling curve is less than 1000 ft ($V_{ramp\ curve} \approx 55$ mph)
- Acceleration lane grades of 2 percent or less

FIGURE 6 Explanations of Variables in Exhibit 10-70 in 2004 Green Book (1)

Metric		US Customary	
Design speed (km/h)	Average running speed (km/h)	Design speed (mph)	Average running speed (mph)
20	20	15	15
30	30	20	20
40	40	25	24
50	47	30	28
60	55	35	32
70	63	40	36
80	70	45	40
90	77	50	44
100	85	55	48
110	91	60	52
120	98	65	55
130	102	70	58
		75	61
		80	64

FIGURE 7 Reproduction of Exhibit 3-14, Average Running Speeds, 2004 Green Book (1)

Research Project Objective

The goal of this research project is to review the current guidelines of the 2004 Green Book and determine if the guidebook's recommendations for **minimum** acceleration lengths are reasonable and if it is feasible to achieve the **desirable** objective that "the geometrics of the ramp proper should be such that motorists may attain a speed that is within 5 mph of the operating speed of the freeway by the time they reach the point where the left edge of the ramp joins the traveled way of the freeway." This definition of the geometry of the ramp infers that the ramp should be configured to successfully achieve its two purposes stated earlier, within a range of minimal to desirable levels.

Review of the evolution of the Green Book's advice on acceleration lane design indicates that the recommendations are solely for passenger cars. This research project is also concerned with the impact of high percentages of heavy trucks operating on a system designed for smaller vehicles.

Since acceleration lanes have the two basic geometric design styles of tapered and parallel types, it is also of interest to determine which style may serve best in a given situation. There is anecdotal evidence that when conditions are at or near capacity at merging ramps, a tapered design tends to back up drivers on the through roadway.

Expected Benefits

Expected benefits of this research project should provide more realistic guidelines to improve vehicle operations along accelerations lanes on high-operating-speed roadways. These guidelines for realistic improvements should result in reduced delay and an increase in safety at merge locations, which are common locations for accidents along high-operating-speed multi-lane roadways.

Chapter 2
LITERATURE REVIEW

History of the Development of the 2004 AASHTO Guidelines

Acceleration lane length values that most closely match those in the 2004 Green Book are shown for the first time in the 1965 rural version of the same guidebook, *A Policy on Geometric Design of Rural Highways*, often called the Blue Book because of its blue cover (2). This guidebook documented the procedure used to develop recommendations for acceleration lane lengths and accompanying criteria.

Three contributing factors were used to arrive at values for minimum acceleration lane lengths including:

1) the speed at which drivers chose to merge with through traffic,
2) the speed at which drivers entered the portion of the lane dedicated for acceleration, and
3) the manner in which the acceleration was accomplished.

Assumptions held for the first two contributing factors were:

- that drivers would enter the acceleration lane at an average running speed (which may be estimated by the mean speed of a given traffic flow sampling) which was determined based on the speed chosen for the design of the ramp's controlling horizontal curvature, and
- that drivers would merge with through traffic at a speed equal to the average running speed of the through traffic minus 5 mph.

Acceleration rate values used in the development of the recommendations were from 1937 Bureau of Public Roads study data plotting the normal acceleration of a passenger car.

Recommendations for acceleration lane lengths remained relatively similar through the various editions of the AASHTO guidebooks used through recent history which include the 1973 *A Policy on Design of Urban Highways and Arterial Streets*, referred to as the Red Book. In 1984, both rural and urban guidebooks were combined into *A Policy on Geometric Design of Highways and Streets*, and the color of the book cover was changed to green and nicknamed the Green Book to be carried forward into the 1990, 1994, 2001 and current 2004 updated versions.

Previous Recent Research on Acceleration Lanes

NCHRP Report 505

In 2003, the National Cooperative Highway Research Program (NCHRP) completed the research study for Report 505, *Review of Truck Characteristics as Factors in Roadway Design*, the goal of which was to verify that trucks could be adequately accommodated using geometric guidelines presented in the 2001 version of the Green Book (3). The following recommendations resulted from findings of Report 505:

- model parameter values for passenger cars and trucks should be different, and
- models should be revised to better represent truck characteristics.

A significant result of Report 505 was the use of truck performance equations from the TWOPAS computer simulation model to develop an adaptable tool using a truck weight-to-power ratio, a roadway profile, and an initial truck speed to establish a speed profile for given conditions. This model was called the Truck Speed Performance Model (TSPM). Authors of the TSPM used it to conclude what truck weight-to-power ratios could be accommodated by the minimum acceleration lane lengths for less than 2 percent grades given in Exhibit 10-70. Results of the analyses are shown in TABLE 1 indicating average trucks were adequately served but heavily-loaded trucks were not.

TABLE 1 Modern Truck Acceleration Accommodation Using Exhibit 10-70 of 2004 Green Book (3)

Profile Grade, Percent	Truck Weight-to-Power Ratio Range Accommodated by Minimum Acceleration Lengths, pounds per horsepower	Accommodated by Exhibit 10-70 Minimum Acceleration Lane Lengths
0-2	170 to 210	No
0	100 to 145	Yes
2	65 to 110	Yes

When the TSPM was used to estimate minimum acceleration lane lengths for a 180 lb/hp truck on a 0 percent grade, lane lengths resulted that were about 1.8 times greater than those values provided in Exhibit 10-70, as shown in TABLE 2.

TABLE 2 Acceleration Lane Lengths Calculated in NCHRP Report 505 using the TSPM for a 180 lb/hp Truck on a Zero Percent Grade (3)

Hwy Design Speed, mph	Speed Reached, mph	Acceleration Length, ft, for Entrance Curve Design Speed, mph								
		Stop	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
		Entrance Curve Initial Speed, mph								
		0	**14**	**18**	**22**	**26**	**30**	**36**	**40**	**44**
30	**23**	275	160							
35	**27**	400	300	230						
40	**31**	590	475	400	310	170				
45	**35**	800	700	630	540	400	240			
50	**39**	1100	1020	950	850	720	560	200		
55	**43**	1510	1400	1330	1230	1100	920	580	240	
60	**47**	2000	1900	1830	1740	1600	1430	1070	760	330
65	**50**	2490	2380	2280	2230	2090	1920	1560	1220	800
70	**53**	3060	2960	2900	2800	2670	2510	2140	1810	1260
75	**55**	3520	3430	3360	3260	3130	2960	2590	2290	1850

Texas Transportation Institute (TTI) Acceleration Lane Studies

A study completed in 2007 by Fitzpatrick and Zimmerman titled *Potential Updates to the 2004 Green Book Acceleration Lengths for Entrance Terminals* (4), included an in-depth study of the evolution of the values used in Exhibit 10-70 and an examination of other more realistic methods to calculate acceleration distance which included NCHRP Report 505, Texas Department of Transportation (TxDOT) Project 5544, information from the Institute of Transportation Engineers' (ITE) Traffic Engineering Handbook and a Canadian study. After a comparison of all methods to the 2004 Green Book values, the final recommendation by the authors included using the average constant acceleration rate of 2.5 ft/sec^2 (from the Canadian study), the through highway design speed, and the ramp curve design speed to determine acceleration lengths for passenger cars and light trucks. The resulting values are shown in TABLE 3.

TABLE 3 Acceleration Lane Lengths for Passenger Cars and Light Trucks, Fitzpatrick and Zimmerman (4)

Highway Design Speed, mph	Acceleration Length for Entrance Curve Design Speed, mph								
	Stop 0	15	20	25	30	35	40	45	50
30	389	292	216						
35	529	432	357	259					
40	691	594	519	421	303				
45	875	778	702	605	486	346			
50	1080	983	908	810	691	551	389		
55	1307	1210	1134	1037	918	778	616	432	
60	1556	1459	1383	1286	1167	1026	864	681	475
65	1826	1729	1653	1556	1437	1297	1134	951	746
70	2118	2020	1945	1848	1729	1588	1426	1243	1037
75	2431	2334	2258	2161	2042	1902	1740	1556	1351

Fitzpatrick and Zimmerman also examined the 2004 Green Book factors to be applied when acceleration lanes were on greater than 2 percent grades. Their recommendations for changes in the factors are in TABLE 4 and FIGURE 8 below.

TABLE 4 Potential Adjustment Factors for Passenger Car/Light Truck Vehicles for Acceleration Lanes, Fitzpatrick and Zimmerman (4)

Highway Design Speed, mph	-6	-5	-4	-3	-2 to 2	+3	+4	+5	+6
50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60	1.00	1.00	1.00	1.00	1.00	1.05	1.10	1.15	1.20
70	0.85	0.89	0.93	0.96	1.00	1.08	1.15	1.23	1.30
80	0.80	0.85	0.90	0.95	1.00	1.10	1.20	1.30	1.40

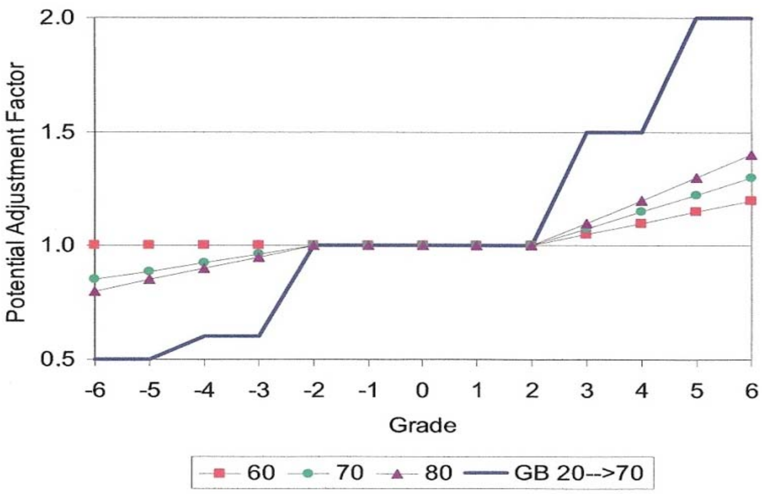


FIGURE 8 Potential Adjustment Factors for Grades from -6 to +6 Percent for Acceleration Lanes (4)

Acceleration Lane Lengths Considering High Truck Volumes

In December 2008, Gattis et al (5) completed a study of acceleration lane design for facilities with high truck volumes. Mathematical models predicting average and 10th-percentile speeds for tractor-trailer trucks on slight upgrades, downgrades and level conditions were developed from truck acceleration data collected at four commercial weigh stations in Arkansas and Missouri. Percentages of trucks in the freeway flow ranged from 14 percent to 52 percent and weights ranged from 40,000 to 80,000 pounds.

The basic model formula developed from the data for truck speed estimation was:

Truck Speed = Y-axis Intercept + Distance*(First Order Term) + Distance*(Second Order Term)

The values for the factors in the truck speed equation are shown in TABLES 5 and 6. TABLE 5 includes speed data values collected at the static scales of the weigh stations beginning at the scale position. TABLE 6 includes speed data values collected beginning 1000 ft from the scale position. An especially large number of data points collected in the first 1000 ft from the scale adversely affected the model development and resulted in unrealistic predictions at large distances so two models were created, one with all the data and another with the data from the first 1000 ft of acceleration length removed.

TABLE 5 Mean and 10th-Percentile Truck Speed Model Coefficients for All and Unimpeded Truck Acceleration Event Models Beginning at 0 Feet Beyond Static Scales (5)

Data Type	**Truck Speed Model**	**Y-Axis Intercept**	**First Order (x)**	**Second Order (x^2)**
Downhill, All Data	Mean	21.0337	0.0200	$-2.50*10^{-6}$
	10th-Percentile	15.3950	0.0189	$-2.01*10^{-6}$
Downhill, Unimpeded	Mean	20.4545	0.0206	$-2.73*10^{-6}$
	10th-Percentile	13.3221	0.0217	$-2.83*10^{-6}$
Level, All Data	Mean	17.3881	0.0216	$-2.73*10^{-6}$
	10th-Percentile	16.3419	0.0185	$-2.18*10^{-6}$
Level, Unimpeded	Mean	16.1577	0.0226	$-2.88*10^{-6}$
	10th-Percentile	14.4975	0.0195	$-2.24*10^{-6}$
Uphill, All Data	Mean	17.2398	0.0208	$-2.97*10^{-6}$
	10th-Percentile	12.2669	0.0200	$-2.76*10^{-6}$
Uphill, Unimpeded	Mean	17.2545	0.0210	$-2.95*10^{-6}$
	10th-Percentile	12.5832	0.0211	$-3.06*10^{-6}$

TABLE 6 Mean and 10th-Percentile Truck Speed Model Coefficients for All and Unimpeded Truck Acceleration Event Models Beginning at 1000 Feet Beyond Static Scales (5)

Data Type	Truck Speed Model	Y-Axis Intercept	First Order (x)	Second Order (x^2)
Downhill, All Data	Mean	20.1187	0.0200	$-2.37*10^{-6}$
	10th-Percentile	15.2327	0.0185	$-1.83*10^{-6}$
Downhill, Unimpeded	Mean	19.8869	0.0201	$-2.44*10^{-6}$
	10th-Percentile	15.1563	0.0186	$-1.84*10^{-6}$
Level, All Data	Mean	22.8188	0.0165	$-1.73*10^{-6}$
	10th-Percentile	20.8749	0.0185	$-1.46*10^{-6}$
Level, Unimpeded	Mean	22.2720	0.0146	$-1.80*10^{-6}$
	10th-Percentile	19.6650	0.0151	$-1.41*10^{-6}$
Uphill, All Data	Mean	14.5263	0.0231	$-3.42*10^{-6}$
	10th-Percentile	8.1344	0.0243	$-3.76*10^{-6}$
Uphill, Unimpeded	Mean	15.4647	0.0223	$-3.17*10^{-6}$
	10th-Percentile	12.2413	0.0214	$-3.12*10^{-6}$

TABLE 7 shows a comparison of truck speeds predicted by the models at 500 ft increments beyond 1000 ft from the static scale location to indict the similarity of the two models.

TABLE 7 Predicted Average and 10th-Percentile Truck Speeds from All Truck Speed Models (5)

Data Type	Truck Speed Model Beginning at (X)	Predicted Truck Speed at Distance, Ft					
		1000	**1500**	**2000**	**2500**	**3000**	**3500**
Downhill, All Data	Mean (0)	38.5	45.4	51.0	55.4		
	Mean (1000)	37.8	44.8	50.6	55.3		
	10th-Percentile (0)	32.3	39.2	45.2	50.1		
	10th-Percentile (1000)	31.9	38.9	44.9	50.1		
Downhill, Unimpeded	Mean (0)	38.3	45.2	50.7	54.9		
	Mean (1000)	37.6	44.6	50.3	54.9		
	10th-Percentile (0)	32.2	39.5	45.4	49.9		
	10th-Percentile (1000)	31.9	38.9	45.0	50.2		
Level, All Data	Mean (0)	36.3	43.7	49.7	54.3	57.6	59.6
	Mean (1000)	37.6	43.7	48.9	53.3	56.8	59.4
	10th-Percentile (0)	32.7	39.2	44.6	49.0	52.2	54.4
	10th-Percentile (1000)	34.0	39.5	44.2	48.3	51.5	54.1
Level, Unimpeded	Mean (0)	35.9	43.6	49.8	54.7	58.0	60.0
	Mean (1000)	37.4	43.6	48.9	53.3	56.8	59.4
	10th-Percentile (0)	31.8	38.7	44.5	49.3	52.8	55.3
	10th-Percentile (1000)	33.4	39.1	44.2	48.6	52.3	55.2
Uphill, All Data	Mean (0)	35.1	41.8	47.0	50.7	52.9	
	Mean (1000)	34.2	41.5	47.1	50.9	53.1	
	10th-Percentile (0)	29.5	36.1	41.2	45.0	47.4	
	10th-Percentile (1000)	28.7	36.1	41.7	45.4	47.2	
Uphill, Unimpeded	Mean (0)	35.3	42.1	47.5	51.3	53.7	
	Mean (1000)	34.6	41.8	47.4	51.4	53.8	
	10th-Percentile (0)	30.6	37.4	42.5	46.2	48.3	
	10th-Percentile (1000)	30.5	37.3	42.6	46.2	48.4	

In general, the models that did not include the first 1000 ft of data predicted speeds which were slightly lower and displayed more acceleration at greater distances, compared with the model developed with data that included the first 1000 ft from the scale location.

Comparisons

TABLE 8 shows comparisons of the recommended acceleration lane lengths from the sources summarized above.

TABLE 8 Summary of Acceleration Lane Lengths from Previous Research (5)

	AASHTO Green Book, 2004	Fitzpatrick & Zimmerman, 2006	NCHRP 505	Gattis, et al 2008
Model Design Vehicle Type	Passenger Car on Zero to 2 Percent Grade	Passenger Car, Light Truck	180 lb/hp Tractor-Trailer Truck on Level Grade	Tractor-Trailer Truck on Level Grade
Assumed initial speed, mph	22	20	22	17
Speed Reached, mph	**Distance to Reach Speed, ft**			
39	550	-	850	-
40	-	908*	-	1203
50	1020	1383*	2230	2119
55	1580	1653*	3260	2731
60	-	1945*	-	3655

*Values shown are for a design speed of 10 mph above the "Speed Reached" value.

Previous Research on Driver Behaviors on Acceleration Lanes

A study by Fukutome and Moskowitz (6) focused on driver behavior relative to the geometric design of acceleration ramps. From the field data they collected, they reported the following:

- a 50:1 tapered ramp design led to drivers using a greater portion of the ramp than a parallel-style ramp of the same length,
- more of the ramp length was used to accelerate at low volumes than at high volumes,
- the necessary merging distance at high speed was as great as that at low speed, and
- a 50:1 tapered style ramp design provided enough acceleration distance for all turning speeds.

Michaels and Fazio (7) developed a driver behavior merging model that was based on merging drivers incorporating the angular speed of through vehicles in their merge process through iteratively executing four steps in parallel as well as sequentially during the final merge:

1) initial steering control,
2) acceleration,
3) search for an acceptable gap, and
4) steering to merge.

A noticeable pattern was observed in field testing that showed drivers initially accelerated but would begin to slow during their search for an acceptable gap, seemingly inattentive to maintaining or increasing speed while focusing on through traffic vehicle spacings. The data collected indicated that the majority of drivers successfully merged after 3 attempts: 20 percent after one attempt, 62 percent after two attempts and 98 percent after three attempts.

Michaels and Fazio's development of a merging model indicated that a tapered ramp with a small angle convergence led to a more effective merging process allowing an increase in the ability to determine acceptable gaps.

Hunter, et al conducted an operational evaluation of freeway ramp design (8) and found with a large volume of ramp traffic, drivers were observed performing smooth merging with through traffic close to the end of well-designed on ramps while poorer designs led drivers to more aggressive merge maneuvers nearer the gore area. Poor ramp geometry also led to a significant reduction of right-lane speed. Freeway right-lane headway and accepted gaps are influenced by ramp traffic volume and not ramp design. Observed vehicles tend to begin the acceleration/merge process only after gaining proper sight of the freeway traffic.

Kondyli and Elefteriadou (9) concluded the following from conducting three focus groups to investigate drivers' intentions at a freeway merge segment.

- Drivers indicated they would be more aggressive on tapered ramps than parallel ramps
- Right-through-lane drivers preferred changing lanes and avoiding decelerating when faced with a merging vehicle
- A driver's choice of forcing a merge depended mostly on traffic factors like through traffic speed, congestion, and gap availability affecting right-through-lane drivers' decision to change lanes or decelerate.

Kondyli and Elefteriadou (10) followed up the focus group study with a field study that observed similar results to those concluded from drivers' intentions. The following behaviors were observed:

- More cooperative merges occurred when freeway drivers changed lanes rather than decelerating behind merging vehicles
- Drivers used more length of acceleration lane at tapered ramps than at parallel installations with higher merging speeds suggesting tapered styles are used more efficiently.

Brewer and Fitzpatrick (11) studied the behavior of 12 individuals driving a TTI instrumented 2006 Toyota Highlander sport utility vehicle through nine acceleration ramps on freeways in the Dallas/ Ft. Worth, Texas metropolitan area to identify patterns and influences that determine how drivers perform when merging on an acceleration ramp. Six of the 9 ramps were of the tapered type. Conclusions from their data analyses resulted in the following comments:

- In uncongested or lightly congested conditions, a driver's typical glance into a mirror or over the shoulder to assess through roadway conditions for a future merge is typically about 2.5 to 3.0 seconds and the driver tends to take 3 such glances on a given entrance ramp. The driver travels between 100 and 200 ft and increases speed by about 2.5 mph in the typical glance time.
- In uncongested or lightly congested conditions, a merging driver tends to use about half of the acceleration lane provided and rarely more than 80 percent of it.
- The 2004 Green Book guidelines for acceleration ramps provides sufficient acceleration lengths for merging a recent model sports utility type vehicle into through traffic under uncongested and lightly congested conditions.

Given the fact that drivers use sequential glancing to assess the conditions of the freeway in advance of their merge, the researchers emphasized the need for adequate sight distance for the merging driver to see the through-traffic lanes to properly plan the execution of behaviors required to smoothly enter the traffic stream.

Ahammed et al (12) developed models for speed and merging behavior of passenger cars and observed the following from their data which focused on off-peak periods with no traffic congestion:

- The merging distance from gore to merge point increased with speed change length up to about 1300 ft during off-peak periods indicating that a longer lane would not increase driver comfort during the acceleration and merging maneuvers.

- Right-through-lane speed models showed that freeway right-lane speed decreases as the right-lane volume increases and right-lane speed increases as merging speed increases. To quantitatively evaluate impacts of acceleration lane designs, the following formula may be used:

$$V_{85RL} = 91.002 - 0.015Q_{RL} + 0.324\ V_{85Merge}$$

  where:
  V_{85RL} = 85th-percentile speed of vehicles in right through lane of freeway, km/h
  Q_{RL} = passenger cars per hour per lane in right through lane of freeway
  $V_{85Merge}$ = assumed 85th-percentile speed of ramp vehicles at merge point, km/h

- Prediction for merging speed for a given speed change lane length with given gore speeds may be estimated by using any of the formulas below:

$$V_{85Merge} = 42.662 + 0.463_{V85Gore} + 0.047L_{LIM}$$

$$V_{85Merge} = 68.193 + 56.053/\theta + 0.067L_{LIM} - 7.343\text{x}10^{-4}\ AADT_{SCL}$$

$$V_{85Merge} = 68.475 + 55.470/\theta + 0.067L_{LIM} - 0.011Q_{SCL}$$

  where:
  $V_{85Merge}$ = predicted 85th-percentile speed at merge point, km/h
  V_{85Gore} = assumed 85th-percentile speed at gore, km/h
  L_{LIM} = speed change lane lengths between 188 to 468 meters
  θ = angle of gore nose convergence, degrees
  $AADT_{SCL}$ = annual average daily traffic on speed change lane, pc/h/l
  Q_{SCL} = passenger car hourly volume on speed change lane, pc/h/l

Authors note that θ should provide a natural path that assists drivers in smooth transitions from ramp curve to acceleration lane and should not be attained by an abrupt change in curvature.

Safety Issues Concerning Large Trucks and Their Use of Acceleration Lanes
Glennon's study (13) of evaluating design criteria for trucks with 4 or more axles operating on level grades indicated that the crash involvement rate increases significantly when the truck speed reduction from the average running speed of traffic exceeds 10 mph. Chapter 3 of the 2004 Green Book uses this reduction speed to provide guidelines for safe vertical grades on roadway segments. If this logic is held consistent, the basis for measuring adequate speed attained for a large truck should be 10 mph below the running speed of through traffic.

A recent study conducted by the University of Michigan Transportation Research Institute (UMTRI) (14) looked at freeway interchange truck accidents and their relationship with geometric design. The research identified the controlling ramp curve immediately preceding parallel-type acceleration lanes as a key location providing only a narrow safety margin with respect to truck rollover potential since the controlling horizontal curve is typically designed for passenger cars. The controlling curve radius limitation in addition to the relatively short acceleration lane length provided for trucks were speculated as likely influencing the driving behavior of truckers. Researchers surmised that truck drivers likely maneuver through the controlling curve at as high a speed possible to decrease the lane length they will require to merge on to the through lane of traffic, sometimes resulting in a rollover-type crash.

Chapter 3
INITIAL CONFLICT STUDIES

Initial Behavior Studies

Videos were taken of acceleration lanes at both tapered- and parallel-type installations within and near Lincoln, NE to develop a frame of reference of typical driver behavior on the through lanes as well as the entry ramps of acceleration lanes in Nebraska. The locations were selected based upon the type of ramp style they represented and the ability to get a video camera viewing angle that allowed a full view of the ramp gore area, its full adjacent acceleration lane length to the through lanes and its end. Sites selected for review were the following locations:

- **Site 1: Parallel Type, US 77 and Van Dorn St Interchange, Northbound On Ramp**
- **Site 2: Tapered Type, I180 and Superior St Interchange, Southbound On Ramp**
- **Site 3: Parallel Type, I80 and US 77 (56th St) Interchange, Westbound On Ramp**

Video cameras on tripods were set on the crossroad overpass bridges and were focused to allow the view of the through lane approaches as well as the full acceleration lane length. FIGURES 9 through 12 show typical behavior encountered. NOTE: Camera views are foreshortened due to capturing the entirety of the ramp so merging drivers appear to be accepting very small gaps for merging into through traffic. Photos were clipped from digital video files and vary in clarity.

Photo 4:
Drivers P1 and Ps complete their merges into through traffic.

Photo 3:
Driver P1 merges leaving another acceptable gap behind for a following Driver P2 to merge into after also making a right-left-right turning movement.

Photo 2:
Driver P1 has a moderate length available gap and chooses to follow the ramp lane farther before merging making a right-left-right turning movement.

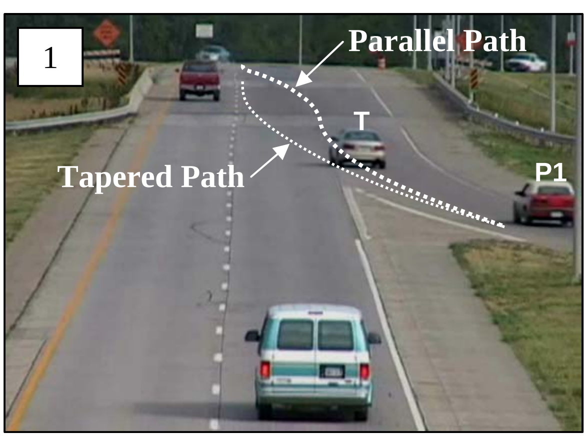


Photo 1:
Driver T has large available gap and chooses to make a direct, tapered path merge with a single right turn.

FIGURE 9 Site 1 Parallel Ramp Merging Traffic Sequence

Photo 3:
Once the large acceptable gap is available, the platoon sequentially merges into the right through lane.

Photo 2:
As the platoon continues in a tight queue, right lane through drivers merge to the left lane allowing a large acceptable gap.

Photo 1:
A platoon of merging vehicles is within the acceleration lane. Drivers in the right through lane apply their brakes to slow down.

FIGURE 10 Site 2: I180 and Superior St – Right Through Lane Traffic Courtesy Lane Change to Accommodate Platoon of Merging Traffic

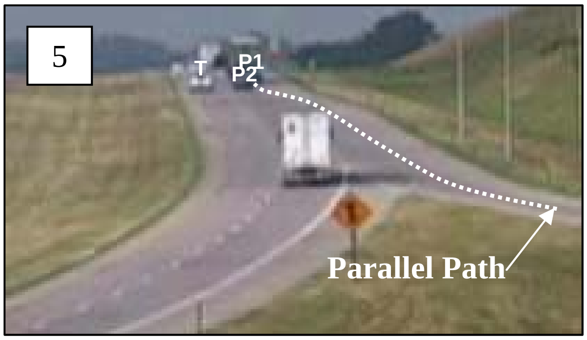


Photo 5:
Driver P1 finally merges in front of Driver P2 in a right-left-right turning path.

Photo 4:
Driver P1 is still searching for an acceptable gap.

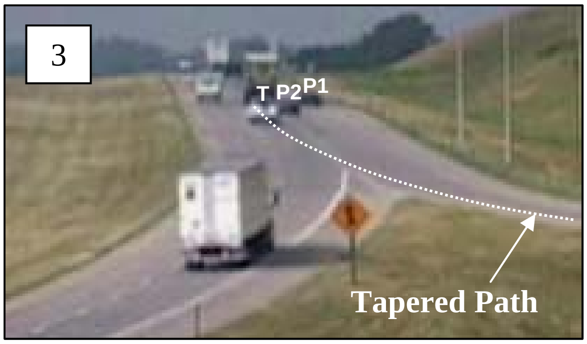


Photo 3:
Driver T successfully merges using a direct, tapered path. Driver P2 successfully merges using a right-left-right turning path.

Photo 2:
Drivers P1 and P2 remain adjacent to a truck and must wait to merge but Driver T has a large acceptable gap.

Photo 1:
Drivers P1 and P2 are adjacent to a truck and must wait to merge.

FIGURE 11 Site 3: Parallel Ramp Merging Traffic Sequence

FIGURE 12 Merging Driver Using Surfaced Shoulder When Necessary for Safe Merge

Review of the video from the three conflict study sites revealed a plethora of driver behaviors and varied situations in merging traffic areas. It appeared clear that a ramp driver near the gore area preferred a direct, tapered turning path into the through traffic lane if there was a large acceptable gap to enter. Faced with an unacceptable gap, drivers chose a path parallel to the through traffic, adjusted speed and eventually merged, choosing a right-left-right turning path. When faced with an unacceptable gap through the end of the acceleration lane, drivers continued on the surfaced shoulder until a through driver allowed entry.

Chapter 4
FULLY-LOADED HEAVY TRUCK STUDIES

Review of the Current Heavy Vehicle Fleet

Model software of engine performance was supplied to the research team by the leading heavy truck engine manufacturer, Detroit Diesel Corporation (DDC). The engine performance model called the Spec Manager was used to examine vehicle acceleration under loaded conditions. The examination simulated current vehicle performance characteristics on both level and inclined roadway surfaces. These current fleet characteristics were then used to calculate acceleration lengths that were needed if a heavy truck was used as a design vehicle which were then compared to the lengths defined by previous recent research projects summarized earlier.

Spec Manager Origins (15)

The origins of the route simulation portion of the Spec Manager program began in the 1960s. General Motors engineers at the Technical Center wrote a simple program called AL2 to simulate a truck driving a route. This was a batch program using IBM cards and was operated on an IBM 360 mainframe computer. During the 1970s and 1980s, the program was enhanced substantially by DDC engineers.

Spec Manager Program Logic (15)

The simulation was written in Fortran and based on physics and dynamics principles. Engineers had the fuel, horsepower and torque data for engines. Rolling resistance data for different types of tires and air resistance coefficients for different types of vehicles were obtained from independent testers. After entering the weight of the vehicle and the driveline gear ratios, acceleration and deceleration could be computed on various grades based on available torque and inertia (the inertia of the vehicle mass and the inertia of all the rotating parts like the flywheel, tires, etc). Logic was added to up-shift and down-shift when necessary. Every one mile per hour increase or decrease, the vehicle acceleration, fuel consumption, distance traveled and time traveled was calculated. Each grade on a route was entered into the program by IBM cards. Many “real world” tests were run to verify the accuracy of the program and new logic had to be added from time to time to better simulate what a typical driver would do. It was possible to include the affects of random traffic conditions on a real vehicle.

In the 1980s, separate programs were written to compute and create several of the reports seen in Spec Manager, including the shift schedule, acceleration and vehicle power requirement reports. These programs were written in Fortran and ran on a time sharing system. In the late 1980s and early 1990s, all of the programs were combined and rewritten with additional reports added. The new program was called Application, Design and Analysis Methods (ADAM). The new system was written for a PC using a DOS operating system. This new system was taken out of the engineering world and made very user friendly. It was then distributed to all Detroit Diesel Corporation regions and distributors to assist in specifying attributes of truck desired by customers. In the late 1990s, the program was rewritten again for a Windows operating system and renamed Spec Manager.

It was necessary to confirm the Spec Manager’s ability to accurately predict the acceleration characteristics of heavy vehicles in different situations. This was accomplished by setting up a test with heavy vehicles that were recreated in the Spec Manager program. Tests were completed using a GPS device that recorded speed and location of the vehicle. This information was then compared to the predicted information in similar situations in the DDC.

Field studies were conducted with the help of Werner Trucking to collect speed and acceleration data of tractor-trailer trucks with known loads on acceleration ramps with nearly level and relatively steep upgrade slopes. Truck characteristic information was input into the Spec Manager program as well as information on grades which was entered in the "Environment" dialog box as shown in the output of Spec Manager in Appendix A. The options available were the "Surface Type" and the "Terrain" which was in categories of:

- Nearly Flat (0% - 1.5%),
- Rolling (1.6% to 2.9%), and
- Mountainous (3% to 6%).

For a fully loaded truck (80,000 lbs) the Spec Manager output showed no difference in acceleration capability from a nearly flat to mountainous terrain type. Repeated requests for justification of the output were unanswered from sources at Detroit Diesel Corporation. This research study approach was abandoned due to lack of feedback from DDC. Appendix A includes the output from Spec Manager showing the discrepancies.

Detroit Diesel Corporation Spec Manager Acceleration Length

Although the field verification of Spec Manager could not be completed, the program was used to input the characteristics of what DDC considered to be a "typical" truck configuration based on their sales.

The following choices were made to develop an acceleration length table similar to that in the 2004 Green Book.

Engine Type: 430 HP DDC 12.7L

Transmission Type: Eaton 10 Speed

Gross Vehicle Weight: 80,000 (not typical but used to determine outcomes with maximum loading)

Pounds Per Horsepower: 80,000/430 = 186 lb/hp

Terrain Conditions: 0% - ±1.5%

TABLE 9 shows the results of the software output.

TABLE 9 DDC Spec Manager Length Based on 186 lb/hp Truck on 0 to ±1.5 % Grade

Highway Design Speed, mph	Speed Reached, mph	Controlling Ramp Curve Design Speed, mph								
		Stop	15	20	25	30	35	40	45	50
		Initial Speed, V′a, mph								
		0	14	18	22	26	30	36	40	44
30	**23**	126	84	51	-	-	-	-	-	-
35	**27**	179	136	103	53	-	-	-	-	-
40	**31**	308	265	232	182	129	-	-	-	-
45	**35**	403	360	327	277	224	95	-	-	-
50	**39**	649	606	573	523	470	341	183	-	-
55	**43**	807	764	731	681	628	499	341	84	-
60	**47**	1009	967	934	883	830	701	543	286	109
65	**50**	1300	1257	1224	1173	1121	992	833	576	399
70	**53**	1623	1580	1547	1496	1444	1315	1156	899	722
75	**55**	1792	1749	1716	1666	1613	1584	1326	1068	891

As shown in TABLE 10, the Spec Manager values were very close to the 2004 Green Book and to Fitzpatrick and Zimmerman's values, which represent passenger cars and light trucks. It appears that advancements in truck engine performance are closing the gap between acceleration abilities of cars, light trucks and tractor-trailer combinations. At this point in time, most of the large truck fleet represents older engine designs with less performance capability but this is evidence that the replacement vehicles will be better able to match passenger car speeds on freeways when accelerating. Both the NCHRP 505 and Gattis et al study are a result of data collected prior to 2003 and 2008 respectively.

TABLE 10 DDC Spec Manager Values Compared to Previous Research Values

	AASHTO Green Book, 2004	DDC Spec Manager	Fitzpatrick & Zimmerman, 2006	NCHRP 505	Gattis, et al 2008
Model Design Vehicle Type	Passenger Car on Zero to 2 Percent Grade		Passenger Car, Light Truck	180 lb/hp Tractor-Trailer Truck on Level Grade	Tractor-Trailer Truck on Level Grade
Assumed initial speed, mph	22	22	20	22	17
Speed Reached, mph	**Distance to Reach Speed, ft**				
39	550	523	-	850	-
40	-	-	908*	-	1203
50	1020	1173	1383*	2230	2119
55	1580	1666	1653*	3260	2731
60	-	-	1945*	-	3655

*Values shown are for a design speed of 10 mph above the "Speed Reached" value.

Chapter 5
TAPERED VS PARALLEL DESIGNS

Free-Flow Traffic Conditions

Conclusions from previous research as well as studies performed as part of this research project indicated that tapered style acceleration ramps operated best under free-flow or lightly congested traffic conditions. The following list summarizes findings.

- A 50:1 tapered design led to drivers using a greater portion of the ramp than a parallel design of the same length (findings in two studies).
- A tapered ramp with a small convergence angle led to a more effective process allowing an increase in the ability to determine acceptable gaps.
- Drivers indicated they would be more aggressive on tapered ramps than parallel ramps.
- Behavior studies in Nebraska indicated a tapered merging path on parallel ramps when available gaps in right-lane through traffic were readily available.

Tapered ramps are preferred on roadways designed for the higher end of the design speed range, greater than or equal to 65 mph.

Moderately to Heavy Traffic Conditions

If the location of the acceleration ramp is prone to moderate to heavy traffic conditions, either due to peak-hour traffic or the potential for frequent incidents, a preferred design would be that of the parallel type. In this condition, merging into a gap (either naturally occurring or provided as a courtesy from a right-lane through driver) is the overriding purpose of the ramp, rather than acceleration, since through speeds would be lower due to congestion and queuing. Under free-flow or light traffic conditions, it is very likely that a driver will choose a tapered driving path on the parallel lane to enter the right through traffic lane, using less than the length provided to accelerate. Parallel ramp styles should be considered on roadways with design speeds of 60 mph or less. As previous research shows, more of the ramp length is used to accelerate at low volumes than high volumes.

One of the cautions identified from previous research indicates that the controlling ramp curve immediately preceding parallel-type acceleration lanes commonly provides only a narrow safety margin with respect to truck rollover potential since the curve is typically designed for passenger cars. If the acceleration lane is designed too short, truckers tend to maneuver through the controlling curve at as high a speed possible for their merge which sometimes results in a rollover crash. Special attention should be given to this curve if a significant number of trucks use the ramp and the available acceleration lane is fairly short for large trucks.

Practical Length

Previous research indicated that there was a “practical” acceleration length of about 1300 ft over which additional length was seldom if ever used by drivers, even though drivers may not have achieved a speed near that of the through traffic. Given this fact, consideration should be given to paving a full-depth, 12 ft wide surfaced shoulder at least 300 ft beyond the end of the taper on both tapered or parallel installations to allow drivers of cars or trucks to exceed the painted end of the acceleration lane if needed to accomplish a merge into through traffic. This driving behavior was observed in the Nebraska studies and allowing for additional pavement strength and width beyond the end of the ramp would prevent roadside maintenance issues of failing shoulder pavement and gouged turf beyond the paved shoulder edge.

Chapter 6
EXAMPLE OF HOW TO USE THE GUIDELINES

Example of Analysis of Existing Acceleration Ramp Adequacy

Using an example of an existing acceleration ramp near Lincoln, NE, the preceding guidelines will be used to determine the adequacy/inadequacy of the ramp. This ramp is near a truck stop which is located to the south of the southwest quadrant of the interchange.

The basic geometry for the westbound on ramp at NW 48th and I80 on the west side of Lincoln has been in use for many years. The current style of the ramp is a parallel type installation with about 1000 ft from the point where the ramp starts at NW 48th Street for the northbound to westbound movement to the point of tangency (PT) of the controlling horizontal curve near the gore area. The controlling curve has a radius of about 700 ft and is designed for about a 50 mph design speed. The through roadway (I80) has a posted speed of 75 mph at the end of the acceleration ramp so the operating speed of I80 can be roughly estimated to be the posted speed of 75 mph.

Assume that I80 needs to be widened and there is an opportunity to also improve the geometry of the acceleration ramp, if necessary, in conjunction with the interstate construction project. What is the estimated acceleration capability of the current configuration?

According to the 2004 Green Book Exhibit 10-70, which is designed for passenger cars, the **minimum** speed a passenger car should reach at the end of the 12 ft wide acceleration lane is 55 mph. The running speed associated with the design speed (V) of 75 mph, is 61 mph, according to FIGURE 7. Subtracting 5 mph for a minimal merging speed for a passenger car would result in a Va speed of 56 mph. The 2004 Green Book Exhibit 10-70 will be used to determine if the acceleration lane has been designed according to the guidelines, assuming that the grade of the ramp is 2 percent or less. When a truck is used for a design vehicle, a 10-mph speed reduction is deducted from the running speed, resulting in a minimal merging speed of 50 mph.

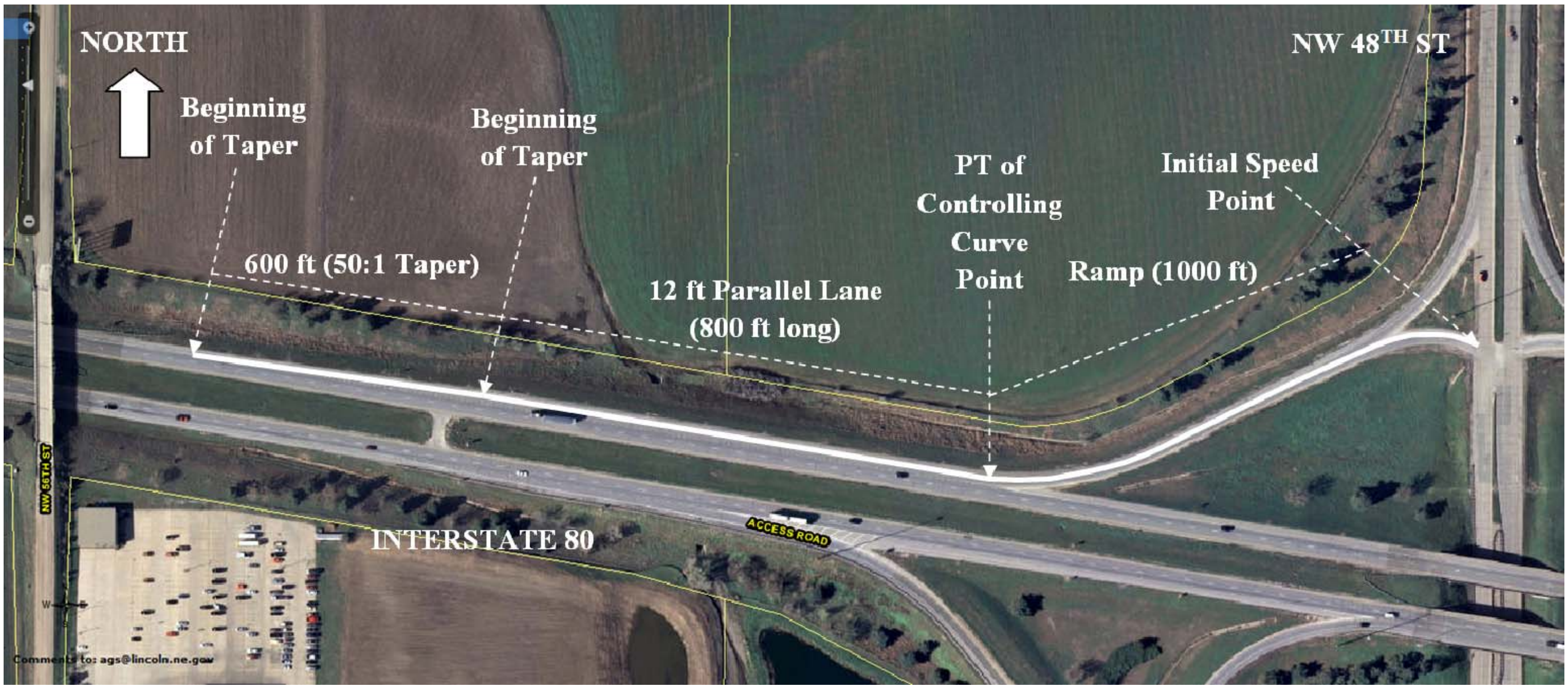


FIGURE 13 Aerial View of NW48th Street and I80 Westbound Acceleration Ramp

US Customary										
Acceleration length, L (ft) for entrance curve design speed (mph)										
Highway		Stop condition	15	20	25	30	35	40	45	50
Design speed, V (mph)	Speed reached, V_a (mph)	and initial speed, V_a' (mph)								
		0	14	18	22	26	30	36	40	44
30	23	180	140	—	—	—	—	—	—	—
35	27	280	220	160	—	—	—	—	—	—
40	31	360	300	270	210	120	—	—	—	—
45	35	560	490	440	380	280	160	—	—	—
50	39	720	660	610	550	450	350	130	—	—
55	43	960	900	810	780	670	550	320	150	—
60	47	1200	1140	1100	1020	910	800	550	420	180
65	50	1410	1350	1310	1220	1120	1000	770	600	370
70	53	1620	1560	1520	1420	1350	1230	1000	820	580
75	55	1790	1730	1630	1580	1510	1420	1160	1040	780

FIGURE 14 Determination of Acceleration Length for Example from Exhibit 10-70

Assuming the entry speed of a passenger car turning from northbound to westbound onto the ramp at a design speed of 15 mph, there is a distance of roughly 1000 ft to the end of the controlling horizontal curve near the gore area of with the through roadway which has a design speed of about 50 mph. The mean speed of a passenger car should increase from 14 mph at the ramp entrance to 44 mph at the end of the controlling curve. In 1000 ft of distance, a passenger car should reach a speed of about 45 mph (interpolated as 44.7 mph). The circled values in the table correspond to the estimates above.

From the location of the point of tangency of the controlling curve, there is about 800 ft of parallel lane length. The desired speed to attain at the point where the parallel lane is 12 wide is 55 mph according to the table (or 56 mph according to running speed calculations above). If a passenger car starts from the PT of the controlling curve at 44 mph and must get to Va speed of 55 mph (or 56 mph), it should take about 780 ft. The boxed values in the table correspond to this estimate. It appears that this acceleration ramp has been designed according to the Green Book guidelines.

TABLE 11 shows all the key features of this on ramp and resulting vehicle speeds.

TABLE 11 Analysis of Minimum Length Adequacy of Example On Ramp for Vehicle Acceleration Using Previously Mentioned Guidelines

Guide Used	Veh Type	Initl Curve Des Spd, mph	Initial Speed, V′a	Cont Curve Design Speed, mph	Cont Curve Initial Speed, V′a, mph	Dist from PT to 12' Pt, ft	Est Speed Reached, Va, mph	Des Speed to be Reached, Va, mph	Adequate Design?
2004GB	Car	15	14	50	45	800 (need 780)	55	5	Yes
DDC	186 lb/hp Truck	15	-	50	50	800 (891)	55	50	Yes
NCHRP 505	180 lb/hp Truck	15	14	50	39	800 (need 1220)	47	50	No
F & Z	Car/ Lt Truck	15	-	50	50	800 (need 746)	55	55	Yes
Gattis	Mean Truck	-	17	50	38	800 (need 1100)	47	50	No

From the analyses done above, it appears that using the NCHRP 505 or Gattis guidelines indicate that tractor-trailer trucks with heavy loads may not quite meet the **minimum** speed to be reached given by the 2004 Green Book guidelines. The example acceleration ramp meets **minimum** standards for the 2004 Green Book, DDC and Fitzpatrick & Zimmerman guidelines. The ramp doesn't meet the **desirable** 2004 Green Book guideline of being within 5 mph of the operating speed of I80 which would require that the design vehicle would need to reach a speed of 70 mph (assuming the posted speed approximates the operating speed of the through roadway).

Since the minimal speed for heavy trucks has not been met, would there be a benefit to lengthening the acceleration lane enough to attain an additional 3 mph of speed at the merge location? At least 3 years of accident history of the existing ramp should be reviewed to determine if there is evidence that the minimum length of the acceleration lane available resulted in safety impacts related to merging in the proximity of the parallel segment of the lane. If there is likelihood that the number of heavy trucks has a negative influence upon safety or if the volume of trucks is expected to increase, consideration should be given to lengthening the parallel portion of the lane.

Equations on page 21 may be used to estimate the operating speed of vehicles in the right-through-lane of the freeway and the operating speed of merging vehicles in free-flow traffic conditions if traffic volume estimates are available. Equations on pages 16 and 17 may be used to estimate the mean and 10th-percentile truck speed more precisely, if needed.

General Planning Guidelines

Consideration for acceleration ramps that accommodate large trucks should be made under the following conditions:

- Commercial vehicle weigh stations
- Freeway intersections near truck stops
- Freeway intersections near high industrial areas
- Speed limit of through facility is 60 mph or greater
- Undesirable to locate commercial vehicle weigh stations where an acceleration lane would be on an upgrade of more than +0.2% for 3000 ft or more.

Since the estimates of acceleration capability of the ramp used in the example doesn’t quite meet the minimum 50 mph for heavy trucks, a decision on extending the length of this ramp should be seriously considered. Special speed studies should be conducted at the existing location to get more information that would either verify keeping the existing length or provide more evidence that a lane extension is required.

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15 Bowen, W. Detroit Diesel Corporation, E-mail Correspondence, Sept 12, 2007

APPENDIX A

OUTPUT FROM DETROIT DIESEL CORPORATION'S SPEC MANAGER SOFTWARE PROGRAM

Summary Letter

DETROIT DIESEL

Spec Manager

University of Nebraska - Lincoln
W348 Nebraska Hall
Lincoln
Nebraska, 68588
402-472-1975

Prepared by: Devin Townsend
Master's Research Assistant

Dear ,

Subject: Computed Vehicle Performance(Spec Manager)

Predictions of the vehicle performance and fuel economy have been completed. These estimates have been calculated with the use of the computer vehicle simulator Spec Manager and are based on the specifications which you have provided and certain other assumptions about the vehicle, power train, and operating conditions. A summary of these results is shown below:

	RPM r/min	Speed mile/h	Engine Power hp	Acc. hp	Resistance Air hp	Resistance Roll. hp	Grade-ability %	Fuel Economy mile/gal
9	1200	39.2	354.2	7.0	24.4	45.5	3.1	9.06
9	1533	50.1[1]	447.0	11.6	50.8	63.9	2.7	7.11
9	1990	65.0[2]	438.2	19.6	111.0	93.1	1.4	5.19
9	2100	68.6	430.0	21.8	130.5	100.9	1.0	4.84
10	1200	53.0	354.2	7.0	60.1	69.2	1.7	7.32
10	1472	65.0[2]	437.1	10.6	111.0	93.1	1.4	5.88
10	1554	68.6[1]	448.3	11.9	130.5	100.9	1.2	5.51
10	1937	85.5	443.3	18.6	253.0	141.1	0.0	3.91
10	2100	92.7	430.0	21.8	322.1	160.0	-0.5	-

[1] Shift-in RPM
[2] Cruise Speed

VEHICLE CONFIGURATION

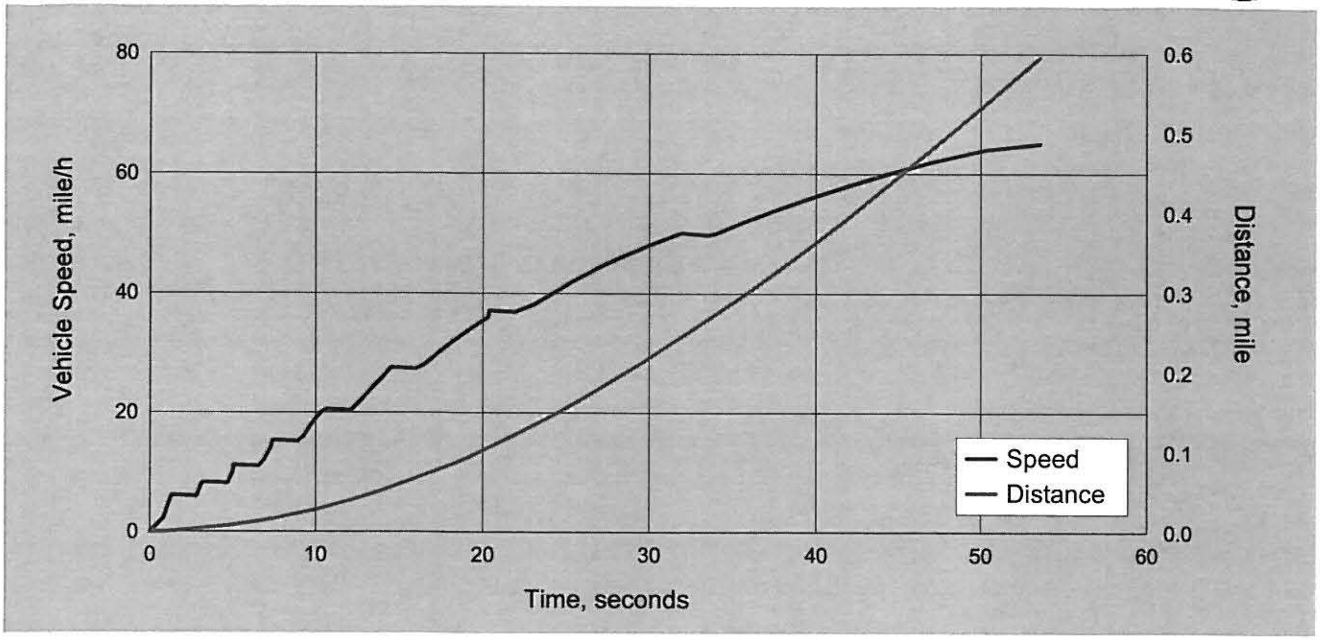
Application	Line Haul Tractor
Vehicle Type	Conv. Truck/Trailer
Description	Van
Vehicle Speed Limit	65.0 mile/h
Vehicle Cruise Speed	65.0 mile/h
Aerodynamics	Full package
Height	13.5 ft
Width	102.0 in
Number of Trailers	1
Side	Smooth
Top	Closed
Gap	30.0 in
Weight (GVW)	80000 lb
Total Number of Axles	5

DRIVE TRAIN

Engine Series	SERIES 60
Rated Power	455 hp @ 1800 r/min
Peak Torque	1550 lb-ft @ 1200 r/min
Droop	75 r/min
T800 Torque	870.0 lb-ft
Fan Type	On/Off (Clutch)
Air Conditioning	Yes
Transmission Manufacturer	Meritor
Transmission	MO-15F10A-S15
Shift Schedule	Standard
Drive Axle Manufacturer	Meritor
Drive Axle (Ratio)	Tandem (3.58)
Tire Type	Low Profile Radial
Tire Model	275/80 R22.5
Tire Size	513 revs/mile

DISCLAIMER: The vehicle performance and fuel economy data is an estimate for the specified vehicle and power train based on the simulation of vehicle and power train components for certain conditions. Since vehicle or power train performance variations and operation conditions can cause actual vehicle performance and fuel economy to vary, Detroit Diesel Corporation does not represent and hereby disclaims that, under all conditions, the actual vehicle will achieve the indicated performance or fuel economy. Thank you for giving us the opportunity to support your vehicle specifications requirements. If you have any questions, please contact me.

Devin Townsend



VEHICLE CONFIGURATION

Application	Line Haul Tractor
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Drive Axle (Ratio)	Tandem (3.58)
Tire Type	Low Profile Radial
Tire Model	275/80 R22.5
Tire Size	513 revs/mile

ENVIRONMENT

Surface Type	Smooth Concrete (1.0)
Terrain	Mountainous (3% - 6%)

ACCELERATION

Speed mile/h	Engine RPM r/min	Time s	Distance, ft	mile	Distance, mile/h/s
Forward 1, Ratio 11.190; Start					
2.3	800	0.8	1.4	0.000	2.80
4.0	1370	1.0	2.5	0.000	5.03
6.0	2055	1.3	4.5	0.001	3.97
6.1	2100	1.3	4.8	0.001	3.42
Forward 2, Ratio 8.290; Manual Shift					
6.0	1523	2.8	18.2	0.003	-0.09
8.0	2030	3.1	21.2	0.004	3.60
8.3	2100	3.2	22.3	0.004	3.17
Forward 3, Ratio 6.150; Manual Shift					
8.1	1532	4.7	40.3	0.008	-0.09
10.0	1882	5.0	44.5	0.008	3.35
11.2	2100	5.0	45.4	0.009	2.67
Forward 4, Ratio 4.480; Manual Shift					
11.0	1510	6.5	69.8	0.013	-0.10
12.0	1646	6.9	75.3	0.014	3.01
14.0	1920	7.3	83.1	0.016	2.54
15.3	2100	7.4	86.4	0.016	2.12
Forward 5, Ratio 3.340; Manual Shift					
15.2	1550	8.9	119.9	0.023	-0.10
16.0	1636	9.3	128.1	0.024	2.36
18.0	1840	9.7	140.3	0.027	2.10
20.0	2045	10.3	156.5	0.030	1.77
20.5	2100	10.6	166.1	0.031	1.67

Additional Notes:
Acceleration time for 0 - 10 = 0:00:05
Acceleration time for 0 - 20 = 0:00:10
Acceleration time for 0 - 30 = 0:00:17
Acceleration time for 0 - 40 = 0:00:24

Acceleration

DETROIT DIESEL
Spec Manager

VEHICLE CONFIGURATION

Application	Line Haul Tractor
Vehicle Type	Conv. Truck/Trailer
Description	Van
Vehicle Speed Limit	65.0 mile/h
Vehicle Cruise Speed	65.0 mile/h
Aerodynamics	Full package
Height	13.5 ft
Width	102.0 in
Number of Trailers	1
Side	Smooth
Top	Closed
Gap	30.0 in
Weight (GVW)	80000 lb
Total Number of Axles	5

DRIVE TRAIN

Engine Series	SERIES 60
Rated Power	455 hp @ 1800 r/min
Peak Torque	1550 lb-ft @ 1200 r/min
Droop	75 r/min
T800 Torque	870.0 lb-ft
Fan Type	On/Off (Clutch)
Air Conditioning	Yes
Transmission Manufacturer	Meritor
Transmission	MO-15F10A-S15
Shift Schedule	Standard
Drive Axle Manufacturer	Meritor
Drive Axle (Ratio)	Tandem (3.58)
Tire Type	Low Profile Radial
Tire Model	275/80 R22.5
Tire Size	513 revs/mile

ENVIRONMENT

Surface Type	Smooth Concrete (1.0)
Terrain	Mountainous (3% - 6%)

ACCELERATION

Speed mile/h	Engine RPM r/min	Time s	Distance, ft	mile	Distance, mile/h/s
Forward 6, Ratio 2.490; Manual Shift					
20.4	1552	12.1	211.1	0.040	-0.12
22.0	1677	12.7	229.5	0.043	1.72
24.0	1829	13.4	251.4	0.048	1.57
26.0	1982	14.1	278.6	0.053	1.38
27.6	2100	14.5	296.7	0.056	1.23
Forward 7, Ratio 1.850; Manual Shift					
27.3	1548	16.0	357.0	0.068	-0.14
28.0	1586	16.5	377.3	0.071	1.32
30.0	1699	17.4	412.9	0.078	1.22
32.0	1812	18.2	453.6	0.086	1.13
34.0	1925	19.2	501.6	0.095	1.02
36.0	2039	20.3	558.4	0.106	0.92
37.1	2100	20.4	563.9	0.107	0.84
Forward 8, Ratio 1.370; Manual Shift					
36.8	1544	21.9	645.2	0.122	-0.18
38.0	1594	23.0	705.7	0.134	0.91
40.0	1677	24.2	774.4	0.147	0.84
42.0	1761	25.5	851.3	0.161	0.79
44.0	1845	26.8	938.0	0.178	0.74
46.0	1929	28.3	1038.0	0.197	0.67
48.0	2013	30.0	1154.0	0.219	0.60
50.0	2097	31.8	1287.8	0.244	0.54
50.1	2100	32.0	1298.6	0.246	0.53
Forward 9, Ratio 1.000; Manual Shift					
49.7	1522	33.5	1408.4	0.267	-0.24
50.0	1530	33.9	1443.0	0.273	0.59
52.0	1592	35.7	1577.6	0.299	0.56
54.0	1653	37.7	1728.9	0.327	0.52
56.0	1714	39.7	1897.7	0.359	0.48
58.0	1775	42.0	2085.5	0.395	0.45
60.0	1837	44.4	2297.7	0.435	0.41
62.0	1898	47.1	2543.1	0.482	0.37
64.0	1959	50.2	2831.7	0.536	0.32
65.0	1990	53.5	3145.7	0.596	0.30

Additional Notes:
Acceleration time for 0 - 10 = 0:00:05
Acceleration time for 0 - 20 = 0:00:10
Acceleration time for 0 - 30 = 0:00:17
Acceleration time for 0 - 40 = 0:00:24

Advisory Notes

A list of advisory notes, concerning the performance and/or fuel economy of the vehicle, would normally follow. However, the current vehicle configuration has not resulted in any such notes being generated.

Summary Letter

DETROIT DIESEL
Spec Manager

University of Nebraska - Lincoln
W348 Nebraska Hall
Lincoln
Nebraska, 68588
402-472-1975

Prepared by: Devin Townsend
Master's Research Assistant

Dear ,

Subject: Computed Vehicle Performance(Spec Manager)

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	RPM	Speed	Engine Power	Acc.	Resistance Air	Resistance Roll.	Grade-ability	Fuel Economy
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[1] Shift-in RPM
[2] Cruise Speed

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Fan Type	On/Off (Clutch)
Air Conditioning	Yes
Transmission Manufacturer	Meritor
Transmission	MO-15F10A-S15
Shift Schedule	Standard
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Drive Axle (Ratio)	Tandem (3.58)
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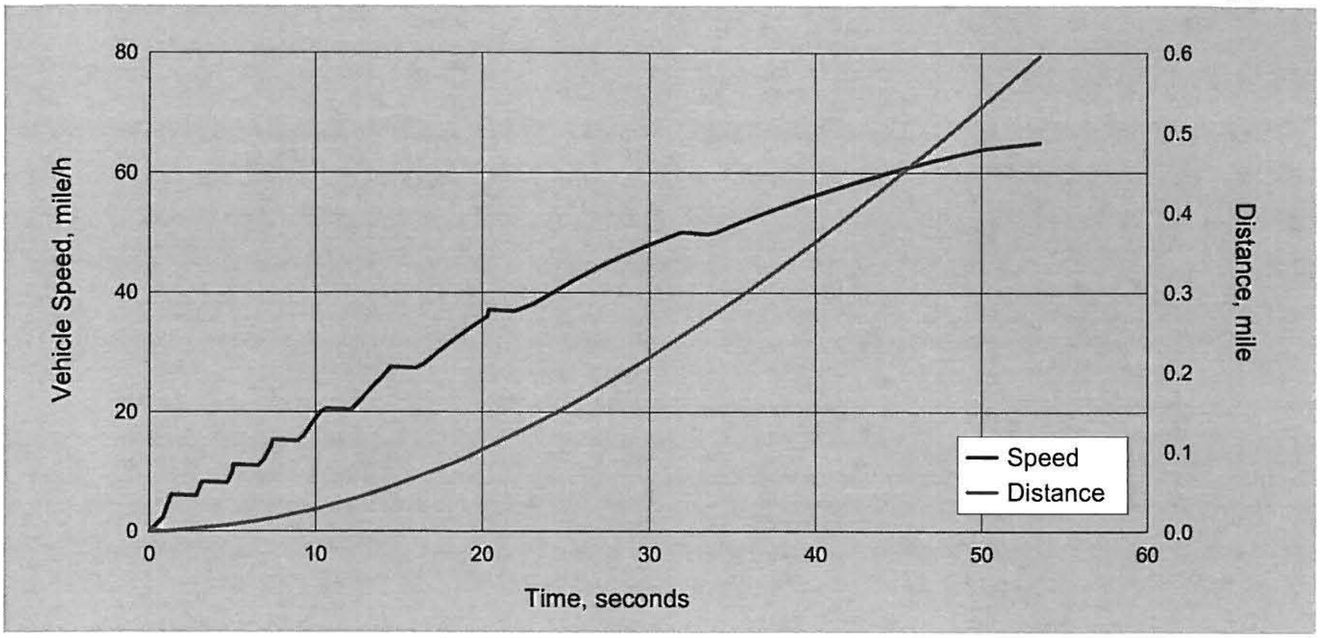
Devin Townsend



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Tire Type	Low Profile Radial
Tire Model	275/80 R22.5
Tire Size	513 revs/mile

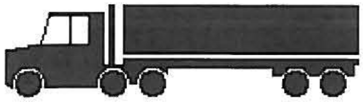
ENVIRONMENT

Surface Type	Smooth Concrete (1.0)
Terrain	Nearly Flat (0% - 1.5%)

ACCELERATION

Speed mile/h	Engine RPM r/min	Time s	Distance, ft	mile	Distance, mile/h/s
Forward 1, Ratio 11.190; Start					
2.3	800	0.8	1.4	0.000	2.80
4.0	1370	1.0	2.5	0.000	5.03
6.0	2055	1.3	4.5	0.001	3.97
6.1	2100	1.3	4.8	0.001	3.42
Forward 2, Ratio 8.290; Manual Shift					
6.0	1523	2.8	18.2	0.003	-0.09
8.0	2030	3.1	21.2	0.004	3.60
8.3	2100	3.2	22.3	0.004	3.17
Forward 3, Ratio 6.150; Manual Shift					
8.1	1532	4.7	40.3	0.008	-0.09
10.0	1882	5.0	44.5	0.008	3.35
11.2	2100	5.0	45.4	0.009	2.67
Forward 4, Ratio 4.480; Manual Shift					
11.0	1510	6.5	69.8	0.013	-0.10
12.0	1646	6.9	75.3	0.014	3.01
14.0	1920	7.3	83.1	0.016	2.54
15.3	2100	7.4	86.4	0.016	2.12
Forward 5, Ratio 3.340; Manual Shift					
15.2	1550	8.9	119.9	0.023	-0.10
16.0	1636	9.3	128.1	0.024	2.36
18.0	1840	9.7	140.3	0.027	2.10
20.0	2045	10.3	156.5	0.030	1.77
20.5	2100	10.6	166.1	0.031	1.67

Additional Notes:
- Acceleration time for 0 - 10 = 0:00:05
- Acceleration time for 0 - 20 = 0:00:10
- Acceleration time for 0 - 30 = 0:00:17
- Acceleration time for 0 - 40 = 0:00:24



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Top	Closed
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ENVIRONMENT

Surface Type	Smooth Concrete (1.0)
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ACCELERATION

Speed mile/h	Engine RPM r/min	Time s	Distance, ft	mile	Distance, mile/h/s
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24.0	1829	13.4	251.4	0.048	1.57
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30.0	1699	17.4	412.9	0.078	1.22
32.0	1812	18.2	453.6	0.086	1.13
34.0	1925	19.2	501.6	0.095	1.02
36.0	2039	20.3	558.4	0.106	0.92
37.1	2100	20.4	563.9	0.107	0.84
Forward 8, Ratio 1.370; Manual Shift					
36.8	1544	21.9	645.2	0.122	-0.18
38.0	1594	23.0	705.7	0.134	0.91
40.0	1677	24.2	774.4	0.147	0.84
42.0	1761	25.5	851.3	0.161	0.79
44.0	1845	26.8	938.0	0.178	0.74
46.0	1929	28.3	1038.0	0.197	0.67
48.0	2013	30.0	1154.0	0.219	0.60
50.0	2097	31.8	1287.8	0.244	0.54
50.1	2100	32.0	1298.6	0.246	0.53
Forward 9, Ratio 1.000; Manual Shift					
49.7	1522	33.5	1408.4	0.267	-0.24
50.0	1530	33.9	1443.0	0.273	0.59
52.0	1592	35.7	1577.6	0.299	0.56
54.0	1653	37.7	1728.9	0.327	0.52
56.0	1714	39.7	1897.7	0.359	0.48
58.0	1775	42.0	2085.5	0.395	0.45
60.0	1837	44.4	2297.7	0.435	0.41
62.0	1898	47.1	2543.1	0.482	0.37
64.0	1959	50.2	2831.7	0.536	0.32
65.0	1990	53.5	3145.7	0.596	0.30

Additional Notes:
Acceleration time for 0 - 10 = 0:00:05
Acceleration time for 0 - 20 = 0:00:10
Acceleration time for 0 - 30 = 0:00:17
Acceleration time for 0 - 40 = 0:00:24

A list of advisory notes, concerning the performance and/or fuel economy of the vehicle, would normally follow. However, the current vehicle configuration has not resulted in any such notes being generated.