Effect of Large Trucks on Traffic Safety and Operations

FINAL REPORT

MDOT Contract No. 91-0578

The University of Michigan Transportation Research Institute

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UMTRI The University of Michigan Transportation Research Institute

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTRI-93-19		

4. Title and Subtitle
Effect of Large Trucks on Traffic Safety and Operations

5. Report Date
June 1993

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
UMTRI-93-19

9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
2901 Baxter Road, Ann Arbor, Michigan 48109

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Michigan Department of Transportation
Transportation Building
425 West Ottawa
Lansing, MI 48909

Great Lake Center for
Truck and Transit Research
201 UMTRI Building
2901 Baxter Road
Ann Arbor, MI 48109

13. Type of Report and Period Covered
Final
11/91 — 3/93

14. Sponsoring Agency Code

15. Supplementary Notes
Supported by the Michigan Department of Transportation and the U.S. Department of Transportation, University Transportation Centers Program through the Great Lake Center for Truck and Transit Research.

16. Abstract

This report presents results, findings, and recommendations concerning the operation of longer combination vehicles (LCVs) in Michigan. Various truck combinations were simulated to operate on roadways and highways that are typical of those in Michigan. Several performance modes (operating situations) were used to evaluate each truck configuration and to analyze the simulation results.

Policy decisions are called for in those cases where drawing the border line between acceptable and unacceptable performance levels involves more than considerations of vehicle mechanics and dynamics. Specifically, policy decisions are needed to choose between increased no-pass striping, restricted access of various truck configurations, and acceptable reduced levels of traffic flow on free-access roads.

Results are presented, and conclusions are drawn regarding combinations that might be accommodated on the current roadway, combinations that require minimal changes to the infrastructure ("optimal" combinations), and the required changes in roadways to accommodate other combinations. Costs and benefits are also addressed.

17. Key Words	18. Distribution Statement
longer combination vehicles (LCVs), offtracking, acceleration, passing sight distance, intersection, ramp, U-turn	no restrictions

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None	184	

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EXECUTIVE SUMMARY

This report summarizes the work done in the study entitled "Effect of Large Trucks on Traffic Safety and Operations." Various longer combination vehicles (LCV) were simulated to operate on roadways and highways that are typical of those in Michigan. Several performance modes (operating situations) were used to evaluate each truck configuration and to analyze the simulation results.

Four distinct tasks defined the structure of this study: (1) literature review, where the state of knowledge on safety and operations of LCVs was reviewed, and performance modes and candidate truck combinations were identified; (2) survey of highway geometrics, where features typical of Michigan highways that might impact on the operation of LCVs were identified; (3) simulation, where truck simulation programs from the UMTRI library and others that were specially devised were used to evaluate the performance level of each of the candidate truck combinations in each of the performance modes identified; (4) analysis of simulation results, where the results from task 3 and results obtained from other pertinent studies were analyzed along several lines:

- Ranking the various configurations for the current highway geometry
- Comparing the various configurations with trucks currently allowed in Michigan
- Discussing the potential impact on safety and traffic operations
- Identifying the necessary highway modifications to accommodate each truck combination
- Generating templates of low speed offtracking
- Making recommendations regarding changes in highway geometry

Costs, benefits, and variations in truck size were considered. Costs are implicitly represented by the amount of highway change needed to accommodate a particular combination, and the benefits are represented by the increase in payload volume or weight associated with LCVs.

It appears from the results that Michigan's freeways and limited-access highways can accommodate all the truck combinations that were studied. However, a lot of interchange ramps and crossroads cannot. Some terminal ramps, might require added pavement due to offtracking.

Under urban traffic conditions, and also on free-access (rural) highways, it seems that the Turner truck (see figure 4) is the optimum size truck that will not necessitate any

roadway changes. Allowing other combinations (turnpike double, Rocky Mountain double, triple, and semitrailers that are longer than 48 ft) will require changes in the infrastructure as listed in the report.

However, for limited-access, rural, and urban traffic conditions, policy decisions are called for in those cases where drawing the border line between acceptable and unacceptable performance levels involves more than considerations of vehicle mechanics and dynamics. Specifically, policy decisions are needed to choose between increased no-pass striping, restricted access of various truck configurations, and acceptable reduced levels of traffic flow on free-access roads.

1.0 INTRODUCTION

This study is aimed at assessing the compatibility (or lack thereof) of longer combination vehicles (LCVs) with the roadways of the state of Michigan. Conclusions are drawn as to the extent of roadway modification required, and recommendations are suggested.

Longer combination vehicle is a rather broad term that encompasses a large variety of non standard heavy trucks. Based on an extensive literature review (see appendix A), several truck combinations were identified as a representative baseline set of LCVs. Dimensions, weights, and typical drivetrain properties were set, so that appropriate calculations could be performed. Task 2 of the work program entailed a survey of highway geometrics (see appendix B). In the course of this part of the work, we identified highway sites and features that are typical of Michigan roadways and might have an impact on the ability of LCVs to operate there. In task 3 which followed, the various truck combinations were simulated to operate under the different roadway conditions, corresponding to the highway features identified in task 2. The simulation results are provided in appendix C. Several performance modes (operating situations) were used to evaluate each configuration and to analyze the simulation results. These performance modes were defined in the work program, and they are listed in table 1 in conjunction with the various truck combinations and the highway sites or the MDOT design guides used in evaluating performance. See appendices A and B for further information regarding the performance modes and the truck designs used.

In addition to performance modes calculated in this work, results of pertinent studies from the literature were considered in evaluating vehicle performance in obstacle avoidance maneuvers. In a study conducted by UMTRI [23], listed in appendix A, general conclusions were developed concerning the rearward amplification stability of heavy trucks during an obstacle avoidance maneuver. These conclusions were of such a nature that the results of that study could be directly imported into this study, and could be applied to evaluate safety implications that the operation of LCVs might have on Michigan roadways.

Table 1. Performance modes, sites and MDOT standard design guides, and truck configurations

Site number or Standard design (see appendix B)	Benchmark Truck Designs							
	LCVs						Reference Trucks	
	53' Tractor Semitrailer	57' Tractor Semitrailer	Rocky Mountain Double	Turnpike Double	Triple	Turner Truck	48' Tractor Semitrailer	Western Double
2		Upgrade speed		Upgrade speed		Upgrade speed	Upgrade speed	Upgrade speed
3	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking	L.S. Offtracking
4	L.S. Offtracking	Accel. from 0	L.S. Offtracking Accel. from 0	L.S. Offtracking Accel. from 0	Accel. from 0	L.S. Offtracking Accel. from 0	L.S. Offtracking Accel. from 0	L.S. Offtracking Accel. from 0
6, 8	L.S. Offtracking	Accel. from speed Accel. from 0 Upgrade speed	L.S. Offtracking	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed	Accel. from speed Accel. from 0	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed
7	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking	L.S. Offtracking
9		Accel. from speed Accel. from 0		Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0
10		Accel. from speed Accel. from 0		Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0
Urban & Rural Interchanges:								
	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking	L.S. Offtracking
Urban & Rural Ramps:								
		Accel. from speed		Accel. from speed	Accel. from speed	Accel. from speed	Accel. from speed	Accel. from speed
VII-710A:								
		Passing sight	Passing sight	Passing sight	Passing sight	Passing sight	Passing sight	Passing sight
VII-670B:								
		U-Turn	U-Turn	U-Turn	U-Turn	U-Turn	U-Turn	U-Turn

According to the general requirements of this study, the simulation results were analyzed with the following items in mind (as they applied to each configuration and performance mode):

1. Ranking the various configurations for the current highway geometry (based on performance levels)
2. Comparing the various configurations with trucks currently allowed in Michigan
3. For various highway situations — discussing the potential impact on safety and traffic operations
3. For each truck combination — identifying the necessary highway modifications to accommodate them
4. Generating templates of low speed offtracking
5. Conducting general cost benefit analysis
6. Determining maximum size of each truck combination
7. Making recommendations regarding changes in highway geometry

Costs, benefits, and variations in truck size are addressed in this report. Costs are implicitly represented by the amount of highway change needed to accommodate a particular combination, and the benefits are represented by the increase in payload volume or weight associated with LCVs.

2.0 BENCHMARK TRUCKS AND LCVs

Based on a review of technical and statistical information concerning the variety of heavy-duty trucks used in the United States, certain combinations were identified and categorized as distinct types (see appendix A). These configurations were used in this study as the benchmark set of trucks and LCVs to assess the potential impact of these vehicles on traffic safety and operations in the state of Michigan. Odd configurations were not considered. The various truck combinations evaluated in this study are presented in figures 1 through 7.

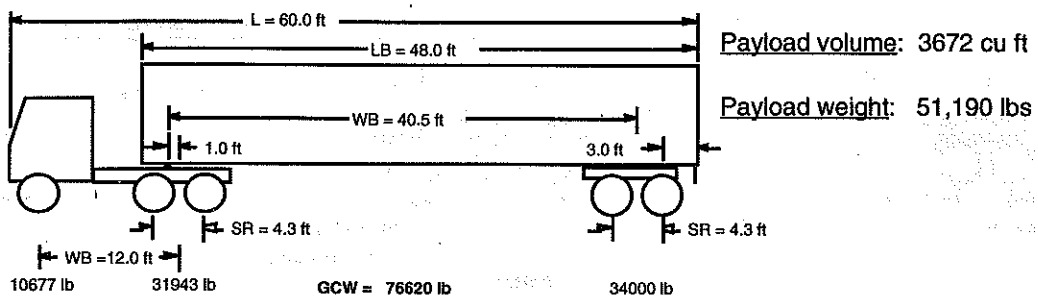


Figure 1. STAA Tractor semitrailer (48 ft)

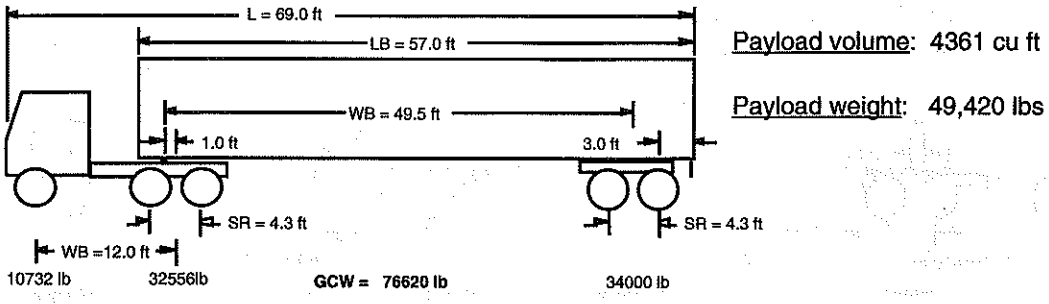


Figure 2. 57 ft Tractor semitrailer

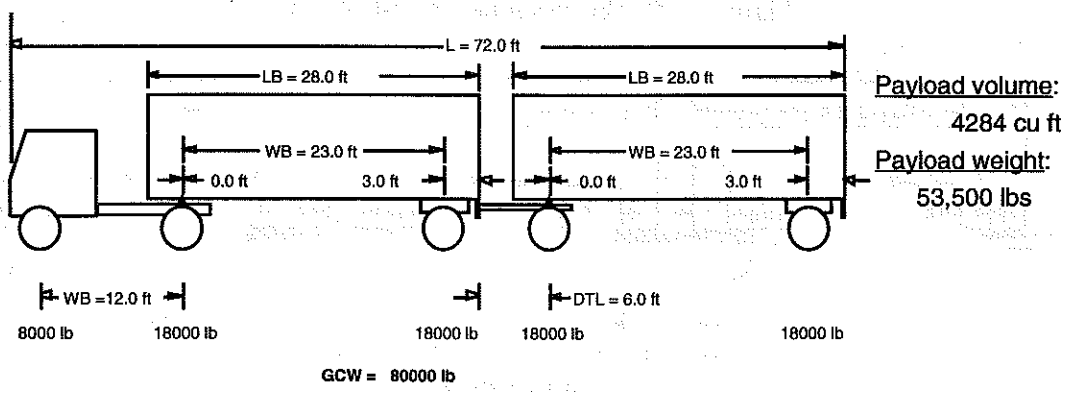


Figure 3. STAA (western) double

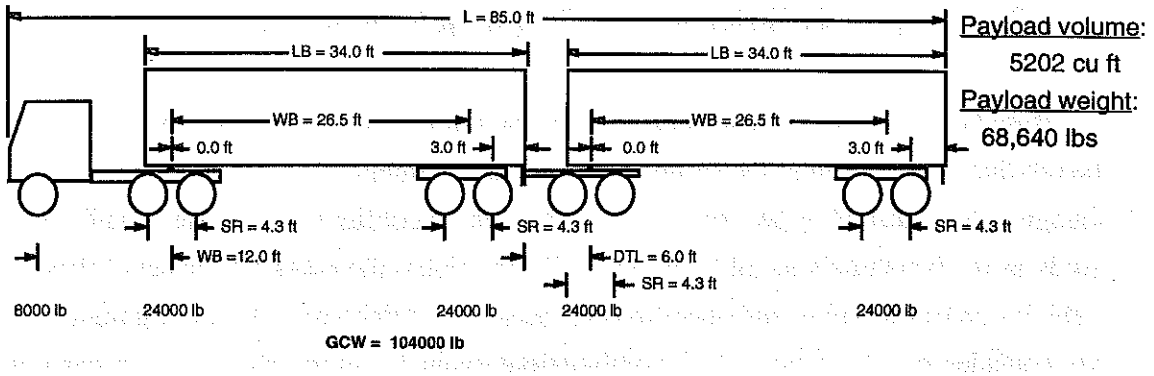


Figure 4. Turner truck (LCV)

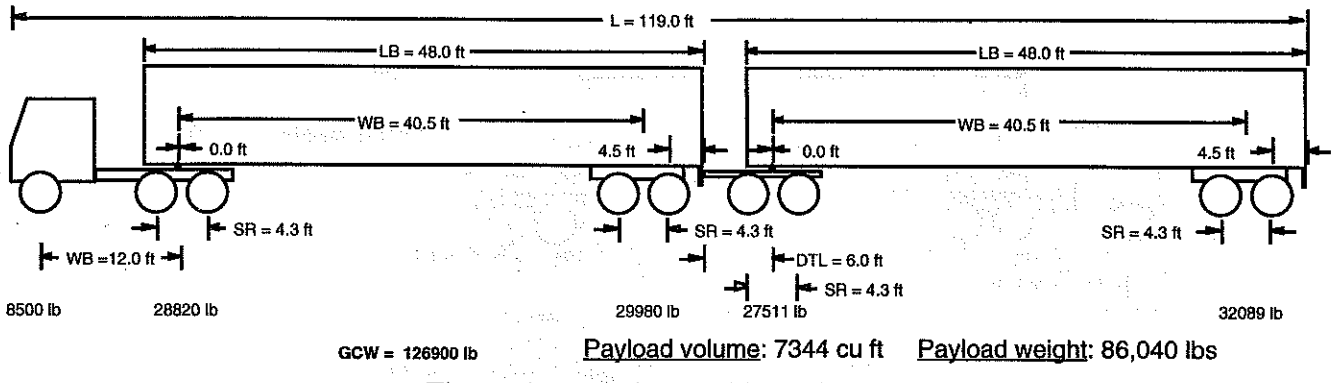


Figure 5. Turnpike double (LCV)

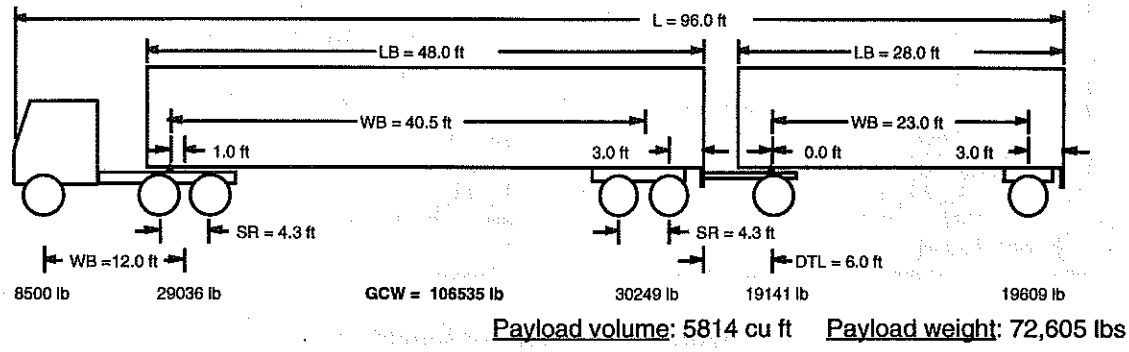


Figure 6. Rocky Mountain double (LCV)

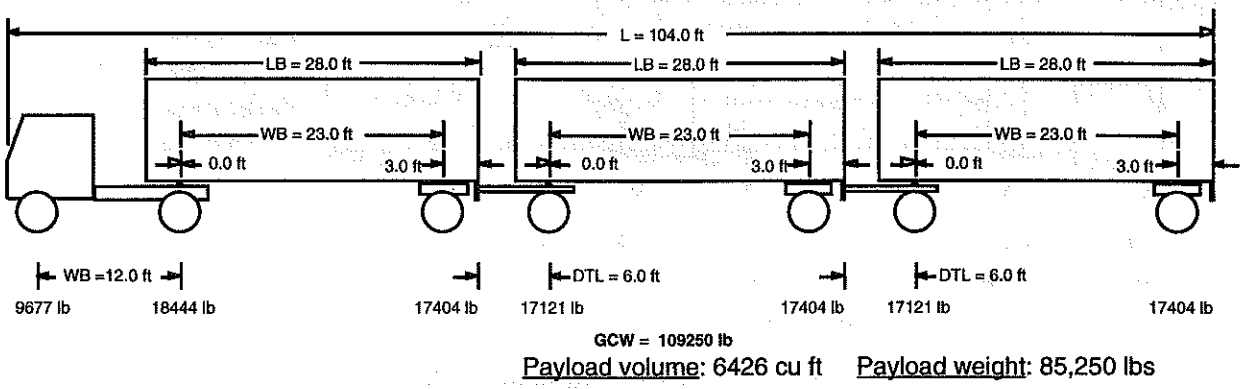


Figure 7. Triple (LCV)

Some of the performance modes addressed in this study were associated with acceleration. Powertrain components therefore, had to be carefully selected. Engine sizes used in the simulations were based on statistical data from TIUS (Truck Inventory and Use Survey) 1987 TC-87-T-52 ([10], listed in appendix A). Commonly installed engines in various combinations are as listed in table 2. Numbers in the table are multiples of 1000.

Table 2. Statistical data regarding engine sizes in heavy trucks

Truck Combination	**Number of trucks**		**Diesel Engine Size (hp)**		
	Total included	*With a diesel engine*	*<250 hp*	*250 - 350*	*350 - 450*
Tractor-Semitrailer:					
4 axles	230.4	201.5	59.1	77.5	38.9
5 axles	706.0	693.4	65.9	286.7	276.3
Double:					
5 axles	26.7	26.7	4.3	14.2	6.7
6 axles	5.0	5.0	—	1.9	2.3
7 axles	2.7	2.7	—	0.4	1.8
Triple:					
7 axles	0.4	0.4	—	—	0.3
8 axles	0.1	0.1	—	—	—

Values selected to be used were 330 hp @ 2100 rpm for the tractor-semitrailer, Turner, and western double combinations; 350 hp @ 2100 rpm for the triple combination; 400 hp @ 2100 rpm for the Rocky Mountain double; 425 hp @ 2100 rpm for the turnpike double.

The transmissions used in the acceleration models for this study were nine-speed gearboxes, of the type similar to series RTO "Roadranger" of Eaton®, ratio set B. Rear axle ratio was typically 4.11, and the tires used were 11.00 x 22.5 radial (rolling radius of 1.67 ft). All the trucks were of 100 ft^2 frontal area, and an aerodynamic drag coefficient of 0.9.

3.0 ANALYSIS OF PERFORMANCE LEVELS

This section analyzes the simulation results that were obtained in task 3. Graphs of the simulation results are provided in Appendix C. A total of six performance modes were addressed:

- Low-speed offtracking in intersections and on ramps
- Acceleration from a standing start and sight distance across an intersection
- Acceleration from a non-zero initial velocity to a final velocity on an entrance ramp
- Passing-sight distance for being passed and passing on two-lane roads
- Speed maintenance on upgrades
- Median opening and U-turns

An additional performance mode — rearward amplification — was addressed based on the results of a recent study conducted by UMTRI [23].

Each performance mode was evaluated under the relevant roadway conditions as depicted by (1) drawings of actual sites selected by MDOT, and (2) generic roadway features from the standard design guides. The results of the calculations are discussed, and principal observations are made.

3.1 Offtracking

Low-speed offtracking calculations were performed for the pertinent roadway elements portrayed in the site drawings and the standard design guides. Four typical scenarios were simulated: (1) urban traffic, (2) U-turns, (3) access ramps, and (4) typical intersections between urban traffic and access ramps (terminal ramp intersections). The U-turns scenario might be considered as a special case of urban traffic. Nevertheless, it was evaluated separately because of its unique application in Michigan and the interest of MDOT in that maneuver.

3.1.1 Urban traffic

The turning radius used in these calculations was the minimum possible by the baseline tractor (40 ft), and it is assumed that the driver is competent enough to "idealize" the turn. That is, in assessing offtracking the swept path of the turning truck combination is positioned to minimize encroaching onto oncoming lanes or over the curb.

Four urban intersections were used as representative sites for the urban traffic offtracking calculations:

- Michigan Avenue and Mills Street in Saline — A 90 deg intersection (see figure 8).
- Michigan Avenue and Monroe Street in Saline — A 76 deg intersection (see figure 9).
- Michigan Avenue and Fosdick Road in Pittsfield Twshp. — A 58 deg intersection (see figure 10).
- Michigan Avenue and Austin Road in Saline — A 30 deg intersection (see figure 11).

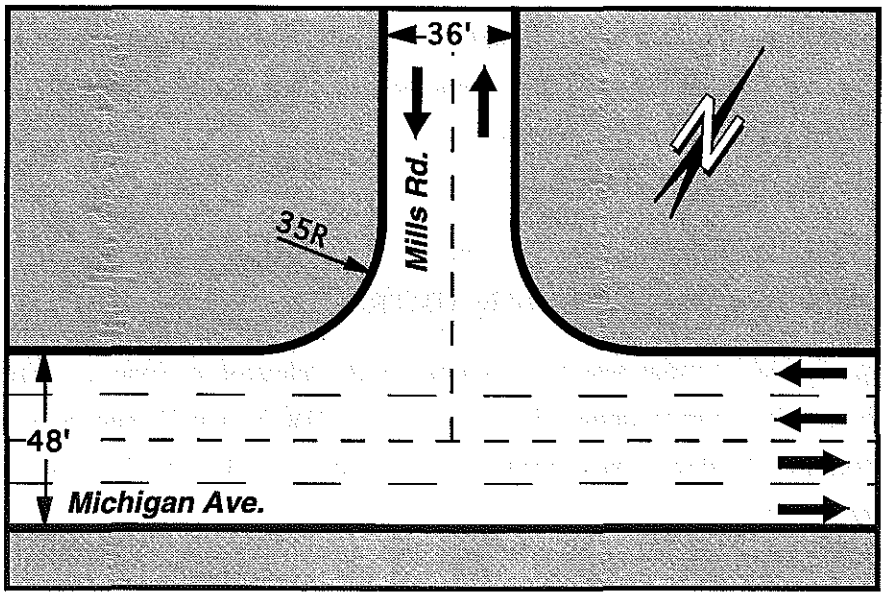


Figure 8. Michigan Avenue and Mills Street in Saline

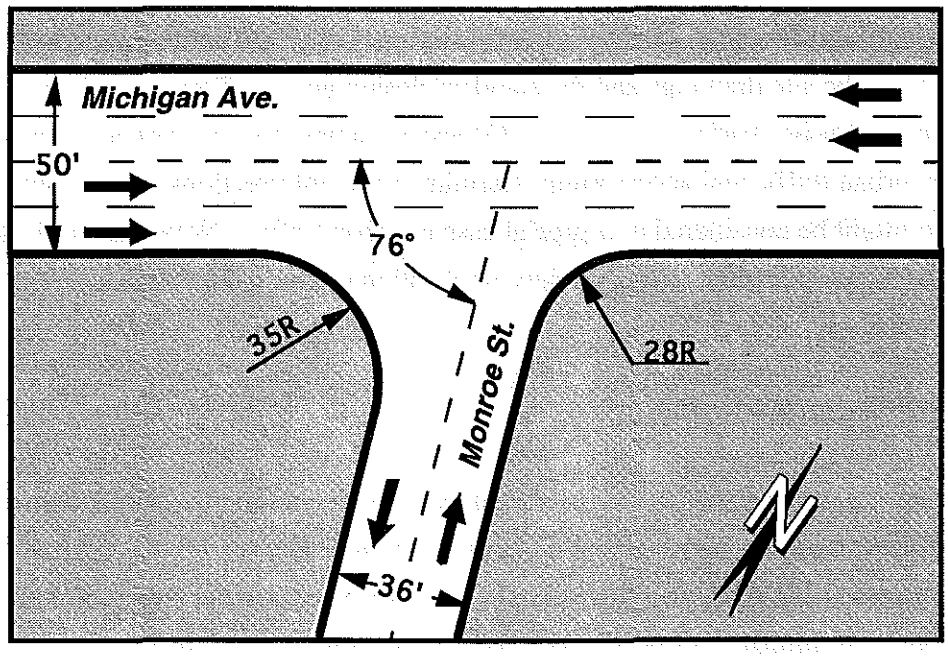


Figure 9. Michigan Avenue and Monroe Street in Saline

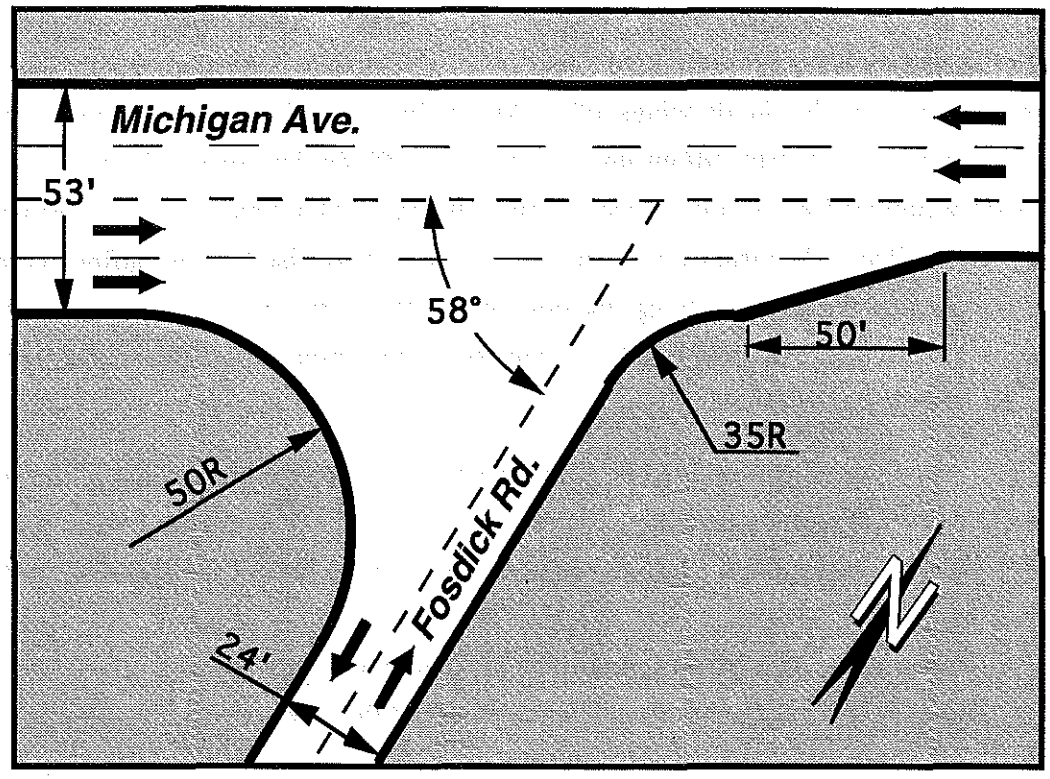


Figure 10. Michigan Avenue and Fosdick Road in Pittsfield Twshp.

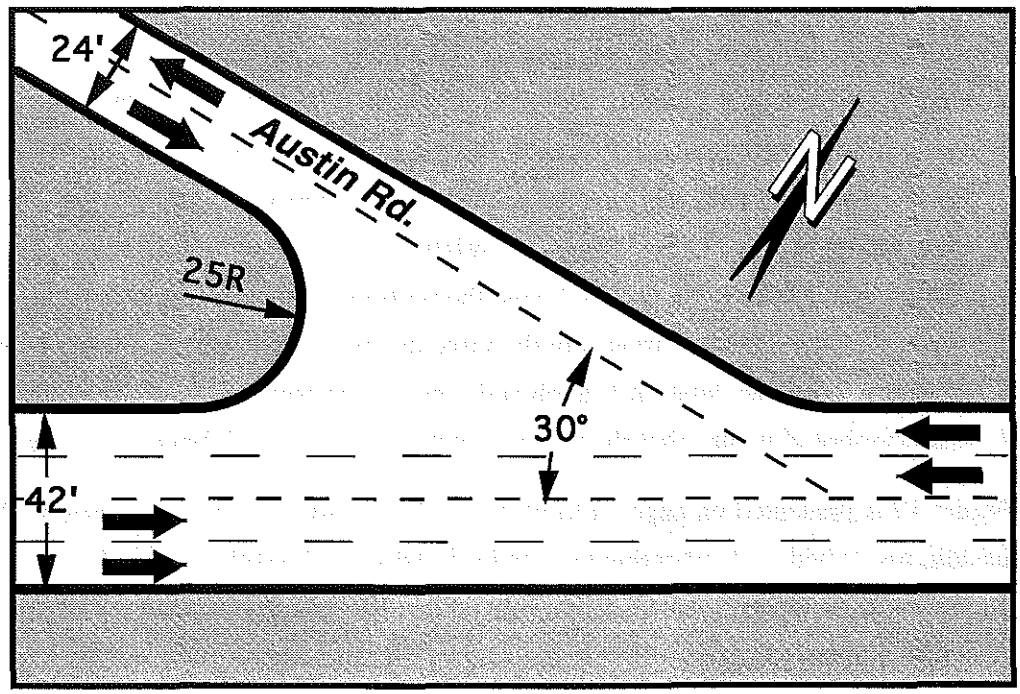


Figure 11. Michigan Avenue and Austin Road in Saline

Offtracking calculations of the various combinations were performed for the sites depicted above. Sets of turning templates (swept paths) were generated, and by overlaying these templates on the site drawings, offtracking values could be then determined. Due to the variety of truck configurations involved and the different intersection layouts, the number of options for positioning each swept path over each intersection was practically infinite. In effect, when truck drivers make the turn — they also have an infinite number of ways to perform the turn involving: the point where they start steering, rate of steering input, etc. Therefore, in order to allow a consistent evaluation of the offtracking, some ground rules had to be set.

The following rules were used as guidelines to determine the positioning of the swept paths over the intersection layouts:

- At the completion of a turn, no encroachment onto a lane of the opposing traffic is allowed.
- When making a right turn, it must be initiated in the right lane.
- If needed, the truck can use the whole width of the lanes of travel in the same direction at the completion of the turn, even if it's more than one lane.
- Steering input of a constant turning radius was assumed.

Results of the offtracking calculations are summarized in tables 3 through 6 (one table per site). The convention used in presenting the tabulated results is as follows:

- The symbols 1 ➨ 2 or 2 ➨ 1 represent the direction of the turn. These sites involve turns between a road with two lanes for each driving direction (four-lane road) and a road with one lane for each driving direction (two-lane road). This convention represents the "from - to" relationship.
- Percentage values in the tables denote the portion of the adjacent lane (if there's more than one lane that travels in the same direction) used by the turning truck in addition to its own lane. It is applicable only at the completion of the maneuver.
- The symbol ✓ means that the turning truck did not offtrack beyond the curb.

Figure 12 is presented on page 14 to illustrate the meaning of the terms used in this discussion, and to aid in interpreting the entries in tables 3 through 6. This figure is an overlay example of the turnpike double swept path at Monroe Street, with the pertinent details being pointed to.

Table 3. Right turn offtracking results at Michigan Avenue and Mills Street in Saline (90°)

Truck combination	**1 ➡ 2**		**2 ➡ 1**
	End	*Curb offtrack*	*Curb offtrack*
Western double	100%	✓	3.9'
Turner truck	100%	1.3'	6.0'
48 ft semi	100%	2.7'	6.7'
Rocky Mountain double	100%	5.4'	12.3'
57 ft semi	100%	7.6'	13.3'
Turnpike double	100%	11.6'	19.8'

Table 4. Right turn offtracking results at Michigan Avenue and Monroe Street in Saline (76°)

Truck combination	**1 ➡ 2**		**2 ➡ 1**
	End	*Curb offtrack*	*Curb offtrack*
Western double	100%	✓	5.5'
Turner truck	100%	✓	7.0'
48 ft semi	100%	✓	7.2'
Rocky Mountain double	100%	4.0'	11.5'
57 ft semi	100%	5.0'	13.6'
Turnpike double	100%	10.7'	23.9'

Table 5. Right turn offtracking results at Michigan Avenue and Fosdick Road in Pittsfield Twshp. (58°)

Truck combination	**1 ➡ 2**		**2 ➡ 1**
	End	*Curb offtrack*	*Curb offtrack*
Western double	100%	✓	✓
Turner truck	100%	✓	✓
48 ft semi	100%	✓	2.5
Rocky Mountain double	100%	2.5'	7.6'
57 ft semi	100%	3.5'	9.6'
Turnpike double	100%	8.0'	21.8'

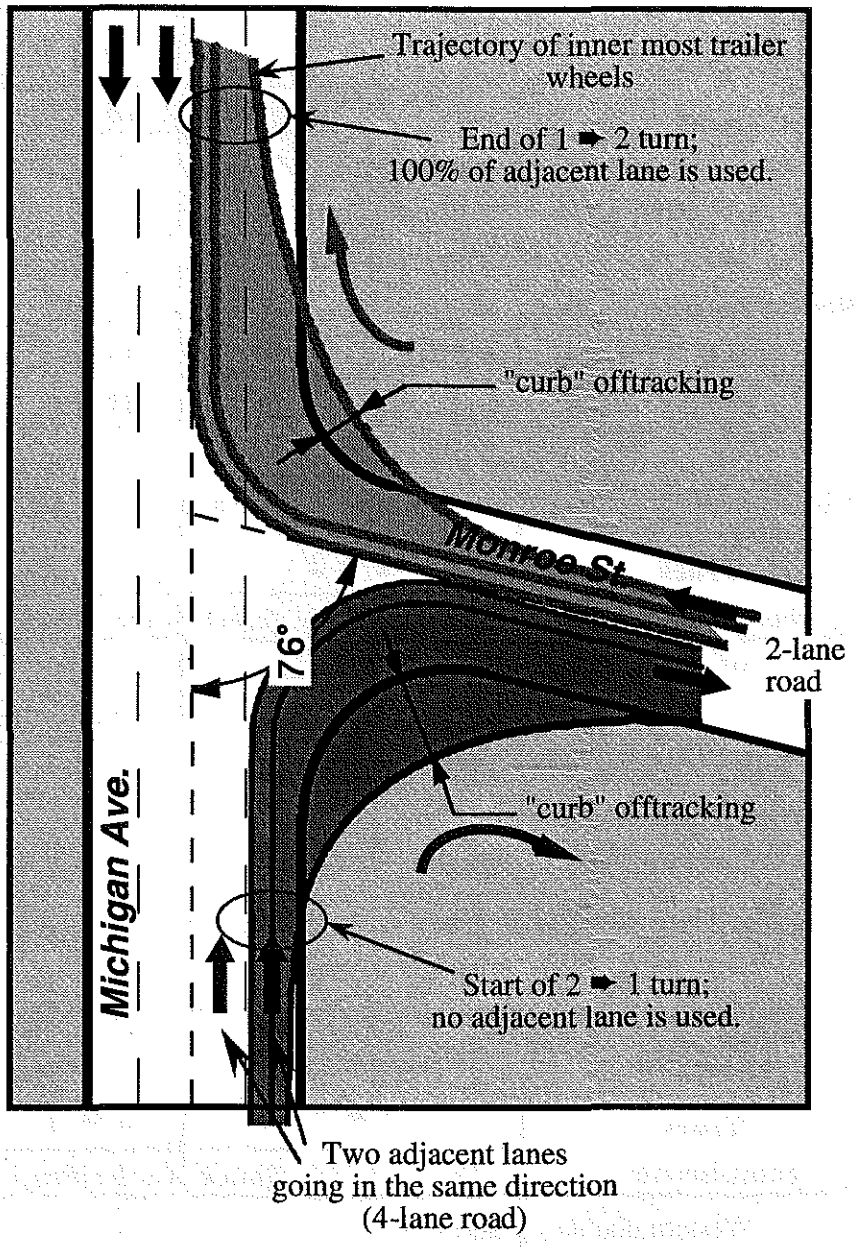


Figure 12. Swept path overlay example
(a turnpike double is shown, see figure 9 for junction dimensions)

Table 6. Right turn offtracking results at Michigan Avenue and Austin Road in Saline (30°)

Truck combination	1 ➡ 2		2 ➡ 1
	End	*Curb offtrack*	*Curb offtrack*
Western double	100%	7.2'	✓
Turner truck	100%	11.2'	✓
48 ft semi	100%	13.7'	✓
Rocky Mountain double	100%	20.5'	✓
57 ft semi	100%	21.9'	✓
Turnpike double	100%	35.8'	3.6'

At the junction of Mills Street, which is a symmetrical 90 deg turn, one can observe that all truck combinations (both those that are currently used and LCVs) consume the full width of two lanes when making the turn. In fact, this situation is true at all the intersections. At the completion of the turn, all the combinations studied consumed the full width of two lanes (100%). Furthermore, in practice, most heavy-truck drivers will use the whole width of the adjacent lane (in the same direction) when making a turn. Such a scenario poses two potential problems of traffic obstruction: (1) as the turning truck changes lanes so that the turning radius is maximized, the traffic flow in the adjacent lanes is obstructed, and (2) when turning right from a four-lane road, the truck might cause a "squeeze" accident and hit the vehicle traveling on the right lane. The existence of this common practice, though, is only mentioned here. It was not used as a calculation model.

At the junction of Austin Road where the trucks make a particularly tight turn of 150 deg, the commonly used 48 ft tractor-semitrailer combination does not stand out as the best. Both the western double and the Turner truck demonstrate a better offtracking performance level, while the 48 ft combination is approximately 7 ft better than the Rocky Mountain double.

Assessing the compatibility of trucks with urban-traffic junctions as they are represented by these roadway elements reveals that some offtracking-related threshold limits can be drawn. In the Mills Street case, it is clear that if the permitted 48 ft semi is used as a baseline, then the western double and the Turner truck can also be accommodated since their offtracking performance is better. On the other hand, the Rocky Mountain double will offtrack almost twice as much as the 48 ft semi, while the 57 ft semi and the turnpike double will offtrack even more. Similar conclusions can be drawn from the other junctions at Monroe Street, Fosdick Road, and Austin Road. It should be emphasized though, that a threshold that is drawn on the premise of currently "allowable" trucks does

not ensure their confinement to paved lanes. Tables 3 through 6 demonstrate that even these combinations will offtrack from the pavement, beyond the curb.

At first, it might seem odd that the trucks going through the tight intersection of Fosdick Road (58 deg) perform better than those going through Monroe Street (which is less tight at 76 deg). Examining figures 9 and 10 reveals that the turning radii are significantly different: 50 ft at Fosdick vs. 35 ft at Monroe.

An initial attempt to combine the data of turning angle and turning radius to determine analytically how various junctions can be made to accommodate the various truck combinations and what the required modifications might be was found impractical. This intangibility is due to the fact that the width of the roadways the trucks are turning to and from has a crucial effect on the offtracking level. Furthermore, the inner bound of the swept path (which defines the offtracking) is a complex tractrix (path curvature). Expressing that trajectory, which is mathematically related to the position of the leading unit, in terms of the intersection's layout is quite complicated. It is possible to develop a special mathematical tool that will take into account all the parameters involved, both those that pertain to the junction's geometry and the truck's dimensions, so that it will calculate the offtracking over the curb to provide an appropriate measure of the required changes. However, the development of such a tool is beyond the scope of this work. It might be recommended that such a tool could be developed within the framework of a separate project. In this work as in current practice, however, the assessment of changes and modifications is done in an experimental way through the use of turning templates (which are provided later in this work).

The following discussion provides some qualitative measures of the extent of changes required in those intersections that were studied. The analysis is based on the method described above, which incorporates overlaying an offtracking template on an appropriately scaled depiction of the intersection. Graphs illustrate the required modifications in term of: (1) offtracking value, (2) modification to curb radius, and (3) additional area that needs to be paved.

Offtracking value, which is displayed in figure 13, is a straightforward graphic representation of the data provided in tables 3 through 6. These values provide an indication of the severity of the offtracking issue caused by a specific truck combination at a specific site. In the case of an unpaved shoulder, figure 13 provides some indication of possible damage to the shoulder or adjacent objects. However, in the case of a curbed sidewalk, typical of urban sites, the implications of such offtracking values portrayed in the

figure might be interpreted as safety hazards. On the other hand, since it provides only one-dimensional information about the offtracking, very limited conclusions can be drawn with respect to practical modifications that might be required at the particular site.

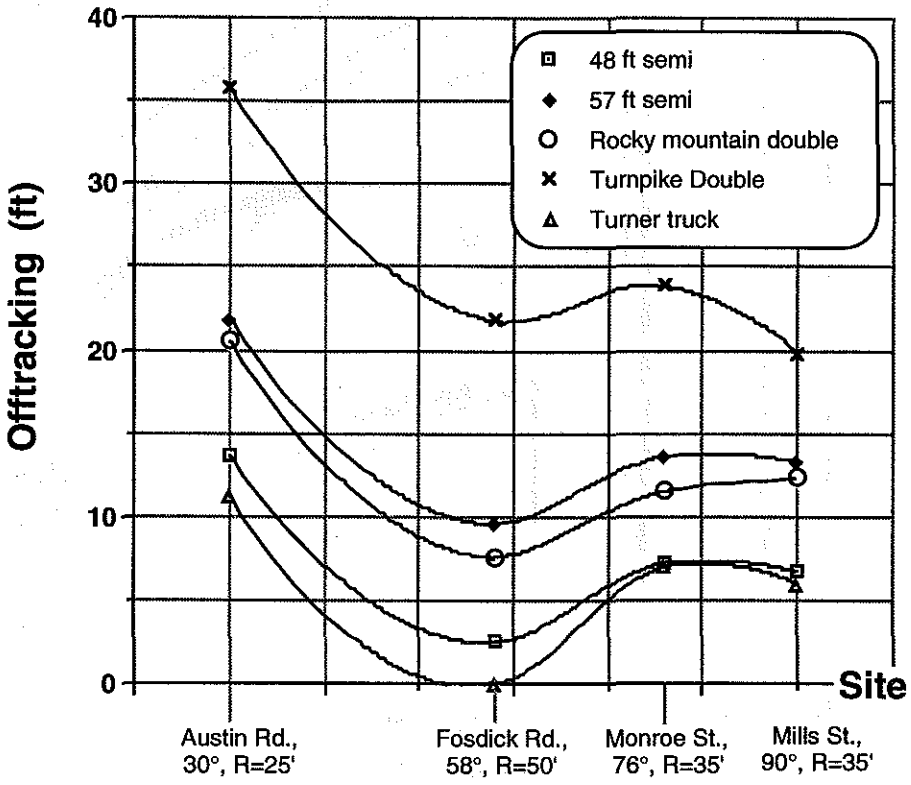


Figure 13. Offtracking values

The extent of changes needed in an intersection might also be assessed in terms of turning radii modifications. As mentioned before, the larger the curb radius, the smaller the offtracking is going to be. Using the offtrack drawings (the turning template overlaid on the intersection) obtained in task 3, a new curb radius was geometrically devised so that it was outside the swept path of the turning truck. Figure 14 illustrates how this was accomplished.

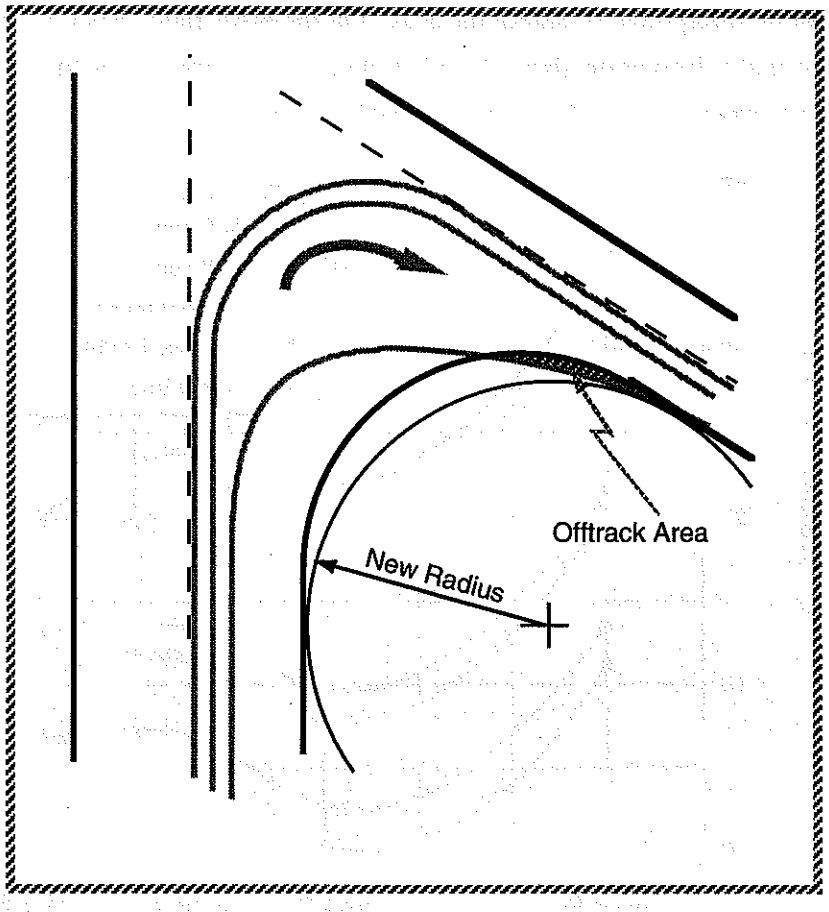


Figure 14. Modification of curb radius

Table 7 summarizes the results of such an analysis, with the following assumptions in effect:

- The tractor is capable of a 40 ft turning radius;
- When turning to a four-lane road, it is acceptable to end the turn in the lane closer to the center of the road.

Analysis results for the junction at Austin Road (last column of table 7) indicate a radius increase that ranges between 3 ft and 17 ft. The 90 deg intersection, on the other hand, requires up to a 42 ft increase in the radius of the curb. Conceivably, it can be interpreted as if the intersection at Austin Road requires smaller modifications to accommodate LCVs. Such is not the case, and the more realistic indication for the level of changes required is provided by the corresponding curb encroachment column. The values in that column indicate the amount of shoulder area that needs to be converted to roadway. As the turning angle gets tighter, smaller radius changes will result in a larger retraction of the curb.

While only 11.6 ft of shoulder will be lost at the 90 deg intersection of Mills Street due to a 42 ft increase in radius, a 17 ft change in radius at Austin Road (30 deg) will result in 35.8 ft of curb retraction.

Table 7. Curb modifications

Angle and existing radius	**2α=90° R = 35'**		**2α=76° R = 35'**		**2α=58° R = 50'**		**2α=30° R = 25'**	
Truck combination	*Curb encr.*	***New curb radius.***	*Curb encr.*	***New curb radius.***	*Curb encr.*	***New curb radius.***	*Curb encr.*	***New curb radius.***
48 ft semi	2.7'	**47'**	1.3'	**38'**	✓	✓	13.7'	**33'**
Western double	✓	✓	✓	✓	✓	✓	7.2'	**28'**
57 ft semi	7.6'	**64'**	7.1'	**47'**	4.0'	**58'**	21.9'	**38'**
Rocky Mountain double	5.4'	**57'**	4.0'	**44'**	2.7'	**56'**	20.5'	**35'**
Turnpike double	11.6'	**77'**	10.7'	**54'**	8.0'	**67'**	35.8'	**42'**
Turner truck	1.3'	**38'**	✓	✓	✓	✓	11.2'	**31'**

The values of these new radii required to accommodate each truck combination at each specific site are plotted in figure 15. By examining these values, the roadway engineer can obtain a better idea of the magnitude of changes needed. It should be emphasized, though, that these values are site specific. As previously discussed, we had attempted to devise a general scheme that will relate the pertinent parameters of both the intersection and the truck, so that new curb radii could be obtained without the need to perform site-specific graphic fits. It was found to be not feasible in a straightforward manner. Furthermore, from the roadway design point of view, addressing the offtracking issue through increased radius might be considered wasteful, as more pavement is provided than is actually needed. The boundaries of the extra pavement needed are elliptically shaped, and as such they consume a smaller area than circular boundaries. Nevertheless, at least for comparison, these new radii are portrayed in figure 15. Comparing figures 15 and 13, we can see that there is no straightforward relationship between the offtracking values and the turning radii.

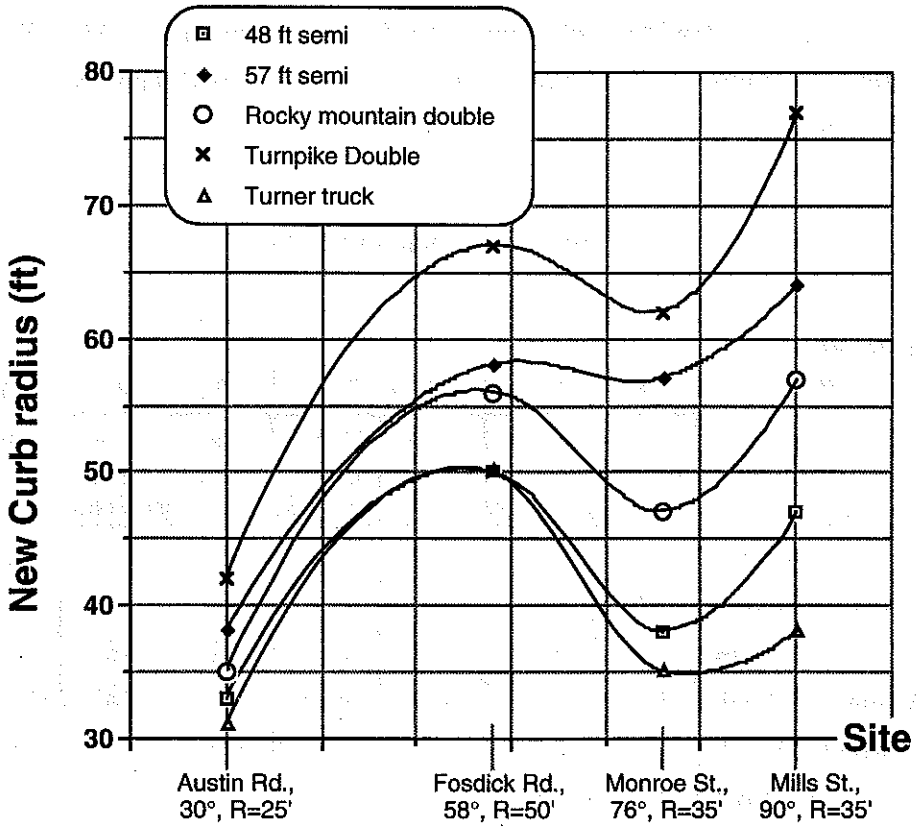


Figure 15. Modification of curb radius — results

Perhaps a more meaningful and appropriate gauge for the required changes in various sites is the additional area that needs to be paved. It is an exact measurement (taken from the offtrack drawings obtained in task 3) of the actual unpaved area that is covered by the swept path of the turning truck (see figure 14). If such trucks are to be allowed on these sites, and at the same time they must not get off the paved road, then the additional amount of pavement as specified in figure 16 should be provided . This pavement should be geometrically deposited as depicted by the offtrack drawings. As before, these values are site specific, and should not be generalized. The analysis was carried out by "manually" overlaying the swept path over the intersection and calculating the area. The results of this third graphical analysis are provided primarily to postulate qualitatively the scope of work needed at these sites to accommodate the various combinations.

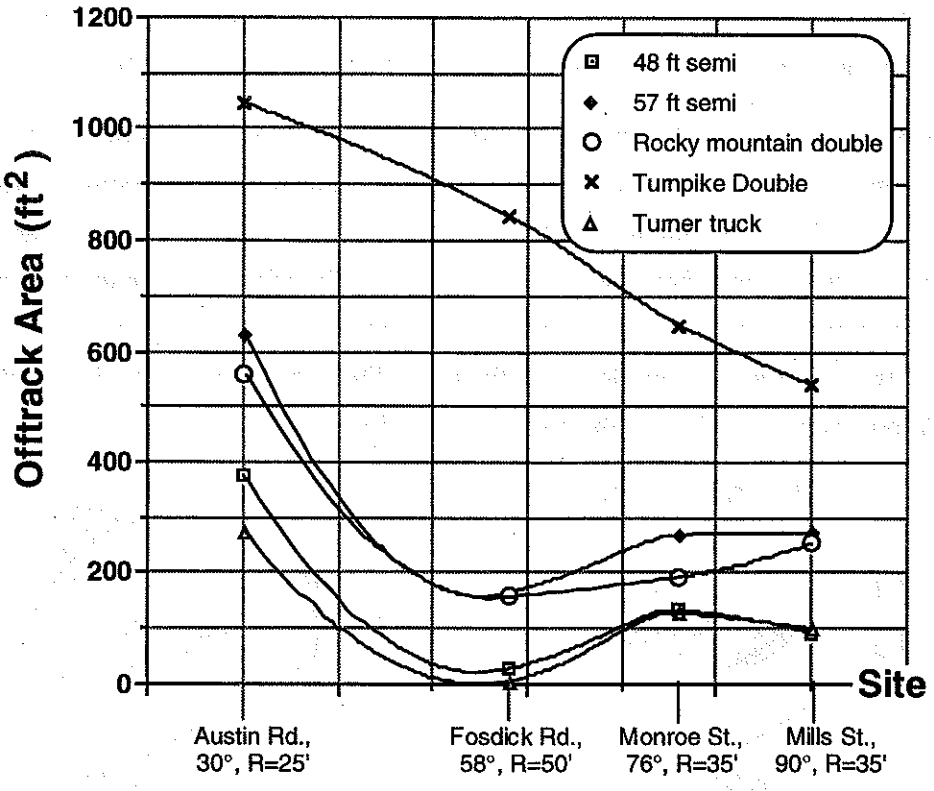


Figure 16. Additional paved area

From among the combinations depicted in figure 16, it can be observed that, using the 48 ft semitrailer as an acceptable baseline performer, the current urban roadways (as represented by the intersections selected for this study) can accommodate only the Turner truck. (This is also true for the western double, which is not shown. Its offtracking performance is even better than the Turner truck). That is, when considering offtracking beyond the paved roadway of the permitted baseline trucks, the Turner truck is acceptable too, and the other LCVs are unacceptable. To accommodate longer trucks within such limitations, or to accommodate all the evaluated combinations without interfering with the curbs at all, modifications as depicted here should be made. Again, assessment of the modifications ought to be performed on an individual basis per truck and per site.

3.1.2 U-turns

Offtracking calculations for U-turns are similar to those performed in section 3.1.1; but the turning angle is now 180 deg. Nevertheless, performance levels of the various truck combinations in U-turns are discussed here separately due to (1) the unique application of this maneuver in Michigan's traffic pattern, (2) the special attention U-turns are given by

MDOT Standard Design Guide VII-670B (where they are referred to as "Crossovers"), and (3) the specially tight limitations imposed by the narrow openings in the medians.

Based on the layouts depicted by the standard design guide, two combinations of opening and median width were selected as representing sites for the computations (see figure 17): (1) 30 ft opening in a 65 ft wide median, and (2) 30 ft opening in an 85 ft wide median. It was assumed here that while turning must be initiated from the lane designated for that purpose (the turning lane, which is the inner most lane), the truck may consume the width of two lanes at the completion of the turn. The turning radii used in the offtracking calculations were according to the above assumption.

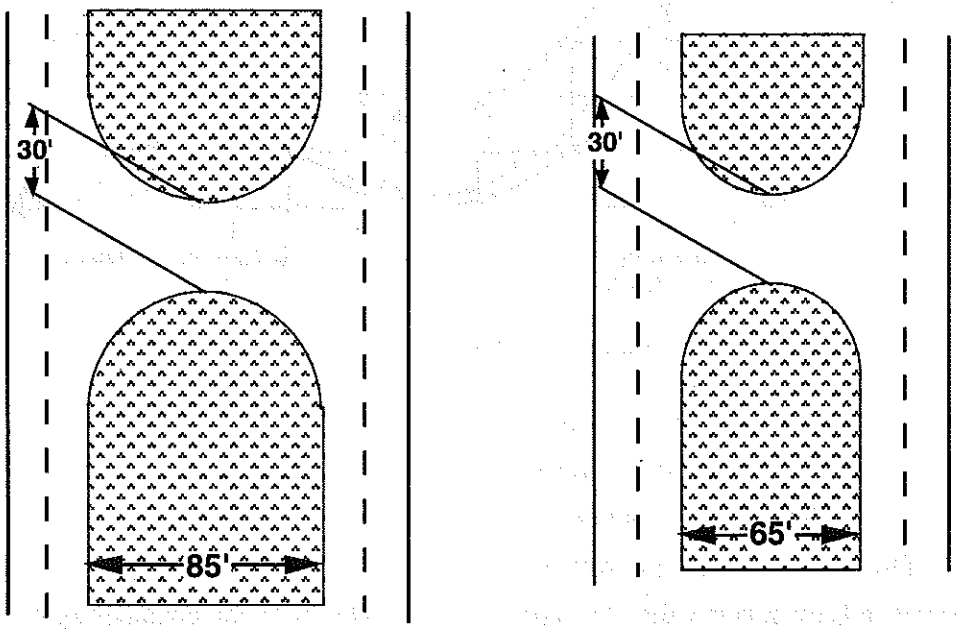


Figure 17. Medians and openings

The offtracking results of the various truck combinations during a U-turn maneuver are summarized in table 8. The width of the median and the opening through which the turns are performed are depicted in the table. For example, 65' x 30' denotes a median which is 65 ft wide, with an opening of 30 ft. Other terms used in the table are "opening" and "width" offtracking. These terms describe the nature and the general location along the opening curb where the offtracking takes place. They are also illustrated in figure 18, which depicts the results of a turnpike double through a 65 ft median. The offtracking results are also presented graphically in figure 19 (the "width" offtracking value is displayed).

Truck combination:	TST48	WSD	Turner	Triple	RMD	TST57	TPD
65' x 30' or 77' x 30' with an auxilliary lane							
Opening offtrack	—	—	—	—	1.2	2.8	14.6
Width offtrack	—	—	—	—	2.8	7.2	16.3
85' x 30' or 97' x 30' with an auxilliary lane							
Opening offtrack	—	—	—	—	—	—	6.5
Width offtrack	—	—	—	—	—	2.1	9.0

Table 8. U-turn — offtracking results

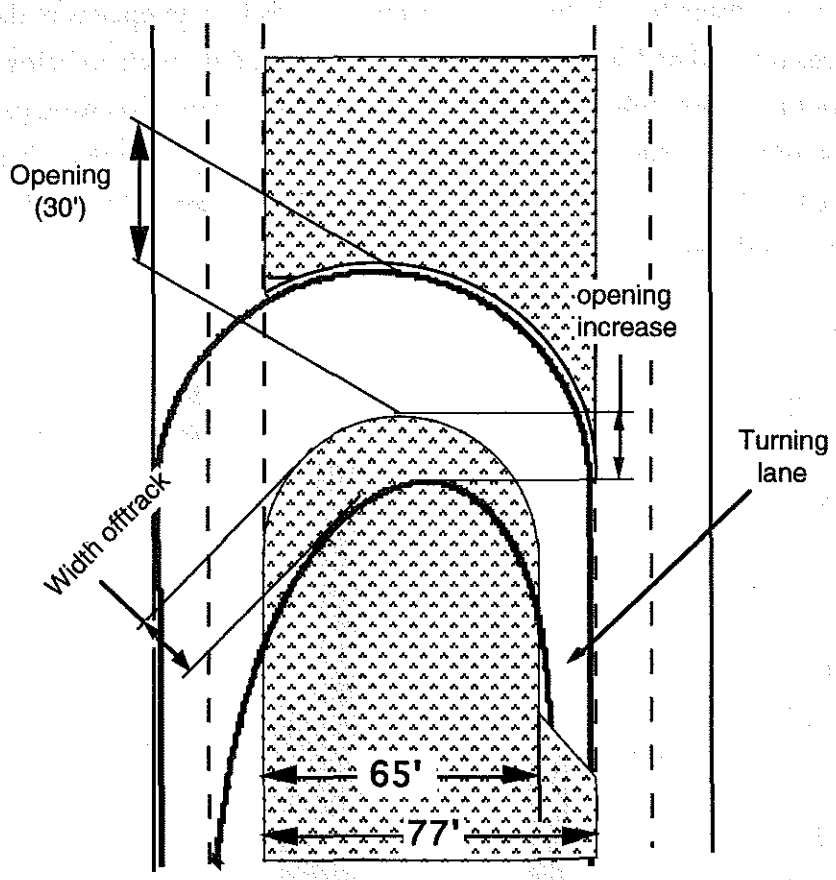


Figure 18. Offtracking dimensions in a U-turn

With the western double and the 48 ft tractor semitrailer as baseline configurations of an acceptable performance level, the results in table 8 and figure 19 show that the Turner truck, the triple, and the turnpike double combinations are also acceptable. They demonstrate levels of performance that are equal or better than the 48 ft semitrailer. It should be noted, though, that the turnpike double requires 1.2 ft additional opening to

pass, where the other acceptable combinations did not offtrack beyond the 30 ft opening. In reality, it is assumed that steering inputs will be adjusted throughout the maneuver, so that a competent driver would probably stay within the given opening. As for the other combinations, the required increase in median opening to allow them to pass without interference with the curb is depicted in table 8. If such a change is to take place, the "descending" portion of the curb curvature (to the left of the apex) should be of an elliptical geometry rather than circular in order to avoid interference with the swept path of the turning truck (or a combination of circular curves of different radii might be used).

As mentioned previously, both this section and the preceding one (urban traffic) are similar in essence. They both involve transient low-speed offtracking calculations, while they differ in the magnitude of the turning angle. Offtracking templates of the various combinations (excluding triple) are presented in figures 20 through 25 below. There is no template for the triple configuration since no offtracking calculations were performed for this combination other than U-turn (it was not planned to be used in the urban-traffic computations). These figures provide an accumulative portrayal of the swept paths of each combination at different turning angles.

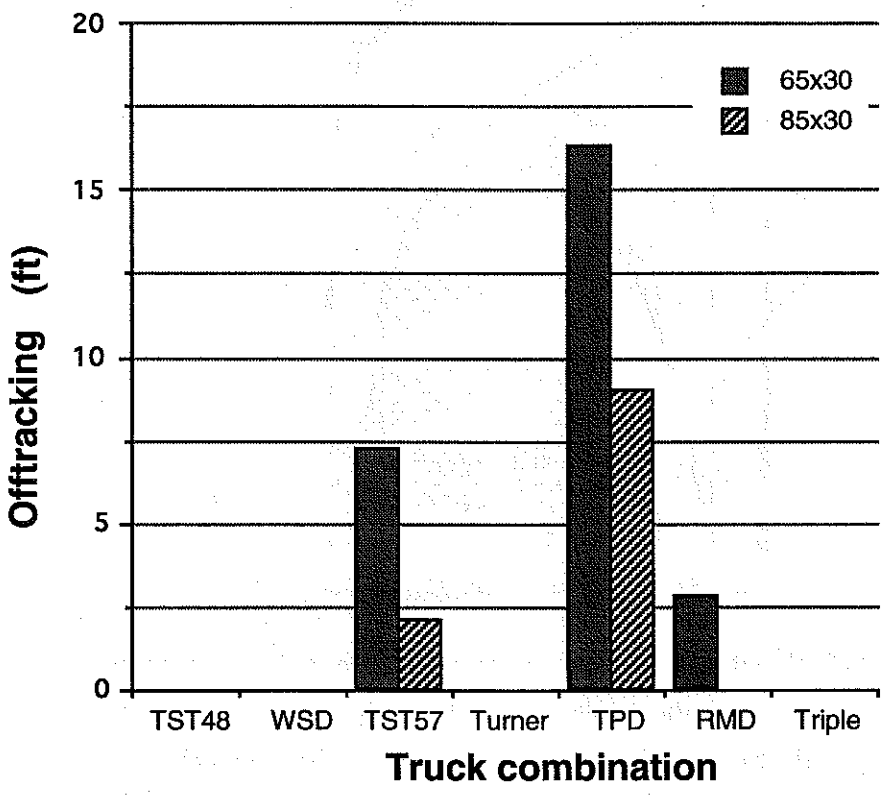


Figure 19. U-turn — width offtracking

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

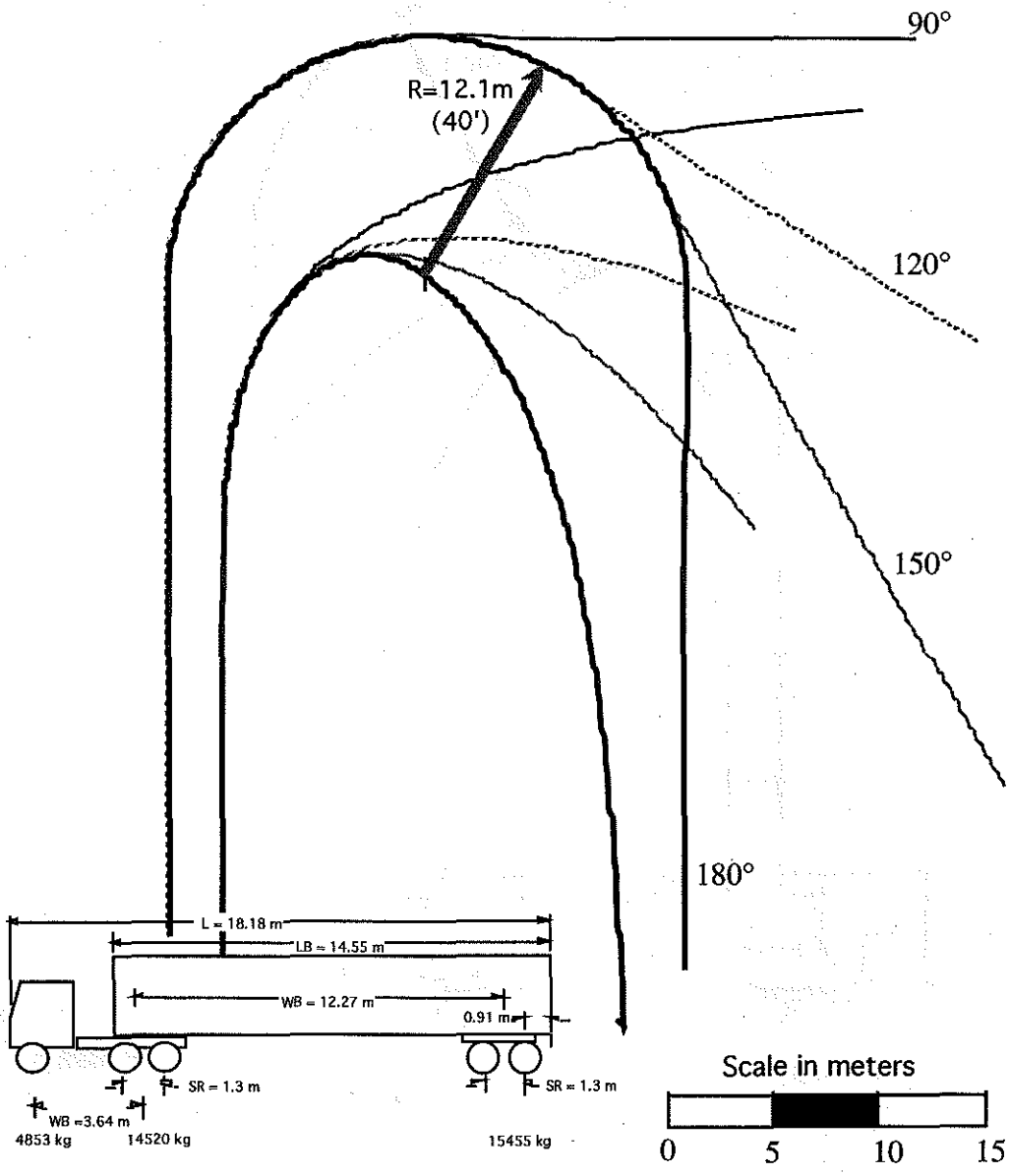


Figure 20. Offtracking templates — 48 ft tractor semitrailer

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

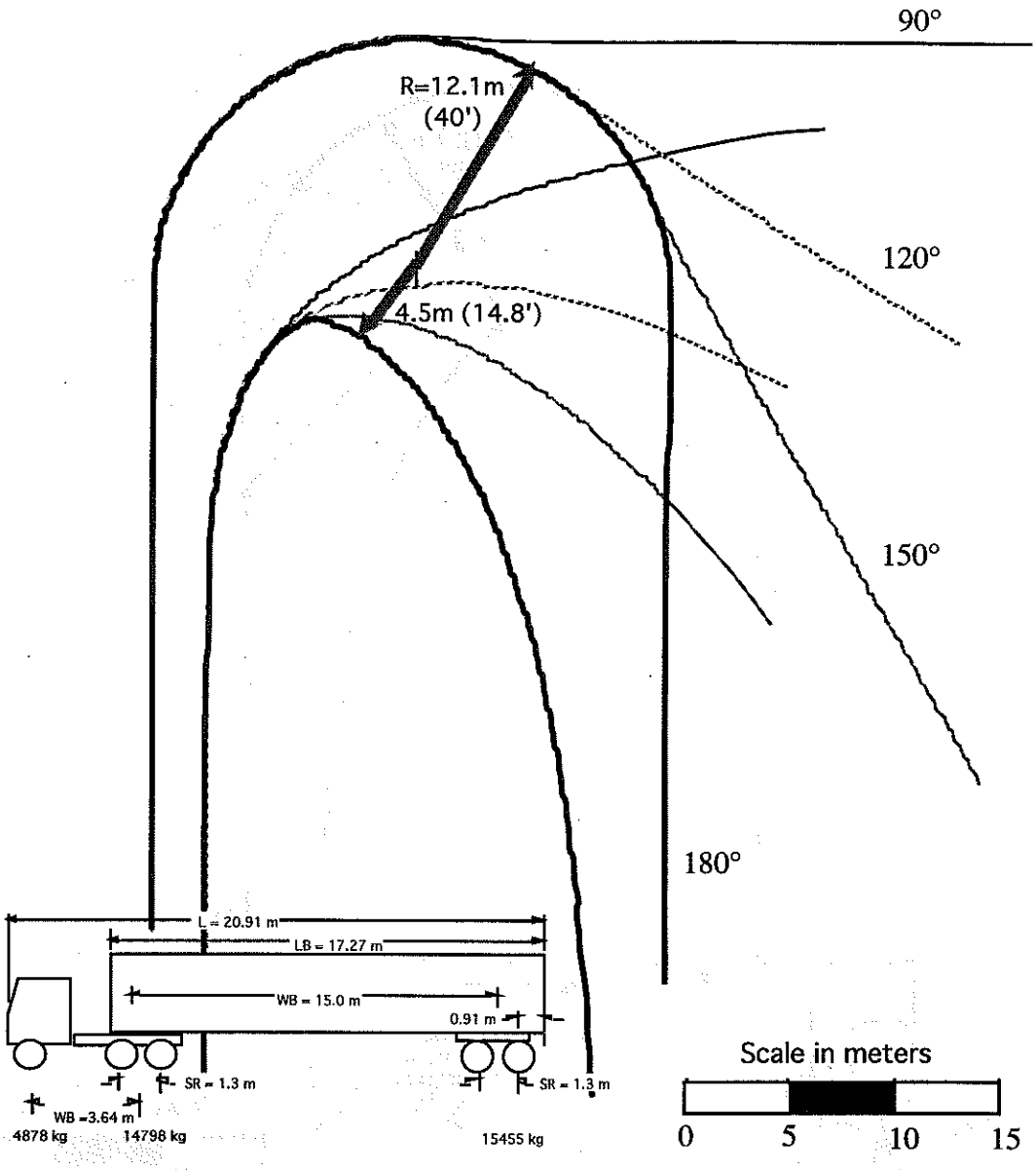


Figure 21. Offtracking templates — 57 ft tractor semitrailer

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

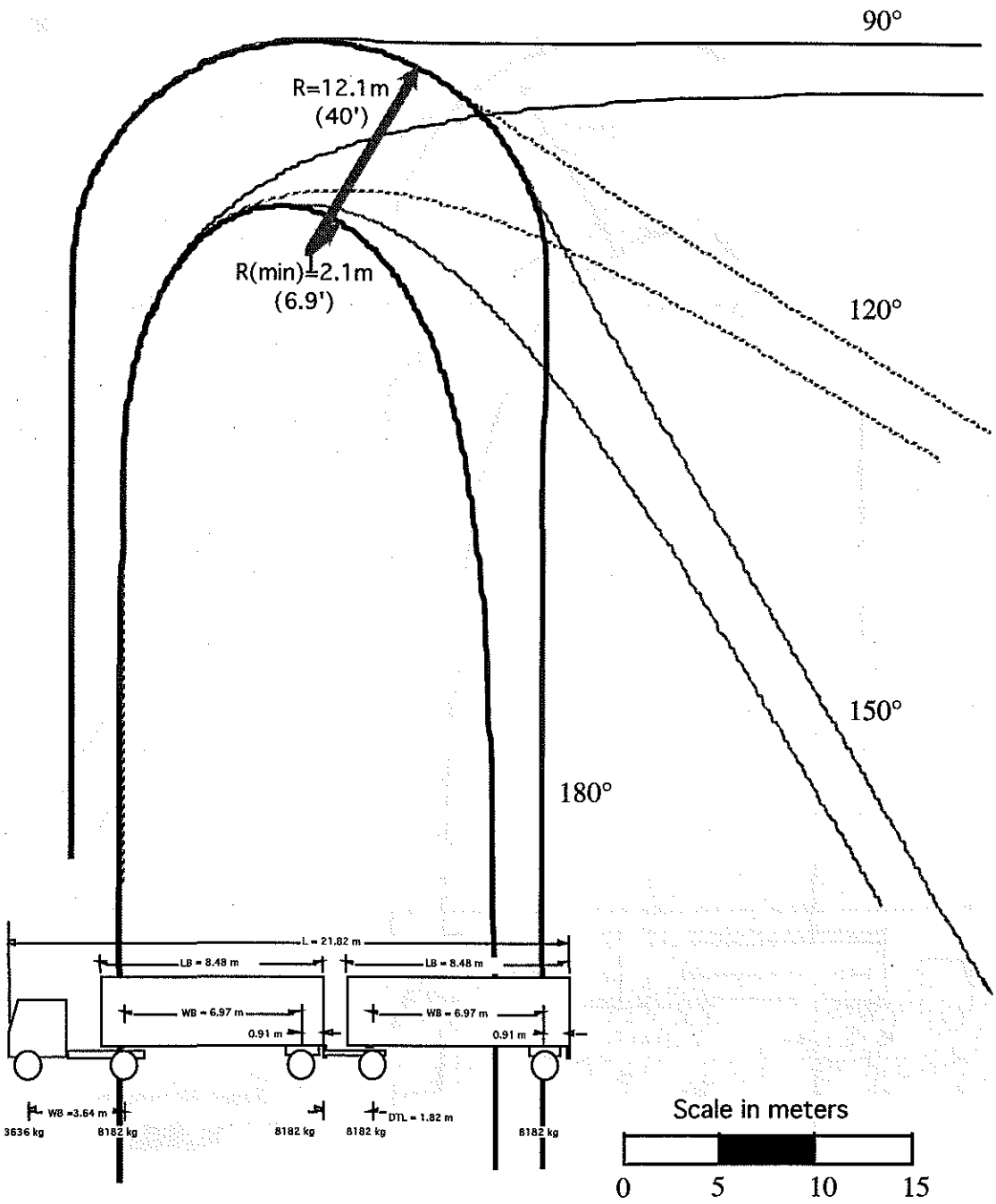


Figure 22. Offtracking templates — western double

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

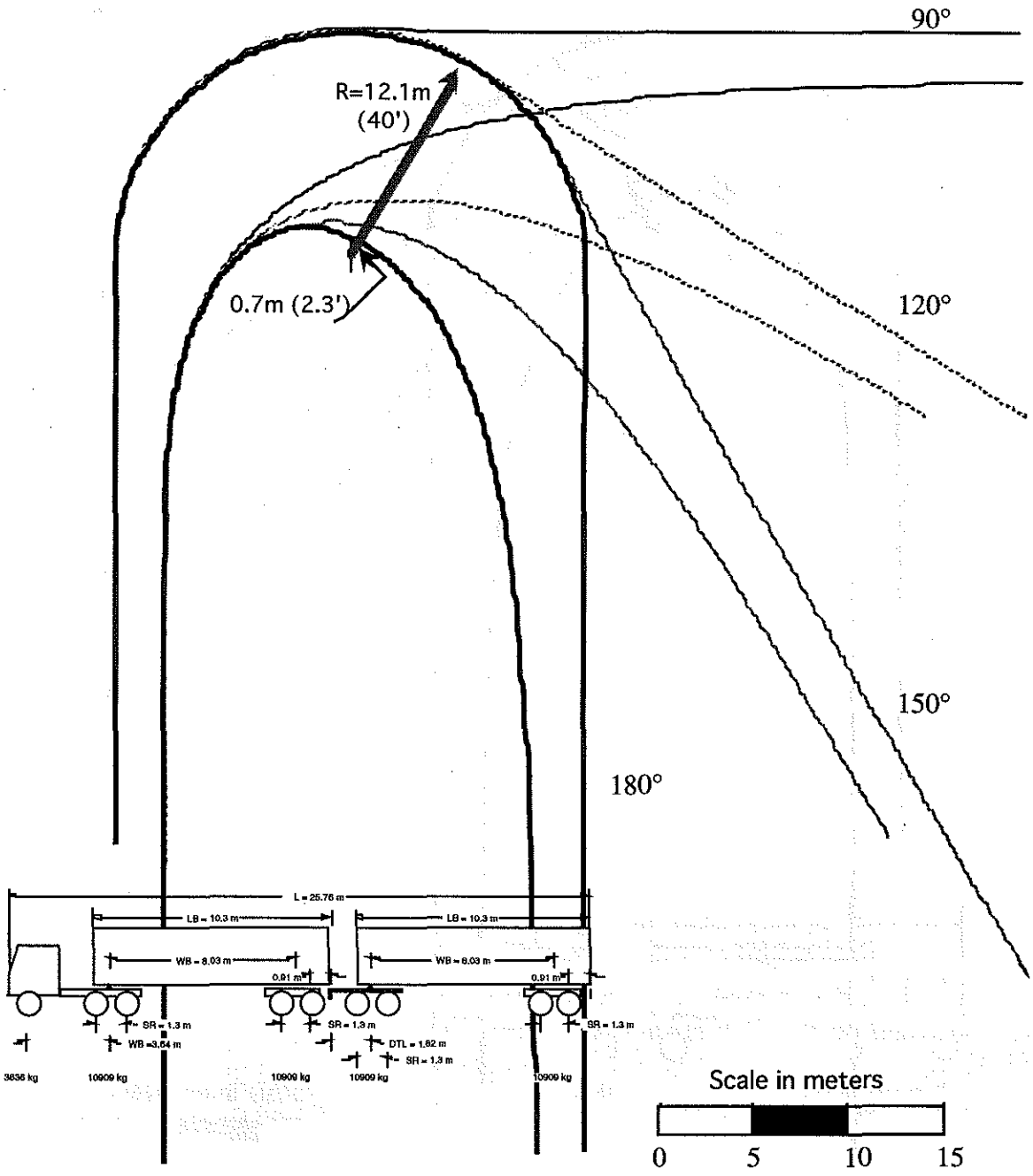


Figure 23. Offtracking templates — Turner truck

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

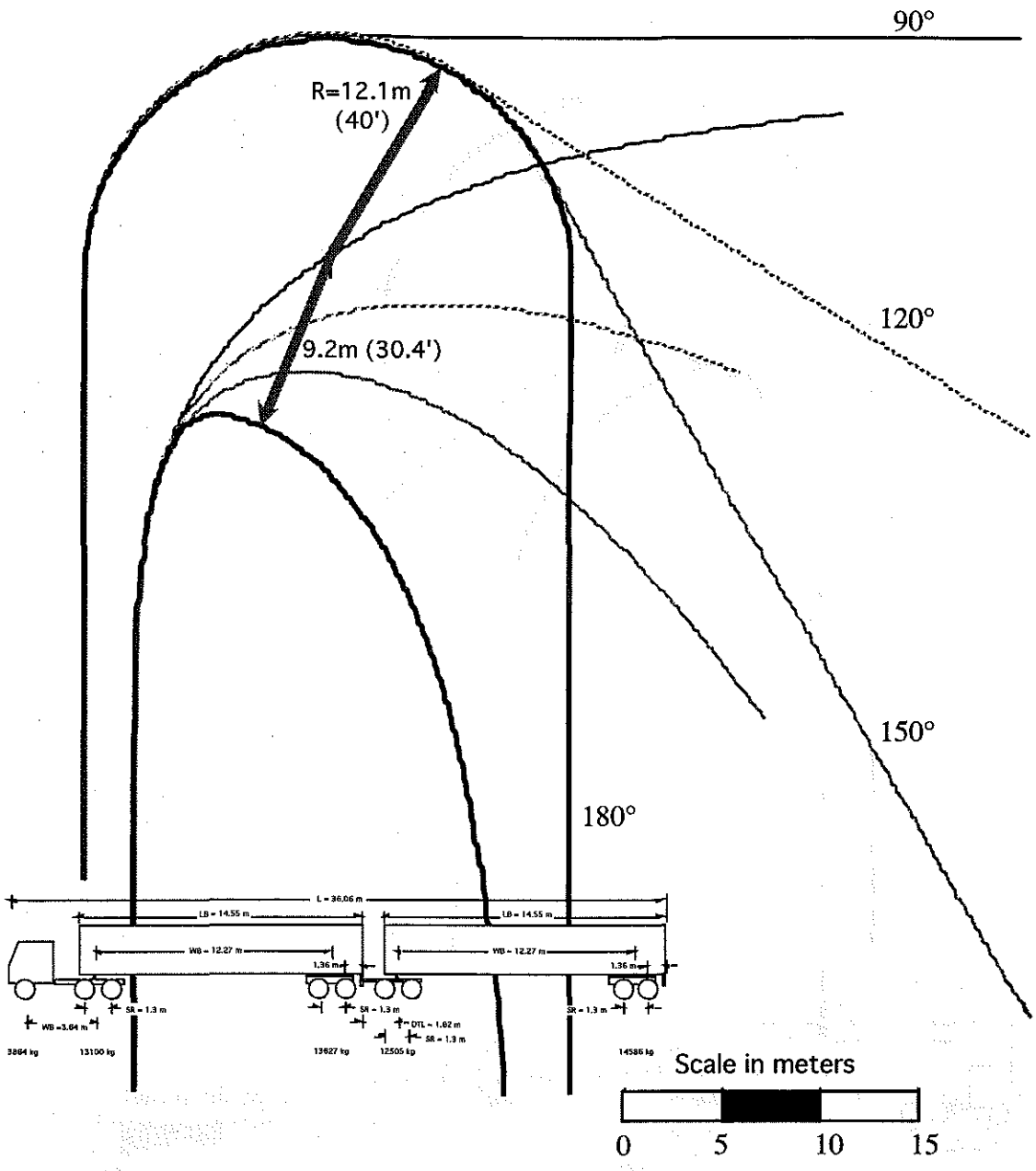


Figure 24. Offtracking templates — turnpike double

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

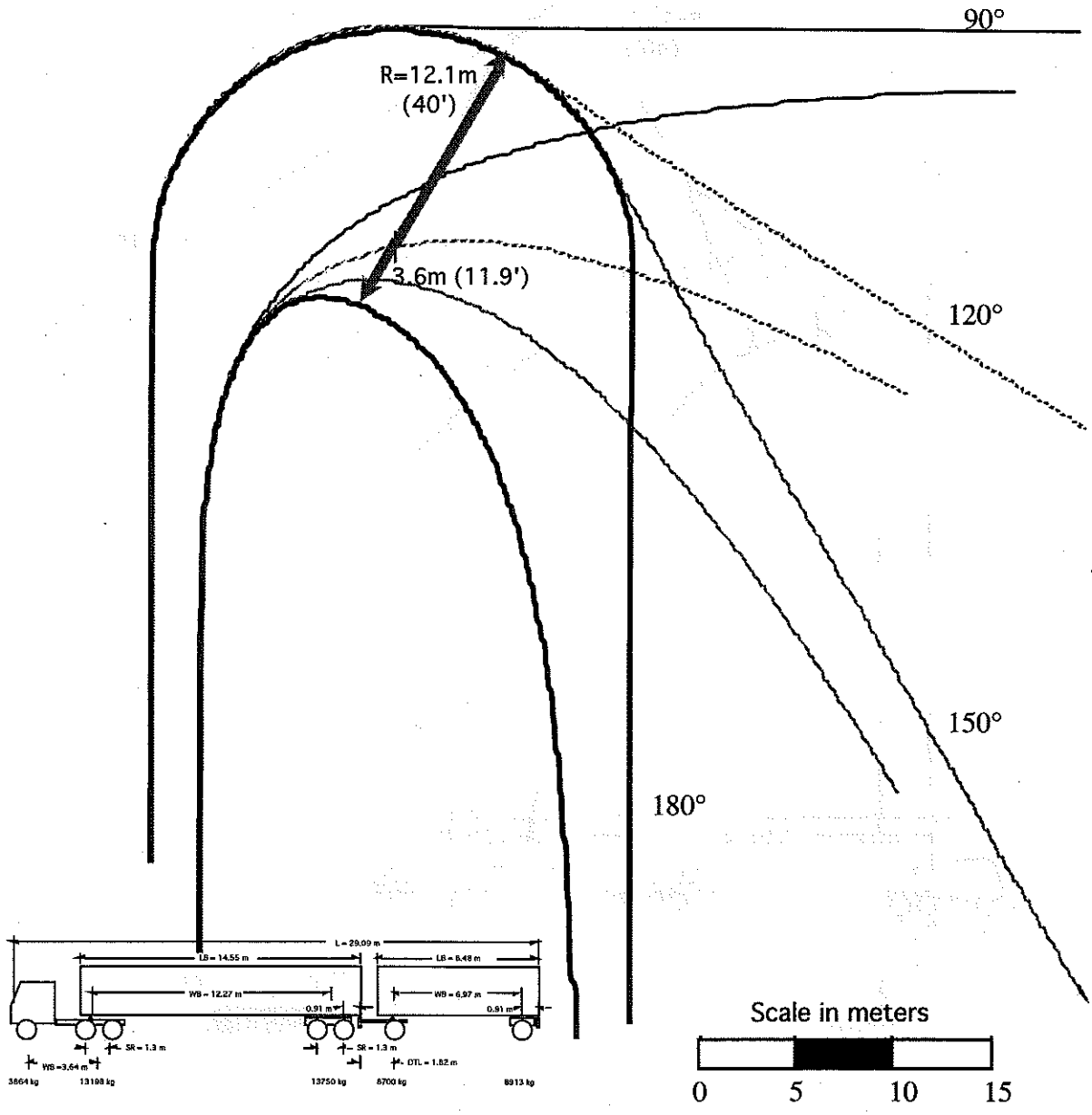


Figure 25. Offtracking templates — Rocky Mountain double

3.1.3 Access ramps

In the previous sections, the performance level of each truck combination was calculated using the method of transient low-speed offtracking. Access ramps in general, and those selected to be studied here in particular, are long enough for the trucks to reach steady-state offtracking values. The swept path of each truck combination was computed, and the resulting plot was then overlaid on a drawing of the ramp in question. The steady-state offtracking value was then compared with the width of the paved lane to verify that the path of the truck does not extend beyond it. As an example, figure 26 illustrates the path of a turnpike double overlaid on ramp F at Whittaker and I-94.

The results of the steady-state offtracking calculations are presented in figure 27. For each truck combination and ramp radius, the resultant width of swept path is denoted. Since all access ramps that were included in the drawings and the standard design guides provided by MDOT were at least 16 ft wide, this width was selected to be used as the margin value.

From figure 27 it can be concluded that with a paved width of 16 ft, access ramps of a 210 ft radius or more can accommodate any LCV configuration without having an offtracking problem. Ramps of a radius that is less than 210 ft (but still 16 ft wide) will cause the turnpike doubles to offtrack beyond the pavement. If the radius becomes tighter than 165 ft, the 57 ft semitrailer will also offtrack outside the paved lane. Additional deductions regarding compatibility of other truck / paved width / radius combinations can be made from figure 27.

Based on the highway drawings provided by MDOT, a ramp radius of 175 ft, which was used here to represent the tightest access ramp, is not very common. It therefore can be safely assumed that ramps of less than a 175 ft radius are unlikely to be found, and hence should not be considered as a limiting factor.

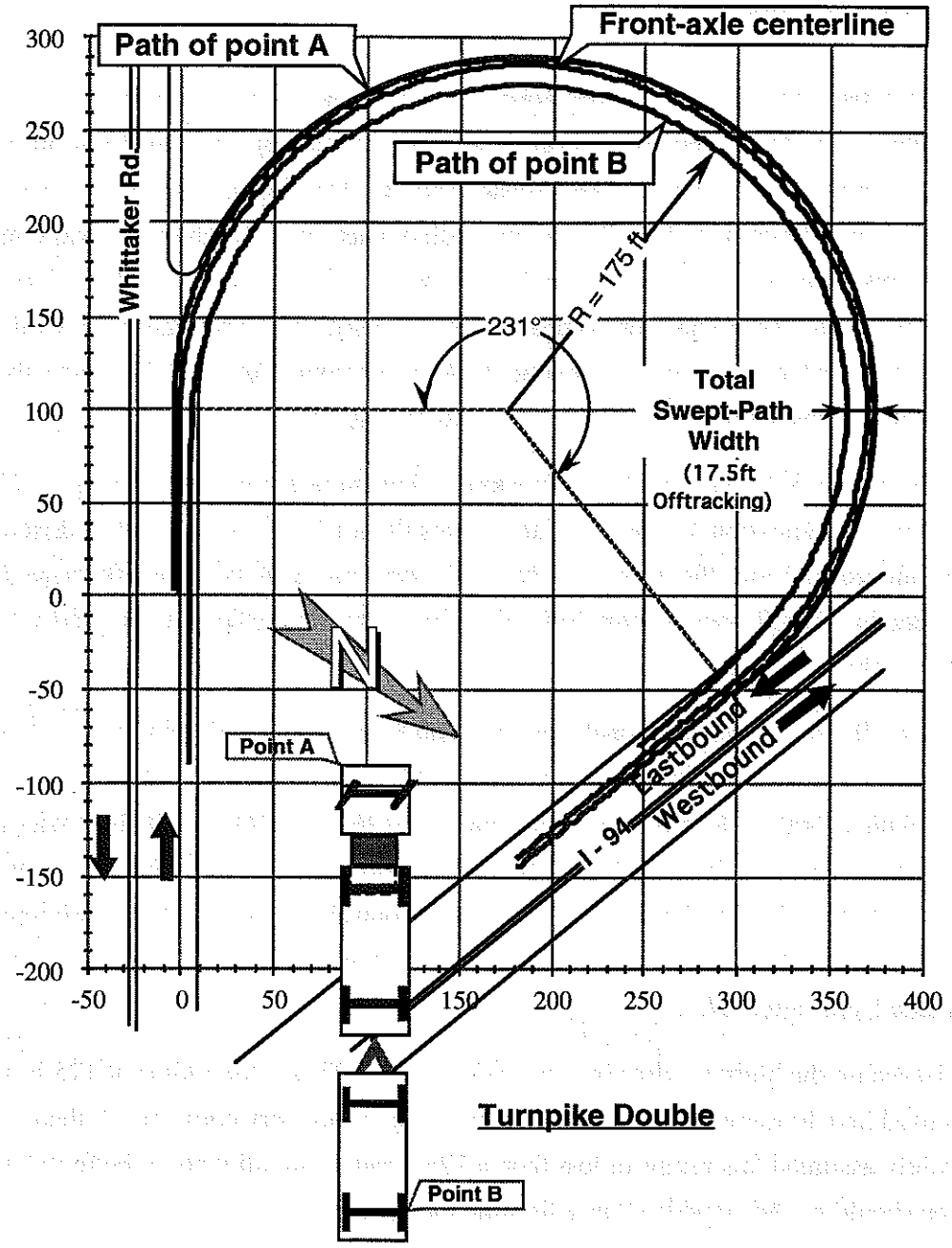


Figure 26. Turnpike double, from Whittaker Southbound to I-94 Eastbound (ramp F)

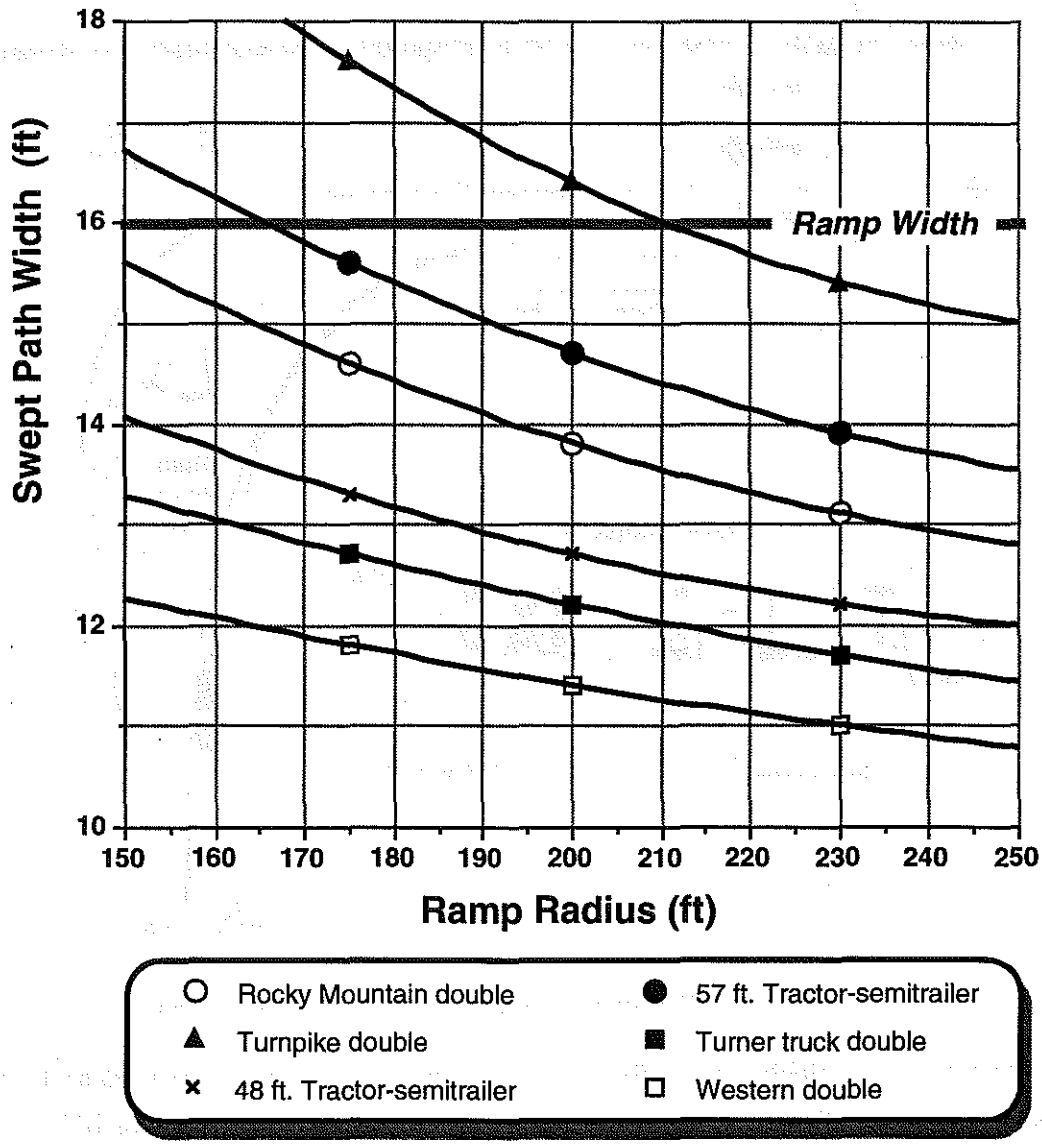


Figure 27. Steady-state offtracking on ramps

3.1.4 Terminal ramp intersections

The entrance to ramp F from Whittaker Road in figure 26 is by means of a smooth merging, as is leaving that ramp onto I-94. Another type of transitioning to and from access ramps is the kind found, for example, in Diamond or Parclo interchanges. The vehicles go through an intersection rather than a smooth merging, when entering or leaving the access ramp. Such intersections are portrayed in figures 28 and 29, overlaid with swept paths of a turnpike double.

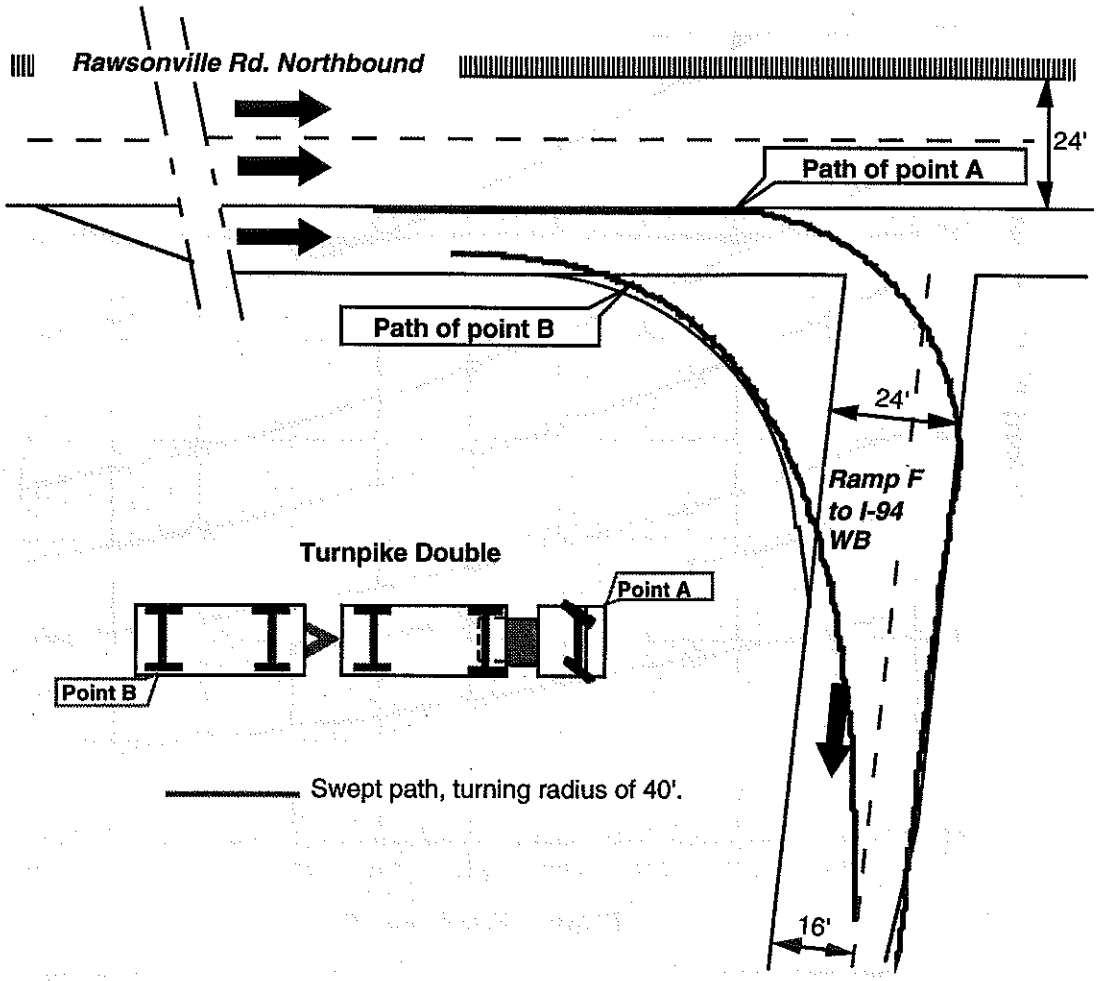


Figure 28. Terminal ramp intersection, entering a ramp

Results of the calculations performed for terminal ramp intersections such as the one described above indicate that they are able to accommodate any configuration of LCV discussed in this study without imposing an offtracking limitation. In most cases, the turning truck was kept well within its prescribed lane. In other cases, which can be regarded as the worst cases, such as with the turnpike double in figure 29, the truck used part of the adjacent lane. Nevertheless, in none of these cases did it encroach onto the opposing lane or off the pavement (when minimum turning radius was used).

A terminal ramp intersection of a different layout is used between Jackson Road westbound and I-94 eastbound (see figure 30). It is of a unique geometry (probably due to construction constraints), and it is not included in the standard design guide. Offtracking in this intersection was calculated in order to obtain some approximated assessment regarding the compatibility of unusual intersections with LCVs. The drawing in figure 30 is qualitative only, and it is provided only as an example.

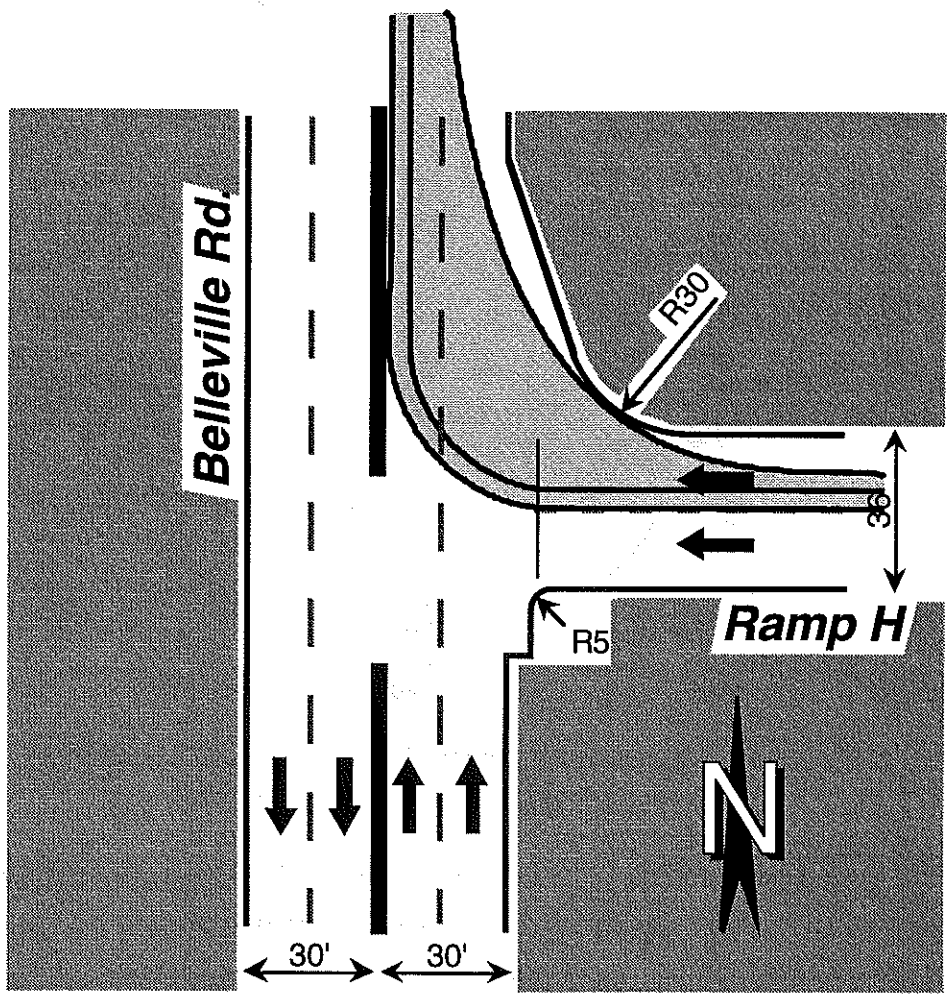


Figure 29. Terminal ramp intersection, leaving a ramp
(The swept path of a turnpike double is shown)

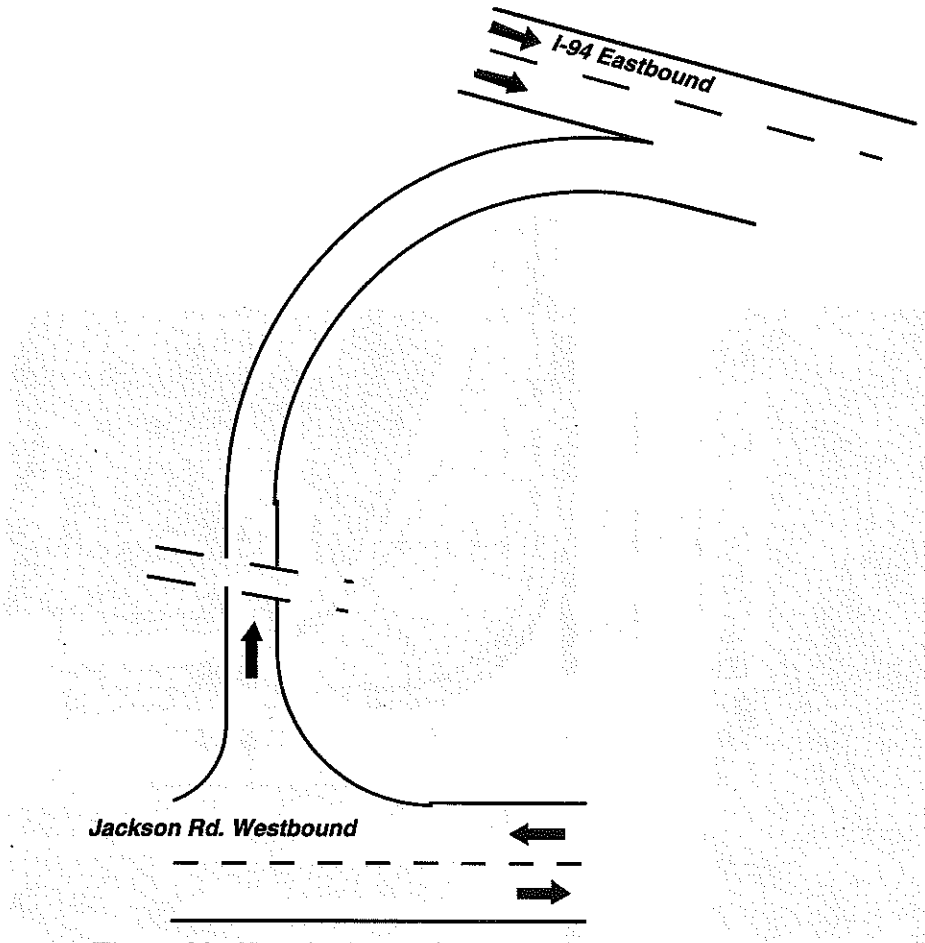


Figure 30. Terminal ramp intersection at Jackson Road and I-94
(A qualitative description only)

As the truck goes through this particular intersection, offtracking can take place in two locations: first, at the right turn from Jackson Road, and second at the curve leading to I-94. Results of the offtracking calculation for the various combinations are given in table 9.

Table 9. Offtracking from Jackson Road to I-94

Truck combination:	TST48	WSD	TST57	Turner	TPD	RMD
At the right turn	3.1	—	5.4	0.9	11.6	4.9
At the curve	2.2	—	7.1	0.9	8.5	4.0

With the baseline trucks (48 ft semitrailer and western double) considered as acceptable, the Turner truck can also be accommodated. The Rocky Mountain double, which offtracks less than 2 ft beyond the 48 ft semitrailer, might be considered as marginally fit. To allow the turnpike double or the 57 ft tractor semitrailer into that

intersection without interfering with the curbside, additional paving (as indicated by table 9) is required.

Unlike urban traffic intersections or access ramps, guideline rules for designing odd intersections cannot be set. In order to determine compatibility of such sites with the various truck combinations, a case-by-case assessment similar to the above example should be made.

3.2 Acceleration Across an Intersection

Acceleration across an intersection, or acceleration from a stand still, is a performance mode that evaluates whether the crossing truck is an obstacle to the other traffic. A slow acceleration combined with a limited sight distance might force the traffic in the crossed road to brake or deviate to avoid the truck, which has not cleared the intersection yet. Two typical scenarios were identified: urban traffic and transitioning from the freeway to arterial roads.

Urban traffic intersections referred to in this work are four-way intersections. The geometric layout of such an intersection is portrayed in figure 31. The criteria used to evaluate truck performance in this situation is the time required to accelerate from a stand still position, until the rear end of the truck has cleared the intersection zone.

Transition intersections in this work are three-way intersections. The geometric layout of such an intersection is portrayed in figure 32. The criteria used to evaluate truck performance in this situation is time and distance traveled by the leading unit of the combination from a stand still position until its rear end has cleared a 12 ft path (lane) for the traffic in the opposite direction.

Scenarios other than those classified as either a four-way intersection or a three-way intersection can be evaluated in most cases when considered as a combination of the two.

The methods that are involved in calculating acceleration performance entail several assumptions and approximations. (for example, timing points for changing gears, times to engage and disengage the clutch, etc.). As such approximations can be considered reasonable for some drivers, others might have different driving habits. Due to inevitable time errors, the accuracy level in the calculations was held to whole seconds. Time computation results in the following discussion are therefore rounded off to the nearest whole second.

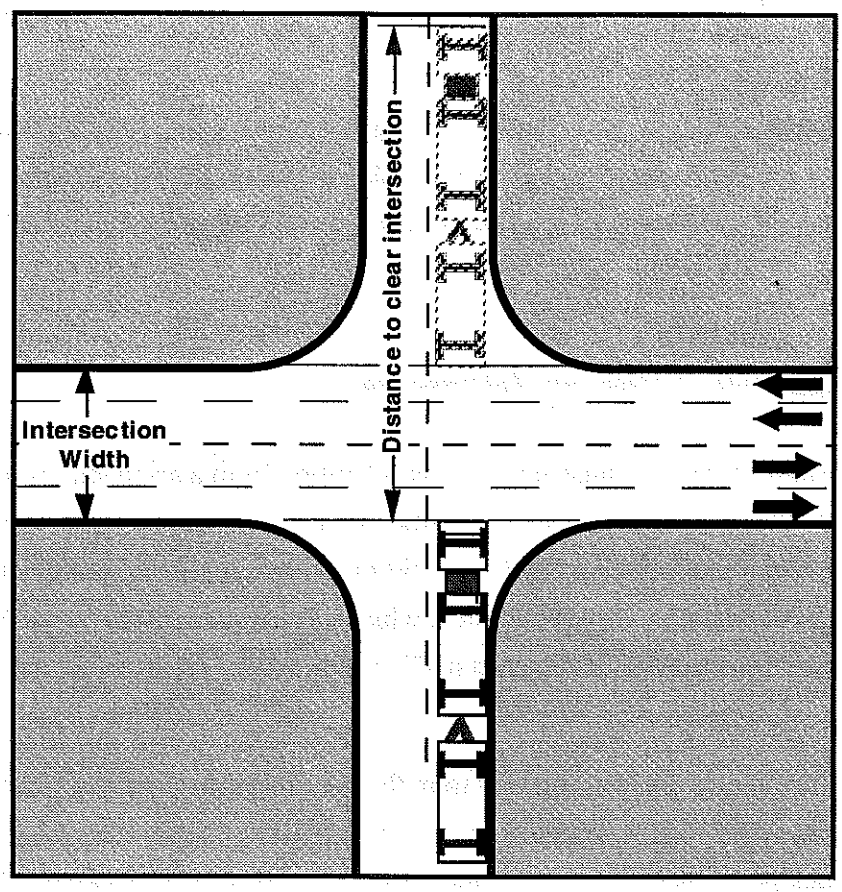


Figure 31. Layout — 4-way intersection

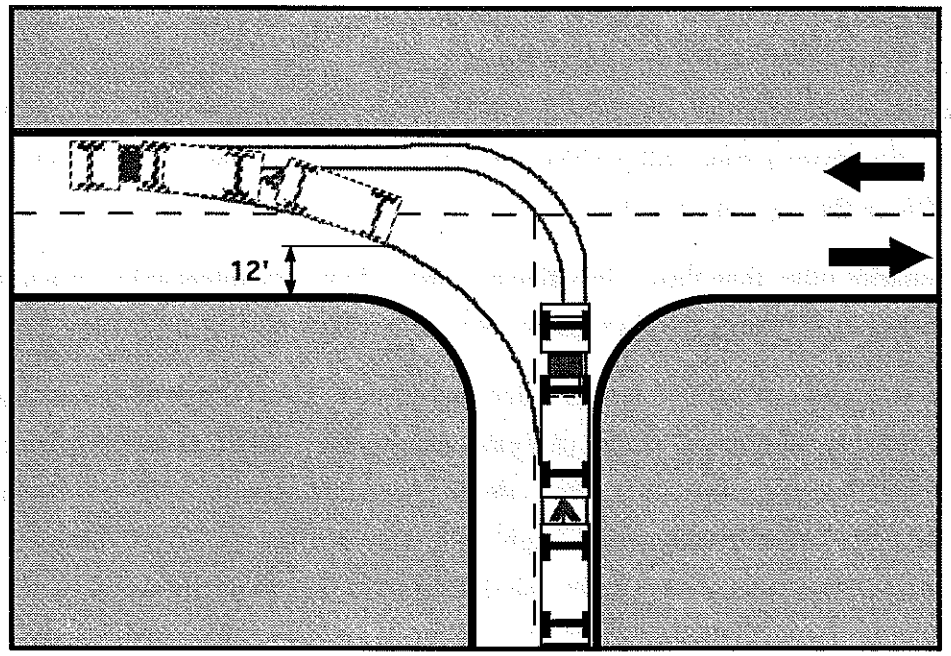


Figure 32. Layout — 3-way intersection

3.2.1 4-Way intersections

Calculation results of acceleration across a four-way intersection are presented in figure 33 in terms of time to clear different intersection widths. Based on characterizing intersections as depicted by the drawings provided, it was assumed that the road is typically close to being level (0% slope). Figure 33 displays accumulative results for all the truck combinations.

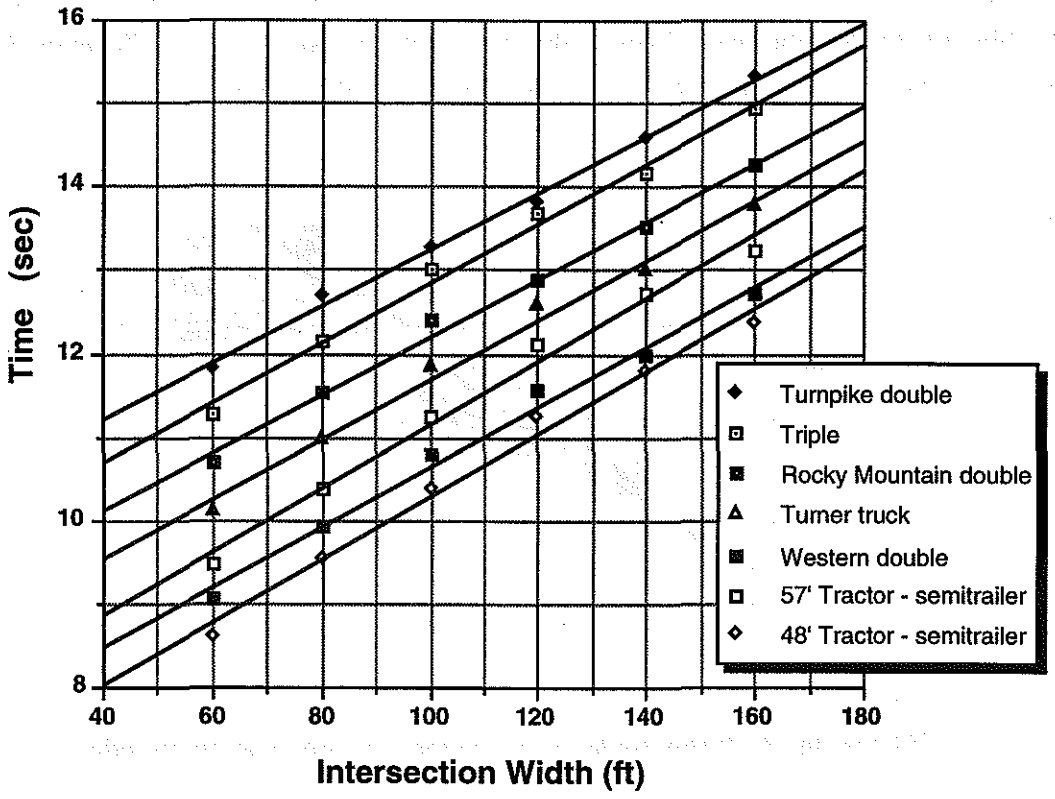


Figure 33. Acceleration across a 4-way intersection

The turnpike double is the truck combination that presents the poorest performance level. On an average, it takes about 2.5 seconds more than the western double (which is currently the longest combination allowed) to cross any given intersection. If we consider the speed of 35 mph (~50 fps) to be a typical speed limit in the vicinity of these urban intersections, the impact that the worst-case scenario of 2.5 seconds might have on the traffic is in a form of a requirement for an additional 125 ft of sight distance, and also the potential for small delays. Given the current roadway design practices, it can be assumed that the existing four-way intersection sites will be able to accommodate LCVs. However, the posting of appropriate signs might be necessary in some places.

3.2.2 Three-Way intersections

Calculation results of the acceleration across a three-way intersection are presented in terms of time - distance plots in figures 34 through 38. For clarity purposes, these charts are also provided at a magnified scale in pages C-25 through C-27 in appendix C. Unlike in the case of a four-way intersection, the level-road assumption is not valid for three-way intersections as indicated by the data from the drawings. Each truck combination was therefore analyzed on slopes varying from 0% to 6%, and the distance computed for each combination to clear the crossed lane is depicted on the appropriate plot. The numerical results used to generate these plots are presented in a tabulated form in appendix C.

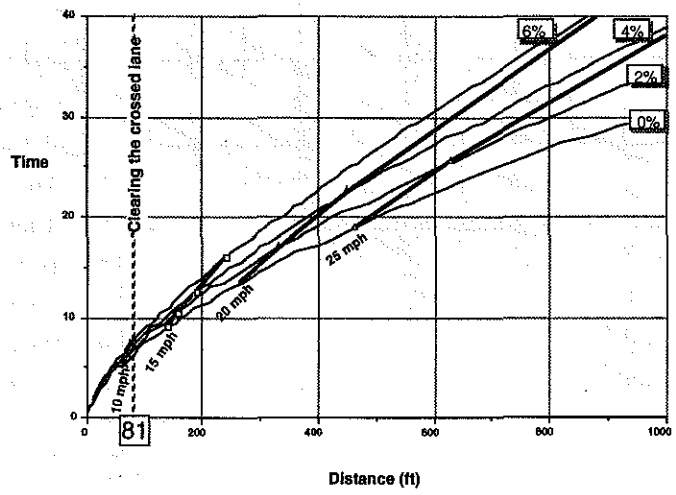


Figure 34. 48 ft semitrailer, acceleration at a three-way intersection

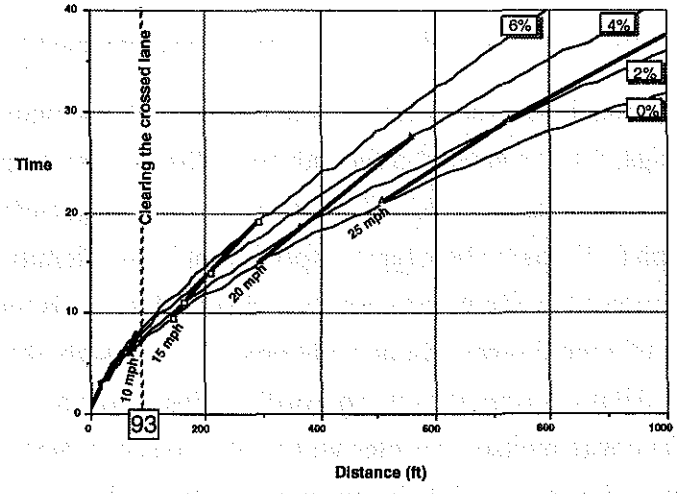


Figure 35. Western double, acceleration at a three-way intersection

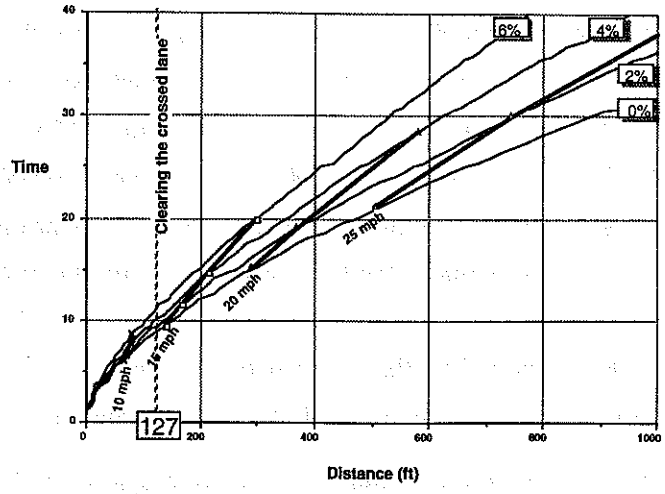


Figure 36. Rocky Mountain double, acceleration at a three-way intersection

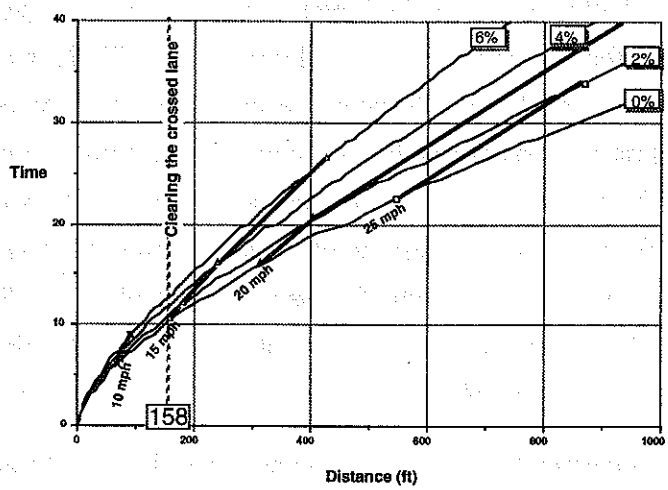


Figure 37. Turnpike double, acceleration at a three-way intersection

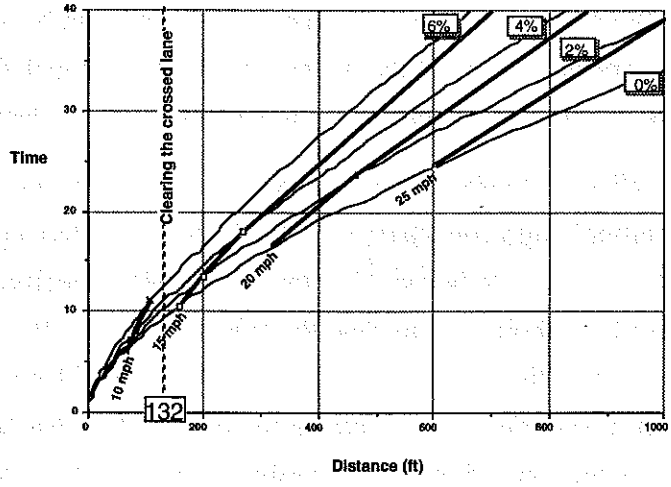


Figure 38. Triple, acceleration at a three-way intersection

The commonly used criterion for a satisfactory merge calls for the joining vehicle to attain at least 85% of the design speed. This means unrealistic sight distance when heavy trucks are involved. For example, if a truck takes 40 sec and 1300 ft to reach 70 ft/sec and the oncoming traffic has a traveling speed of 80 ft/sec (about 55 mph), the truck would need an intersection sight distance of approximately 1500 ft depending upon the deceleration of the oncoming vehicle. In that sense, heavy trucks might always be considered an obstruction to traffic. For the purpose of this study, the acceleration performance levels demonstrated by the 48 ft tractor semitrailer and the western double were used as baseline figures to compare with the other combinations.

From figures 34 through 38 it is evident that the 48 ft semitrailer performs best: it takes the least amount of time to clear the crossed lane at a 3-way intersection on a 6% grade (8 sec). The western double takes a while longer (9 sec) on the same slope, and the Rocky Mountain double is third in performance level with 12 sec. Under similar conditions, the turnpike double and the triple take 13 seconds each to clear the crossed lane. This notion of performance level rating is supported by examining the "specific power" value of each combination. With specific power being defined as the ratio of the total weight of the vehicle to its engine power, the various combinations possess the following values: 232 lb/hp for the 48 ft semitrailer, 242 lb/hp for the western double, 266 lb/hp for the Rocky Mountain double, 299 lb/hp for the turnpike double, and 327 lb/hp for the triple. By these numbers, the triple stands out clearly as the worse, while the 48 ft semitrailer is the best.

However, a comparison between these values of specific power and the time it took for the various combinations to clear the crossed lane brings about the issue of qualitative conformity. When the specific power is plotted over the corresponding time values of each combination (see figure 39), significant changes in the graph can be observed. For example, while the specific power of the western double is not much different than the one of the Rocky Mountain double, the latter took much more time to clear the crossed lane.

This lack of qualitative conformity can be explained when the lengths of the various combinations are brought into consideration. The Rocky Mountain double is 33% longer (96 ft vs. 72 ft), therefore it is to be expected that with similar specific power characteristics it will also consume 33% more time to clear the crossed lane than the western double. Observing figures 35 and 36, the time-distance lines are indeed identical. The only difference lies in the positioning of the clearing-the-crossed-lane line on each plot. A "modified specific power" descriptor was therefore devised, so that the length will also be taken into consideration: (length)•(weight)/(engine power). Table 10 depicts the length, engine power, and weight data items of each combination, with the results for the time to

clear the crossed lane and the two specific power factors. Figure 40 portrays the modified specific power and the time values for each combination. A better correspondence between the patterns of the two plots can also be observed.

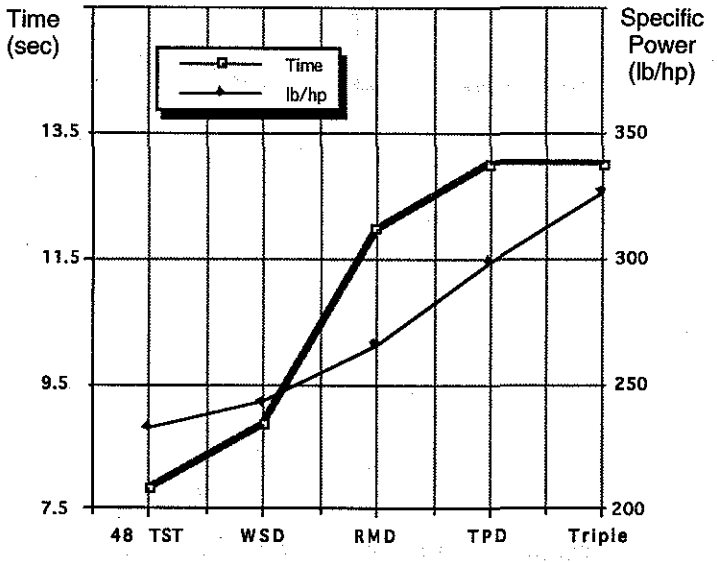


Figure 39. Specific power and time

Table 10. Data and specific power factors

Truck combination:	TST 48	WSD	RMD	TPD	Triple
Length (ft)	60	72	96	119	104
Weight (lb)	76600	80000	106500	126900	114600
Engine power (hp)	330	330	400	425	350
"Time to clear" result (sec)	8	9	12	13	13
Specific power (lb/hp)	232	242	266	299	327
Modified specific power (lb•ft/hp)	13927	17455	25560	35532	34053

There is a correlation between the length of each combination and the distance it needs to travel in order for its rear end to clear a 12 ft lane for the traffic in the opposite direction. In the case of a four-way intersection, that correlation is rather straightforward: each combination needs to travel a distance equal to its length plus the width of the intersection. With three-way intersections, the situation is different as the leading unit performs a turn as it travels forward. From the length values listed in table 10 and the clearing-the-crossed-lane lines in figures 34 through 38, it can be observed that a value of 1.31 is an

acceptable approximation of the ratio between the distance traveled forward by the leading unit, and the length of the combination.

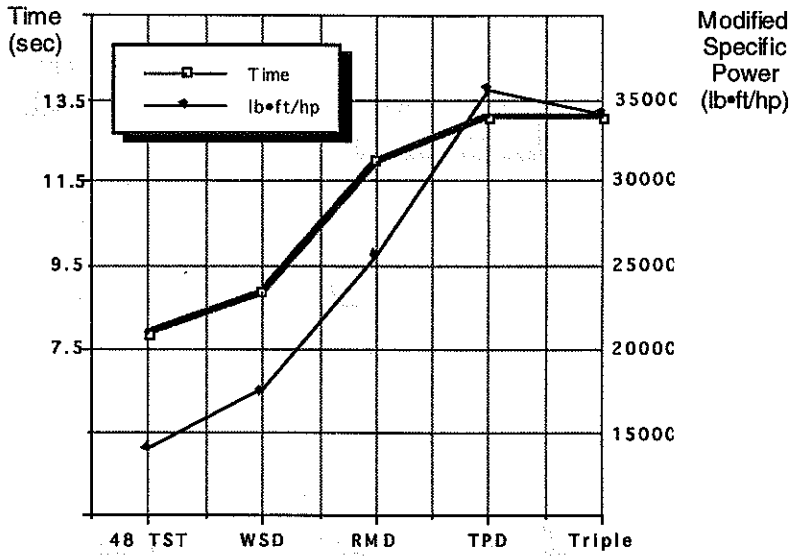


Figure 40. Modified specific power and time

From the standpoint of clearing the crossed lane at a three-way intersection, if the 48 ft tractor semitrailer is considered as the limiting baseline configuration, then no other trucks will be allowed, not even the standard western double. On the other hand, if the western double is considered as the limit and an approach similar to the one used for the four-way intersection is employed (that is, 2.5 additional seconds of crossing time are allowed), some other combinations could be accommodated. From figures 34 through 38 the following combinations satisfy such a requirement:

- Rocky Mountain double on a grade of up to 5%
- Turnpike double on a grade of up to 2%
- Triple on a grade of up to 3%

Among all the combinations, the turnpike double is considered the worst case (the 6% line in figure 37), as it takes 12.5 seconds to cross the intersection. Based on the preceding discussion, the upper limit accepted is 11.5 seconds (9 seconds for the western double plus 2.5 seconds). Permitting the full range of combinations evaluated in this work will therefore require one additional second of sight distance at these intersections. Assuming 50 mph as an average design speed in the vicinity of such intersections (in most cases there are no stop lights), the additional 1 sec is translated to an additional sight distance of 75 ft. As depicted by the drawings and the standard design guides, most intersections of that kind might already have that additional sight distance. Perhaps it could be suggested therefore,

that all combinations will be allowed and where the grade requires the additional 150 ft — an appropriate warning sign might be posted.

Alternate approaches to allow the longer combinations without necessitating the 2.5 second concession were considered. Some of these approaches involved requirements for higher power to weight ratios (lower specific-power values). Such ratios could be achieved either by more capable engines or by limited weight caps under certain grade conditions. Other approaches involved performance classifications that, in addition to weight and power, also incorporate the length of the trucks. These approaches were found to be impractical, as they either demanded engine sizes that were too large, or they cut down truck size and weight so that they were no longer LCVs. Other considerations leading one to reject these approaches are that they might require complex, if not unfeasible, law-enforcing inspection methods.

Based on acceleration performance across an intersection, LCVs can be accommodated on Michigan's roadways, if a concession of 2.5 seconds is allowed and current highway design practices are used. Under these stipulations, no modifications would be required for the highway (with the exception of posting appropriate signs where needed). On the other hand, if safety concerns predominate policy decisions, then longer sight distance may be recommended for intersections intended for substantial level of LCV traffic.

3.3 Acceleration from Speed

Acceleration from speed is a performance mode that evaluates the capabilities of the truck in maneuvers such as passing or merging with highway traffic when leaving an entrance ramp. In the passing scenario, an inadequate level of acceleration might force the highway traffic to slow down significantly, causing unusual delays. On the other hand, an inadequate level of acceleration in the merging scenario might force the highway traffic to brake or deviate, therefore creating a hazardous situation.

Typically, a road section that has a continuous grade should be used as an appropriate site to evaluate trucks performance on a comparison basis. Being a relatively flat (as opposed to mountainous) state, such road sections are not commonly found in Michigan. The drawings that were supplied by MDOT support that observation, as they did not include any such site. In addition, since the distances involved with this type of acceleration maneuver are very long, the length of the subject truck becomes insignificant. For all practical purposes, acceleration related performance levels are determined solely by

combinations of weight and power. With these facts in mind, and in order to establish a comparison basis that is as pragmatic and as realistic as possible, two situations were addressed in evaluating this performance mode: the first involves actual trucks on an actual roadway section from the drawings provided by MDOT, and the other is generic, involving hypothetical long continuous grades and trucks that are represented by mere weight-to-power ratios.

The actual-situation study mode pertained to the scenario where a truck needs to merge with highway traffic after leaving an entrance ramp. Data used in simulating this scenario were taken directly from site drawings. Initially, four actual sites were intended to be addressed (see table 1). Because pertinent data were missing from some drawings, and the available data indicated similarity to other sites, only two sites were studied. The first site was departing Lakeview Drive from Jackson Road, merging with the eastbound traffic on I-94, and the second site was departing ramp I from Whittaker Road, merging with the westbound traffic on I-94. The grade at each of these locations is not constant. Initially it has an ascending trend, and then it either levels-off or even starts to descend.

Calculation results for each site were plotted as an accumulative portrayal of speed vs. distance for the combinations studied. As an example, figure 41 illustrates the results for the first site (Jackson Road). A comparison based on the distance to reach a certain speed (or the speed reached after some distance) was used to classify the performance levels of the different combinations. In each case, the initial speed was based on the posted speed of the ramp.

From a standpoint of the acceleration from speed, figure 41 shows that the tractor semitrailer configurations (both 48 ft and 57 ft) perform best. In that aspect, the triple is the slowest combination. When the specific-power values are considered, this observation can be rationalized: the semitrailers have 232 lb/hp, while the other combinations all have higher values. The points where the simulated trucks go through gear changing can also be easily observed in figure 41. Different power-to-weight ratios and subsequently, different acceleration capabilities result in different timing instants for switching gears.

During the initial stages of the acceleration (up to about 1,000 ft), all the trucks perform similarly. As they progress, a difference of approximately 5 mph is maintained between the fastest combinations (semitrailers) and the slowest (triple). Subsequently, the distance increases so that the fastest trucks attain a speed of 45 mph after 2,320 ft from entering the highway, while the triple needs an additional 1,000 ft to reach that speed. After 2,000 ft from the merging point, the semitrailers reach 44 mph (80% of an assumed 55 mph

highway speed), while the triple reached only 39 mph (71% of the highway speed). The computations for the other site (from Whittaker Road to I-94, not shown here) have similar results: a 5 mph speed differential between the semitrailers and the triple, and 1,000 ft more to get to 45 mph.

With these sites considered as representative ramp-to-highway situations, perhaps the conclusion might be that on an average, an additional 1,000 ft of merging lanes should be provided to maintain the current speed differential between merging and highway traffic. An alternative approach might be compromising larger speed differentials and posting warning signs, to provide only a shorter increase in acceleration lanes. Theoretically, adequate values of speed differential can be assured without lengthening merging lanes through imposing power-to-weight ratio requirements. However, that might be proven as impractical from both technical and law-enforcement points of view.

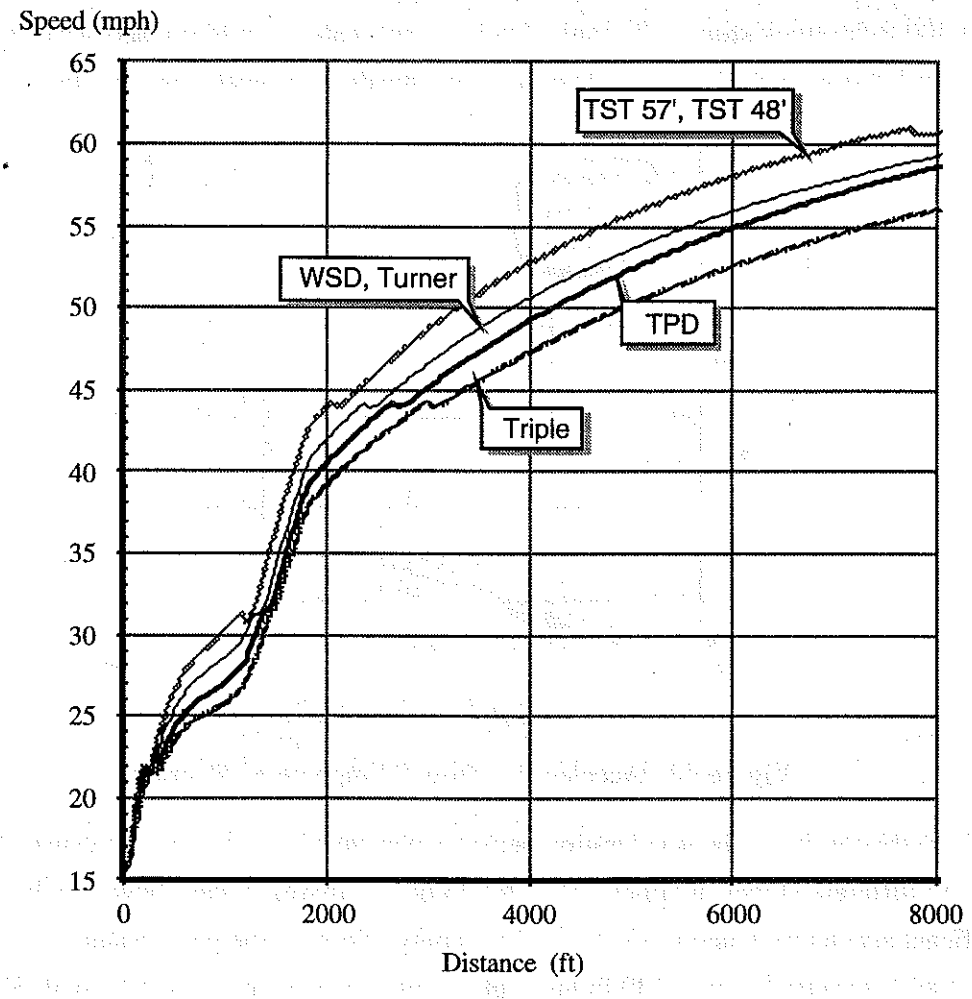


Figure 41. Acceleration from speed—Jackson Road to I-94 eastbound

The generic study mode used fictitious, infinitely long highway sections at various constant grades. The simulated trucks were also of a general nature, represented by specific-power values rather than as particular combinations. As previously discussed in section 3.2.2, the specific weight-to-power ratios of the various combinations were found to be 232, 242, 266, 299, and 327 lb/hp for the 48 ft semitrailer, the western double, the Rocky Mountain double, the turnpike double, and the triple correspondingly. For the purpose of this analysis, these variations were represented as three groups: 230, 265, and 300 lb/hp.

Performance levels of these generic trucks, as represented by the three weight-to-power ratios, were evaluated on level roads, and roads that had 2% and 4% grades. Calculation results were tabulated and then plotted as distances it took to reach certain final speeds from different initial speeds. Obviously, some of the trucks could not reach certain final speed as the specific-power values were too low. For example, figure 42 portrays the acceleration results from an initial speed of 22 mph on a 2% grade. In that figure, the line of the 300 lb/hp truck stops at 31 mph. Such a combination could not accelerate to a higher speed, and maintained 31 mph as its maximum, steady-state speed on this slope.

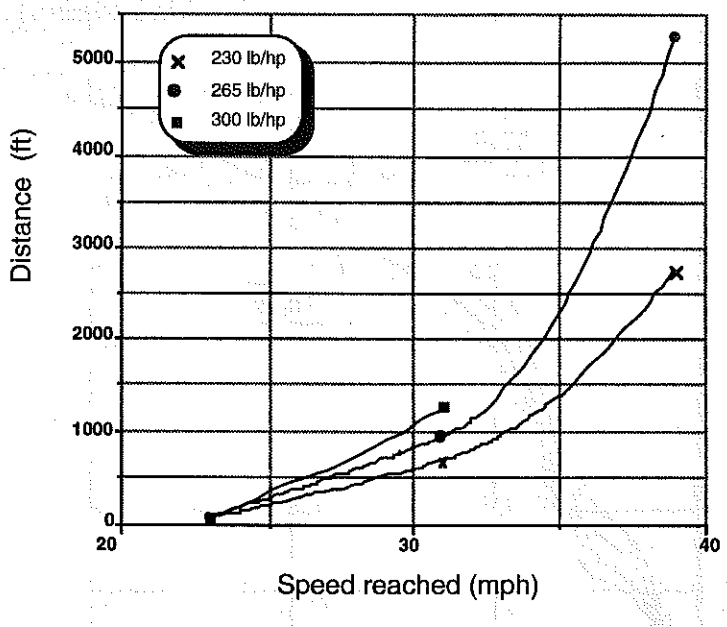


Figure 42. Acceleration from 22 mph on a 2% grade

From the results of the acceleration performance calculated for various power-to-weight ratios on different slopes, it appears that 265 lb/hp is a marginal case beyond which significant acceleration and speed limitations apply. Perhaps the performance level of the typical 48 ft semitrailer with 230 lb/hp might be used as a gauge. If trucks with 300 lb/hp are to perform at the level of trucks with 230 lb/hp, then the merging / acceleration lanes

need to be extended (if the grade is up to 2%). Specially designated lanes for slow moving traffic should be provided if the average steady-state grade is more than 2%. For a better assessment of grade and speed implications, the results of the next section should be considered.

An analysis to assess the required added length of the merging / acceleration lanes was performed. According to the performance measure suggested above, the analysis was based on the premise that 48 ft semitrailers have acceptable operating characteristics from the highway user's standpoint. It was assumed that the speed attained by a 48 ft semitrailer at the end of existing acceleration lanes, is sufficient. Even though the current roadway seldom allows current trucks to reach the desired speed for merging, the procedure developed here will aid in keeping the situation from becoming worse than it is now. Using the appropriate distance-to-speed tables in appendix C, the additional distance consumed by the 300 lb/hp truck to develop the same speed as the 230 lb/hp was computed. The results are plotted in figure 43 for an initial speed of 30 mph (appendix C contains information for other initial speeds). For example, consider a 30 mph ramp curve followed by a 1000 ft acceleration lane. At the end of the acceleration lane, a 48 ft semitrailer will obtain a certain merging speed. In order to enable a 300 lb/hp truck to attain a similar speed, the acceleration lane needs to be extended by 300 ft to a total of 1300 ft.

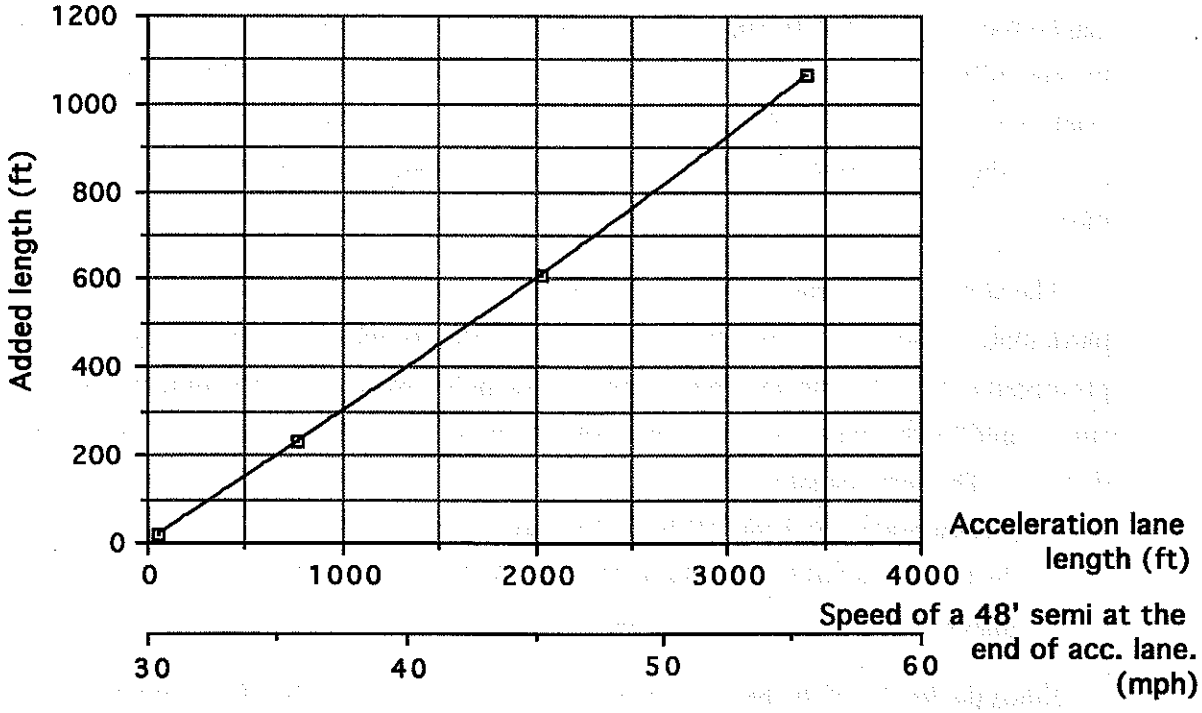


Figure 43. Added length for acceleration lanes

Heavy trucks take long distances to increase speed. A 48 ft semitrailer (230 lb/hp) requires 2720 ft to accelerate to 50 mph from 30 mph. A 300 lb/hp vehicle would take

3500 ft to reach 50 mph from 30 mph. The graphs on pages C-33 and C-35 in appendix C provide more acceleration lane length-to-speed information.

From these results, it can be observed that there is a linear relationship between the required lane extension and its current length. Calculations that were performed based on energy considerations supported that observation. The following equation represents the linear relationship between existing acceleration lanes length and an extension in length for LCVs:

$$\Delta L = 0.31 \cdot L$$

where:

L	is the length of the existing acceleration lane
ΔL	is the required extension for the acceleration lane

3.4 Maintaining Speed on Upgrades

On long, continuous, uphill roads, the speed of heavy trucks is usually bounded not by legal limits, but by their engine capabilities. Unless the road is at a severe grade, the rest of the traffic can maintain its normal highway speed. The combination of handicapped, slow-moving trucks and other vehicles moving significantly faster not only creates delays, but can be hazardous. Maintaining speed on upgrades is a performance mode that represents the capabilities of various trucks in keeping up with the other traffic without hindrance. If trucks are allowed to be driven in areas with long upgrades, but are not capable of maintaining a reasonable speed, then special slow-moving lanes should be provided for them.

The state of Michigan, in general, and the representative sites provided by MDOT, in particular, are not very demanding from a gradeability standpoint. None of the site areas portrayed in the drawing sets incorporated long, uphill slopes. For the purpose of this study, uphill slope values from the drawings were assumed to be continuous for a long distance. The selected sites were:

- working zone on I-94 / Willow-Run exit
- Jackson Road to I-94 eastbound (departing Lakeview Drive)
- Jackson Road to I-94 westbound

Since the length of the truck is not an influential parameter when speed maintenance capability is evaluated, a set of power-to-weight ratios similar to those in the previous section were used as representatives of the LCV population. Based on the selected sites,

the speed maintenance capability of these generic truck combinations on upgrades of 2% to 8% was computed.

When 55 mph highways are considered, a speed of 45 mph is usually the minimum accepted. On this premise, figure 44 was drawn. The figure depicts the distance it takes for the various lb/hp combinations to lose 10 mph when transitioning from traveling on a level road at 55 mph to different upgrade slopes.

Observing the plots in figure 44, it appears that when negotiating up to an approximate 2.5% grade, the different power-to-weight ratios have a significant impact on the distance it takes to slow down from 55 mph to 45 mph. As the grades become steeper, the distance differences diminish until they are completely negligible. Using figure 44 allows one to determine the maximum length of any given uphill slope before a special lane designated for slow-moving traffic is required. Naturally, for any such case, consideration should also be given to the remaining length of the slope. The resultant length of such a slow lane might be too short to be practical.

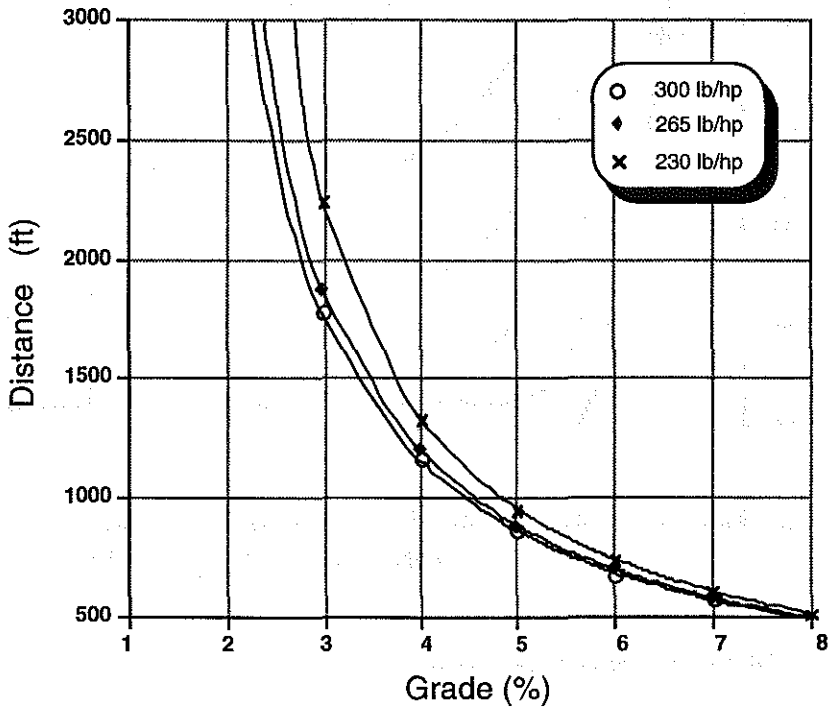


Figure 44. Distance to decelerate to 45 mph from 55 mph

Within the framework of this section, and for verification purposes, speed-distance data for the various power-to-weight combinations were computed on different upgrade slopes from an initial speed of 55 mph. An example plot is presented in figure 45. Sets of similar plots are provided in the appropriate section in AASHTO's "Green Book" [2]. The results of the computations as typically presented in figure 45, were found to agree with those of

the Green Book. Since they are not different than the traditional AASHTO considerations, issues of speed maintenance on upgrades, beyond the aspect illustrated by figure 44 will therefore not be discussed further.

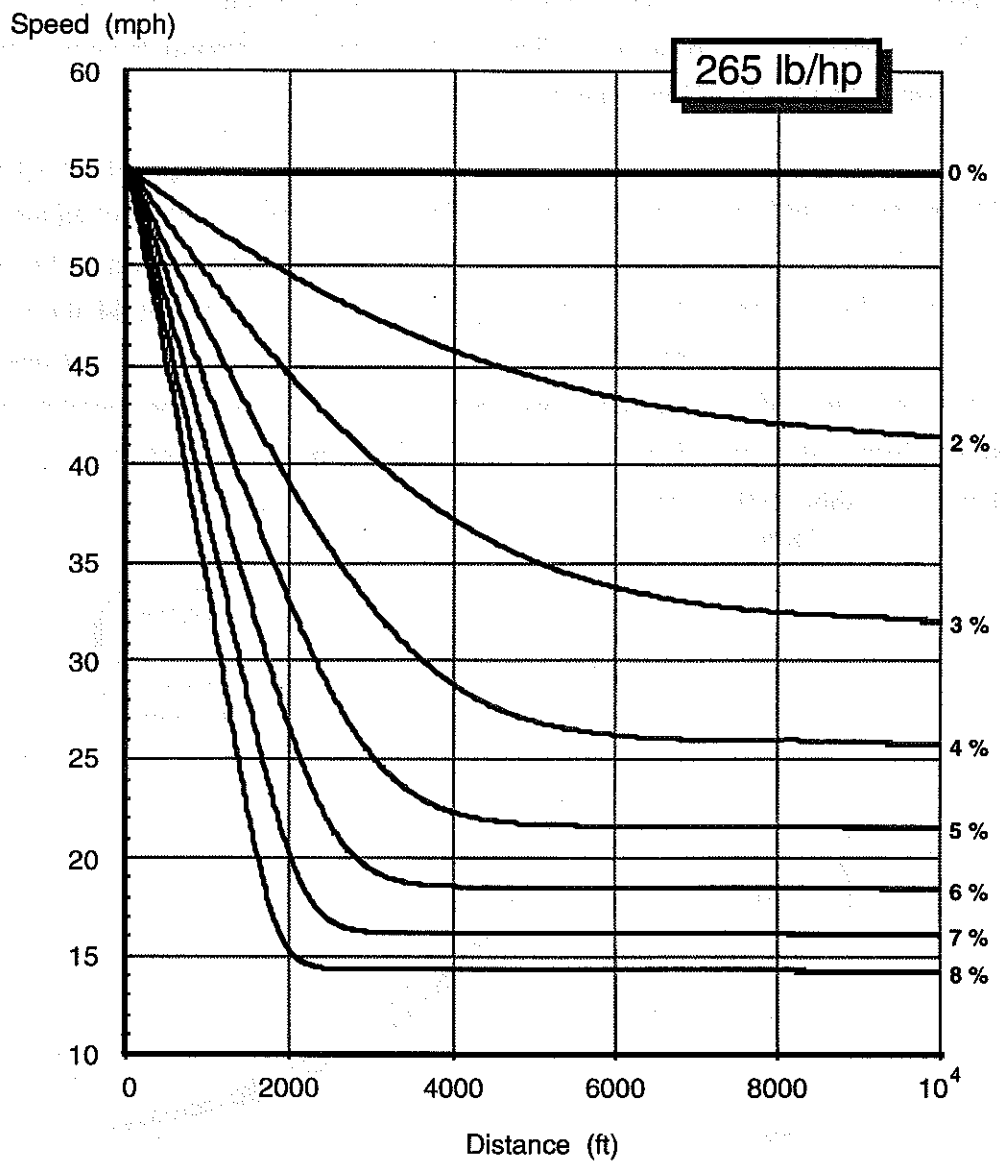


Figure 45. Speed and distance on grades for a 265 lb/hp truck

3.5 Passing-Sight Distance

Due to the nature of this performance mode, it was evaluated in this work and analyzed in this section in generic terms rather than site-related terms. The drawings that were provided are not useful for assessing the available sight distance at the various locations. Furthermore, the layout of those sites as portrayed in the drawings was old and outdated.

New objects that obstruct the view may have been introduced since the drawings were made, and others may have been removed. The potential impact of LCVs on passing-sight distance is therefore determined here solely by the length of the passing and pending vehicles and by their rate of speed.

No formal methods of assessment of passing-sight distance exists that considers the length of the vehicles involved. The primary official document that is currently used as a design guide to determine passing sight distance, is the AASHTO policy, known as the "Green Book." One of the deficiencies of this policy is that the length of passing or passed vehicles is not considered in the computations. The calculations are based on a "zero-length" vehicle. It addresses only passenger cars, and the influence of truck length cannot be assessed. A special method was devised to allow assessment of the influence of various truck lengths on passing-sight distance. Appendix D includes a detailed description of that method.

At the foundation of this method lies the premise that even though the roadways were designed and marked according to practices that do not count for vehicles longer than passenger cars, they successfully accommodate trucks. For the purpose of this study, the 60 ft truck was considered as a commonly accepted baseline, and computations were carried out using two methods. The results of the two methods (AASHTO's and the newly devised one) are listed in tables D-1 and D-2 in appendix D. The latter is considered the safer and more conservative of the two and is used here as the basis for the analysis.

The detailed scenario on which the hypothesis is based is portrayed in appendix D. Nevertheless, it is concisely described here for clarity. An assumption is made that at no time should the passing vehicle be positioned to the left of the solid stripe (no-passing line). The critical situation that determines the limits for a successful completion of a pass is when the passing vehicle barely returns to the right lane, beyond the passed vehicle, and just before the stripe begins. At this critical situation, an opposing vehicle traveling in the left lane has only a marginal safety clearance from the passing vehicle as it returns to the right lane. Since both the passing and the opposing vehicles are assumed to be traveling at the design speed, the distance covered by the passing vehicle while in the left lane is the same distance covered by the opposing vehicle in the same lane. Per this hypothesis, a safe passing-sight distance for a vehicle initiating a pass must be twice the distance it will cover while in the left lane.

As discussed previously, it is assumed that the current roadway markings can safely accommodate 60 ft trucks. The computations performed in appendix D pertained therefore

to the additional distance (when compared to passing a 60 ft truck) used by the passing vehicle in the left lane. Table 11 summarizes these results (it is a reproduction of table D-2). According to the passing scenario and the associated assumptions described above, the table entries are the additional striping lengths for the conditions indicated. The additional passing distance would be twice the value of the entries.

Table 11. Additional no-pass striping to allow for various truck lengths

Design Speed	**Length of vehicle being passed**		
	80 ft (1.3633 sec)	**100 ft** (2.1272 sec)	**120 ft** (4.0908 sec)
40 (58.7 ft/sec)	80	160	240
50 (73.3 ft/sec)	100	200	300
60 (88.0 ft/sec)	120	240	360
70 (102.7 ft/sec)	140	280	420

A sensitivity study revealed that variations in the parameters used in the calculations can significantly change the resulting passing-sight distances. Parameters such as the speed of the passing vehicle, speed of the passed vehicle, clearances at the start and at the end of the pass, and speed of the opposing vehicle all play an important role in determining the passing sight distance. They actually represent the driver's responses and behavior during the pass. Note that computations in this work were mostly based on assumed values for these parameters, but in a real life situation variations from the calculated results can be expected. Unless the road were to be redesigned and rebuilt, the available passing-sight distance would not change. The drivers on the existing road would be expected to judge whether they have enough distance to complete a pass before entering a no-passing zone. (It seems that a much more detailed evaluation of roads should be performed on an individual basis, to identify those sites which require additional restrictions.)

The issue of passing-sight distance involves policies and additional considerations that are beyond the scope of this work. Elements such as human behavior models and factors affecting decision making in the passing maneuver or newly established statistical data are essential to determine an appropriate method to set safe passing-sight requirements and road markings. A separate study that would address such issues might offer a more comprehensive and definite way to mark no-passing zones.

Perhaps a policy decision could be made as to an appropriate course of action with regard to increased no-pass striping, restricting access of various truck combinations, and acceptable levels of reduced traffic flow.

3.6 Rearward amplification

Rearward amplification is a stability issue that is unique to combination vehicles with more than one trailer. It is a performance mode that is aimed at evaluating the obstacle-avoidance capability of multitrailer vehicles. When the driver encounters an unexpected obstacle on the road ahead and initiates an evasive maneuver using a sudden steering input, the rearmost trailer develops a significantly higher lateral acceleration than the tractor. Rearward amplification is defined as the ratio between the lateral acceleration of the last trailing unit and that of the tractor (see figure 46). The more units in the combination, the more manifest the rearward amplification problem will be.

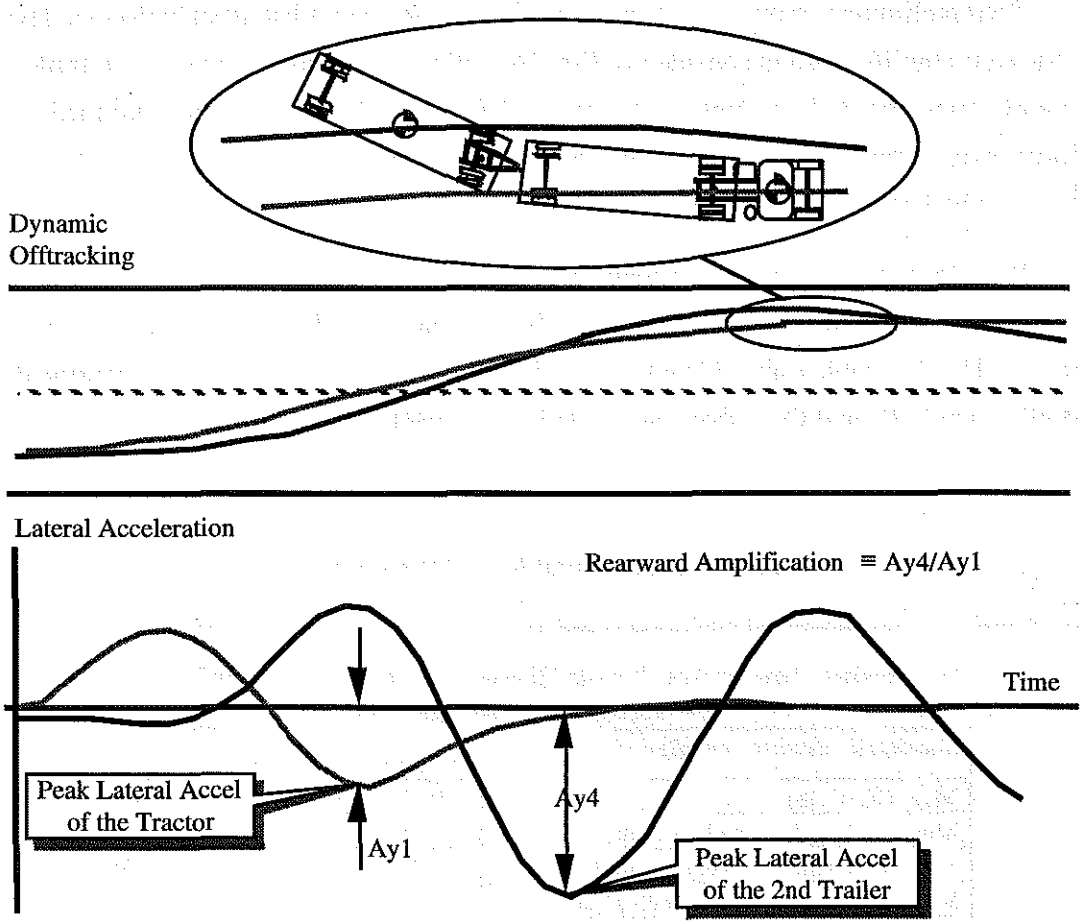


Figure 46. Idealized representation of the rearward amplification phenomenon

This "swinging-tail," or "whipping" phenomenon is further exaggerated when the units of the combination are relatively short. Cross winds and sometimes just high-speed straight forward motion can excite the rear trailer.

In highway traffic, truck combinations with poor rearward-amplification performance not only intimidate other road users, but they can also become a serious hazard. In the less severe cases, the "whipping tail" will consume more than one lane width, where in the more severe cases rollover might occur.

In a recent study, UMTRI investigated methods to test and screen heavy vehicles to ensure that they possess sufficient levels of safety-related performance measures [23]. The results of that study that pertain to rearward amplification are presented in this section. Based on the fact that the western double is currently legal nationwide, it was used in that study as the baseline vehicle. Its rearward amplification level of 2.0 was used as a measuring scale to determine acceptability of other LCVs.

Two preliminary requirements are specified for any candidate truck before its level of rearward amplification is considered: first, the rollover threshold of any single trailer in the combination should be at least 0.35g, and second, the vehicle should be equipped with radial tires. Such a rollover threshold requirement is not peculiar to LCVs and therefore will not be further discussed here.

With these two initial requirements assumed satisfied, screening tables were devised for five-, seven-, and nine-axle doubles (with both A- and C-dollies), and a seven-axle C-triple. The first table (table 12) addresses double combinations that use conventional A-dollies, while B- and C-doubles, and a standard C-triple are summarized in the second table (table 13).

Table 12. Screening for A-train combinations

Screening Summary Table Based on A-Train Configurations — Length Compensation —

Standard double configuration	*5 Axles*	*7 Axles*	*9 Axles*
Max. GCW (lb)	90,000	108,000	120,000
Min. box length of leading trailer (ft)	36	45	36
Min. box length of second trailer (ft)	36	27	36
Max. overhang of leading trailer (ft)	4	3	4

Table 13. Screening for C-train combinations

Screening Summary Table—Hitch Compensations
— Based on C-Dolly or B-Train Configurations—

Standard double configuration	*5 Axles*	*7 Axles*	*9 Axles*
Max. GCW (lb)	90,000	108,000	120,000
Min. box length of leading trailer (ft)	27	45	26
Min. box length of second trailer (ft)	27	20	26
Max. overhang of leading trailer (ft)	4	3	4

Standard triple configuration: Three 28 foot trailers,
3 foot overhang,
3 foot king-pin offset,
Max. GCW (lbs) 117,000

RA correction factor: 1.35

All the truck combinations considered in this study and portrayed in section 2.0 satisfy the requirements presented in these tables. The western double passes the screening test a priori, as its rearward amplification value of 2.0 was set as the limiting value. Nevertheless, one should notice that the five-axle double listed in table 12 weighs 90,000 lb, which is 10,000 lb heavier that the western double. From the standpoint of rearward amplification, if such weight is to be allowed, then the minimum length of the trailers should also be set to 36 ft (instead of 28 ft). Similarly, the Turner truck portrayed in section 2.0 has two 34 ft trailers, while table 12 calls for trailers not shorter than 36 ft. But the Turner truck of this study is only 104,000 lb, while the nine-axle double in table 12 is 120,000 lb The turnpike double, the Rocky Mountain double, and the triple combinations are all within both weight and length limits as depicted in the rearward amplification tables. It should be emphasized, though, that the triple as tested and approved by rearward amplification criteria was equipped with C-dollies. While the type of hitching used in multitrailer truck combinations was not crucial for other performance modes, it is most significant when rearward amplification is considered.

4.0 SUMMARY AND RECOMMENDATIONS

Several long combination vehicle (LCV) configurations were studied to evaluate the effect of large trucks on traffic safety and operations. Various truck combinations were simulated to operate under conditions representative of Michigan roads. Each configuration was evaluated for various performance modes (operating situations), and the simulation results were analyzed. Summaries of the findings are presented here, classified per the different performance modes, with concluding recommendations.

Offtracking in intersections

Analysis of the offtracking performance mode (also valid for offtracking in U-turns and on ramps) was made under the following assumptions:

- No encroachment onto a lane of the opposing traffic is allowed.
- If needed, the truck can use of the whole width of the lanes designated for travel in the same direction, even if it's more than one lane.

By applying the no-encroachment limitation, the cost of allowing all the truck combinations on these roads is represented in terms of added pavement, or "retracted" curbside due to offtracking. Figure 47 (a repeat of figure 16) depicts the added pavement area required at each site studied, to allow the various truck combinations. One can see that even the commonly used 48 ft tractor-semitrailer requires added pavement in most of the cases. This phenomenon prevailed in most other instances that were studied: the baseline truck combination does not always fit the existing roadway. However, its performance level was used to scale and evaluate how well other combinations might be accommodated on Michigan's roads. Due to the nature of this performance mode, it is very site-specific. For each configuration the combination of curb radius, width of starting lane, width of ending lane, and the angle of turn will result in a unique swept path. An analytical extrapolation of the results from one site to another is not feasible. The sites studied in this work were considered as typical and representative only; any different scenario for which offtracking performance might be marginal should be calculated separately.

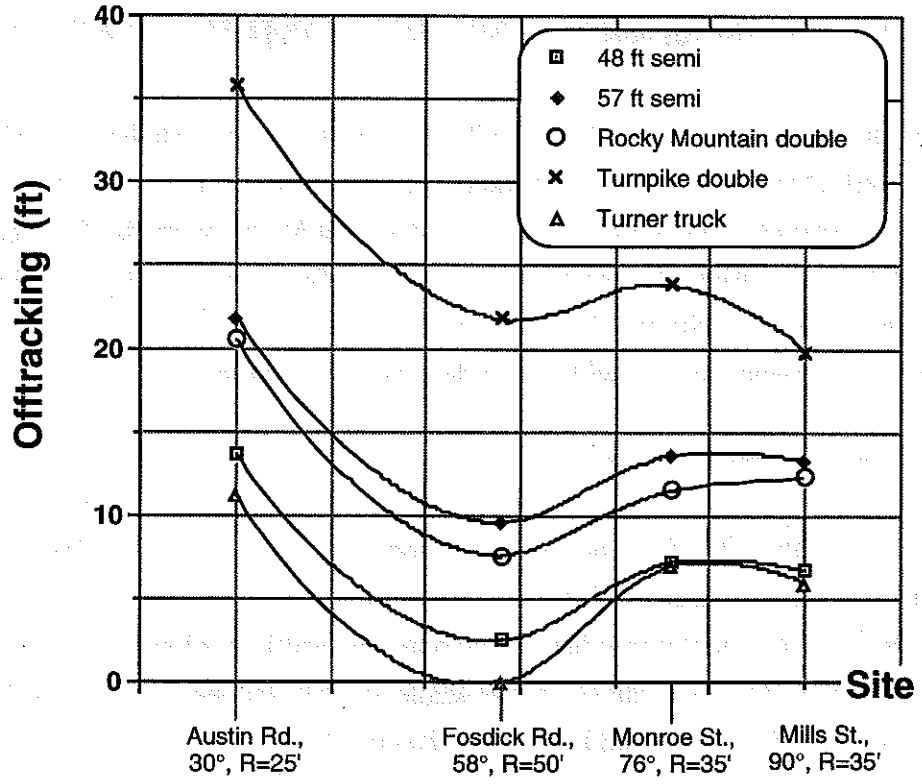


Figure 47. Additional paved area

Recommendations

Based upon the findings of this study, the Turner type of double can operate within the same intersection geometry as that required for a 48' tractor semitrailer. The other types of LCVs would require additional paved area at intersections. Since many intersections have unusual geometry, turning templates are a straightforward means for analyzing specific intersection-vehicle combinations.

Offtracking in U-turns

U-turns, or crossovers, as they are defined in the standard design guide, were considered in conjunction with two median widths: 85 ft and 65 ft. Both layouts had an opening of 30 ft in the medians, with a circular shaped curb. From the offtracking calculations, it was evident that the descending portion of the curb (to the left of the apex) caused most of the interference with the swept path. An elliptical geometry (or a combination of circular curves of different radii) would provide a better clearance to the turning truck. Offtracking and the subsequent modifications to the design of U-turn sites

were evaluated in terms of (1) increased opening, and (2) width offtrack. The latter helps define the elliptical geometry (see figure 48). Section 3.1.2 lists the assumptions used with regards to the way the turn is performed.

For the narrow median, the Rocky Mountain double, 57 ft semitrailer, and turnpike double were not capable of negotiating the turn while keeping off the curb. The 48 ft semitrailer, western double, Turner truck, and the triple combinations did not track off the pavement. At the wide median, only the 57 ft semitrailer and the turnpike double had an offtracking problem. Again, with the 48 ft semitrailer considered as the limiting configuration, the Turner truck and the triple combinations might also be allowed.

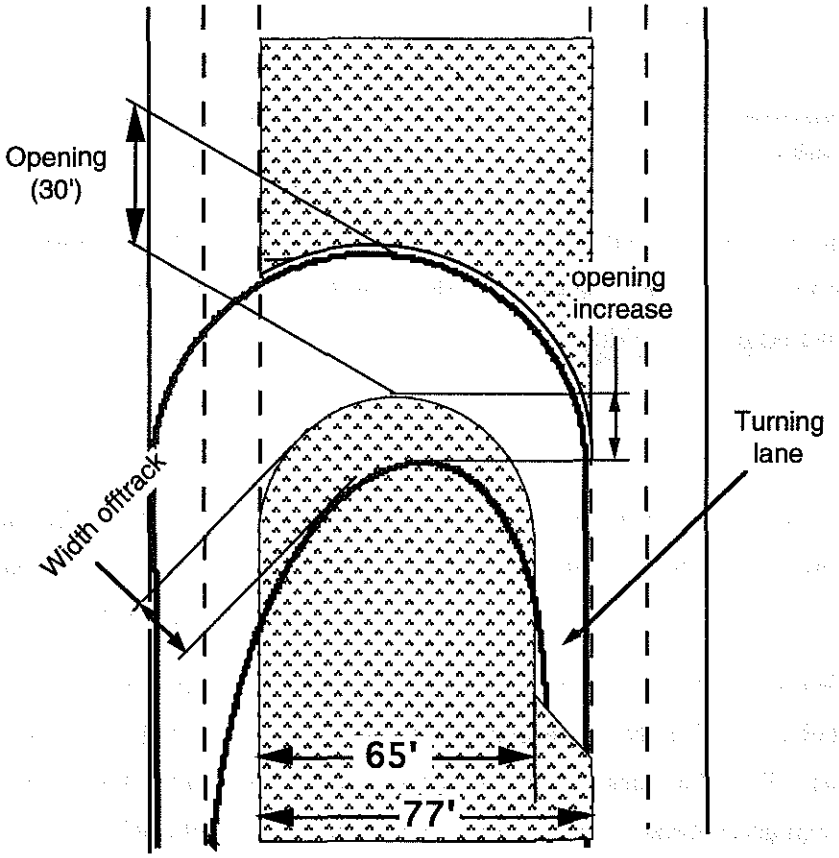


Figure 48. Offtracking dimensions in a U-turn

The opening increase and the width offtrack results are presented in table 14. These are the design modifications required by the various combinations to allow them an unobstructed U-turn.

Table 14. U-turn modifications

Truck combination:	48 ft semitrailer	Western double	Turner truck	Triple	Rocky Mountain double	57 ft semitrailer	Turnpike double
Narrow median (65 ft) or 77' with an auxilliary lane							
Opening increase	—	—	—	—	1.2	2.8	14.6
Width offtrack	—	—	—	—	2.8	7.2	16.3
Wide median (85 ft) or 97' with an auxilliary lane							
Opening offtrack	—	—	—	—	—	—	6.5
Width offtrack	—	—	—	—	—	2.1	9.0

Recommendations

U-turn, or crossover, sites may need to be modified to accommodate heavy trucks. The needed modification depends upon the vehicle types to be allowed. Table 14 gives approximate additional widths.

Offtracking on ramps

Offtracking on access ramps is not expected to be a limiting factor for any combination among those studied here. With 16 ft as the current ramp width, no additional paving is required.

A different situation exists when the ramp is not of a clover-leaf type. Entering the ramp in such a case involves negotiating what is referred to in this work as a *transition intersection* . With the exception of some tight sites, most such intersections that were evaluated can accommodate the various combinations without posing an offtracking problem. It is especially true when the intersections are 90 deg turns that were built in accordance with the standard design guide (e.g., "rural ramp terminal").

A complete set of offtracking templates for each combination performing 90, 120, 150, and 180 deg turns were drawn to scale, and they are provided in the main body of the report.

Recommendations

Routes for LCVs do not have to be constrained because of design features of access ramps built in accordance with the standard design guides. However, offtracking templates should be used to check ramp terminals and cross-roads on a case by case basis.

Acceleration across an intersection

Three-way and four-way intersections were considered within this performance mode. In most cases, both types of intersections are capable of accommodating any LCV evaluated here without posing an acceleration-related problem. Those predicaments where a conflict does exist might be resolved by a limiting factor of 2.5 seconds additional sight distance (over that recommended by the appropriate design guides). That is, in order to allow trucks such as the turnpike double, sight distance requirements that were used as design guides for any particular junction (four-way or three-way) should be extended by 2.5 seconds. It appears that in most cases that added distance is already provided. The increased eye height of truck drivers should be considered in assessing situations where a vertical requirement limits sight distance. For those sites where such a modification is not feasible, perhaps an appropriate warning sign might be posted.

Recommendations

Routes for the longer, heavier LCVs (turnpike doubles, Rocky Mountain doubles, and triples) need to be changed to insure that there is an additional 2.5 seconds worth of sight distance available for crossing intersections. These vehicles may not be suitable for operation at rural intersections on high-speed roads with limited intersection sight distance.

Acceleration from speed

In the context of this work, this performance mode evaluates truck acceleration capabilities for merging with highway traffic when leaving an entrance ramp. By nature, such a highway-related maneuver extends over a long stretch of road. As the length of the truck becomes insignificant in this performance mode, and only its weight and power play a meaningful role, generic trucks were used. Three such trucks were evaluated: 230, 265, and 300 lb/hp.

Weight-to-power ratio of approximately 265 lb/hp was identified as marginal. Significant acceleration and speed limitations will apply to trucks with higher ratios.

Perhaps the performance level of the typical 48 ft semitrailer with 230 lb/hp might be used as a gauge. If trucks with 300 lb/hp are to perform at the level of trucks with 230 lb/hp, then the merging / acceleration lanes need to be extended per figure 43, or per its analytical representation by following equation:

$$\Delta L = 0.31 \cdot L$$

where:

L is the length of the existing acceleration lane

ΔL is the required extension for the acceleration lane

It should be noted that both figure 43 and the above equation are valid for grades up to 2%. Grades higher than 2% were not considered as the 300 lb/hp truck cannot sustain any speed appropriate for normal highway travel on them. Specially designated lanes for slow-moving traffic should be provided if the average steady-state grade is more that 2%. For a better assessment of grade and speed implications, the results of the next section should be evaluated at the same time.

Recommendations

The findings of this study indicate that acceleration ramps need to be lengthened if heavy trucks are to be allowed to operate with more than 230 lb/hp. To accommodate LCVs, if vehicles with 300 lb/hp are allowed to operate on particular routes, the acceleration lanes on these routes need to be lengthened per figure 43 or as computed by the equation above. This means that those sections of enterance lanes in which heavy trucks accelerate would be 1.31 times longer than they are now.

Maintaining speed on upgrades

Maintaining speed on upgrades is a performance mode that represents the capabilities of various trucks in keeping up with the other traffic without hindrance. Similar to the previous section, three generic trucks were used to evaluate this performance mode: 230, 265, and 300 lb/hp.

It appears that 300 lb/hp on grades of up to 2% can be used as a limit: trucks with ratios up to this value might be allowed with only minimal traffic obstruction, while trucks with higher values might significantly hinder traffic flow. For grades that are steeper than 2%,

the grade / length combination should be evaluated to determine whether a special lane is required.

Recommendations

For routes with upgrades of no more than 2%, vehicles with 300 lb/hp or less may be allowed with minimal traffic obstruction. For grades steeper than 2%, the need for climbing lanes and accompanying restrictions on weight-to-power ratios for vehicles should be evaluated on a case by case basis.

Passing sight distance

There is no generally accepted procedure to assess passing sight distance while accounting for the length of the vehicles involved. The primary official document that is currently used as a design guide to determine passing sight distance is AASHTO's "Green Book," but the length of passing or passed vehicles is not considered. A special method was devised for the calculations of this work. At the foundation of this method lies the premise that even though the roadways were designed and marked according to practices that do not account for vehicles longer than passenger cars, they successfully accommodate trucks. A 60 ft truck was considered as a commonly accepted baseline in this work.

Table 15 below depicts the additional striping lengths (over the existing markings) for the conditions indicated. The additional passing distance would be twice the value of the entries. As the results are very sensitive to speeds and clearances used, it is recommended that a policy decision be considered, which concerns the appropriate course of action with regard to increased no-pass striping or restricting access of various truck combinations.

Table 15. Additional no-pass striping to allow for various truck lengths

Design Speed	**Length of vehicle being passed**		
	80 ft (1.3633 sec)	**100 ft** (2.1272 sec)	**120 ft** (4.0908 sec)
40 (58.7 ft/sec)	80	160	240
50 (73.3 ft/sec)	100	200	300
60 (88.0 ft/sec)	120	240	360
70 (102.7 ft/sec)	140	280	420

Recommendations

There is a need for a national policy on the additional passing distance required to accommodate heavy trucks. This policy should consider the demand for trucking along the route, the traffic delays involved, and the safety requirements for increased lengths of no-passing zones. Perhaps this policy should be the focus of an area of research supported by AASHTO.

Rearward amplification

Rearward amplification is a performance mode that can be used to quantitatively evaluate the obstacle-avoidance capability of multitrailer vehicles (doubles and more). With the western double used as a baseline, its rearward amplification value of 2.0 was set as a target. Trucks not exceeding that level will be capable of avoiding unexpected road obstacles in a manner that is at least as controllable as that of the western double. Tables with reference weights and dimensions for various multitrailer truck combinations are provided in section 3.6 of this report to be used as guidelines to ensure satisfying such rearward amplification requirement.

Recommendations

It is recommended that if triples are to be allowed, they will be required to be equipped with C-dollies. It is also recommended that if shorter trailers than those specified in table 12 are allowed for doubles, the use of C-dollies will be required. In any case, use of trailers that are shorter than those prescribed by table 13 is not recommended.

5.0 CONCLUSION

Conceivably, freeways and limited-access highways are capable of accommodating all the truck combinations that were studied here. However, a more careful evaluation on an individual basis might be desired where long grades of more than 2% exist. Also, ramp terminals and intersections may pose problems.

Under urban traffic conditions, it appears that the Turner is the optimum geometric size truck for minimizing any roadway changes. Results of a cost-benefit analysis indicate that allowing other combinations will require some changes in the infrastructure. The benefits of a combination are considered as the added payload weight and added cargo volume relative to an 80,000 lb western double. Costs are the highway changes needed to accommodate that combination. Table 16 below concisely summarizes the benefits and the associated costs for the various combinations. A general cost that is common to all LCVs and is not depicted in table 16 is the cost of special lanes which should be provided for slow-moving traffic on continuous grades of more than 2%.

Table 16. Allowing LCVs in Michigan — Costs and benefits

Truck combination type	**Benefits** *Increase in cargo-*		**Costs** *Required changes to the highway-*		
	Payload *(lb)*	Volume *(ft^3)*	Added pavement in intersections *(ft^2)*	Added opening of medians (U-turns) *(ft)*	Added no-pass striping *(ft)*
57' Tractor-semitrailer	4080	77	≈ 150	≈ 8	None
Turner truck	15140	918	None	None	≈ 110
Turnpike double	32540	3060	≈ 350	≈ 15	≈ 330
Rocky Mountains double	19105	1530	≈ 75	≈ 5	≈ 220
Triple	31750	2142	≈ 50	None	≈ 220

APPENDIX A

LITERATURE REVIEW

This appendix provides a condensed review of the state of knowledge concerning the influences of the safety and operations of longer combination vehicles (LCVs) on issues associated with highway policy, planning, design, and operation. The discussions on the state of knowledge are based upon work that UMTRI has performed in the past, a preliminary examination of an ITE Informational Report entitled "Geometric Design and Operational Considerations for Trucks," [1] and the other literature referred to in the bibliography.

The principal results presented here pertain to the work done in task 1 of this study. In addition to reviewing the state of knowledge, the goals of task 1 were to identify (1) candidate truck combinations that will represent the current types of LCVs either already in service or being considered for service and (2) the performance situations that need to be evaluated in order to determine acceptable vehicle sizes for each category of LCV. This appendix contains a listing of vehicle types that were considered, with the supporting statistical data and the performance modes that were identified.

In the context of this study, an acceptable vehicle is one that can be safely accommodated with minimal effect upon traffic operation. An optimum vehicle size may depend upon geometric changes in the highway that are required to accommodate LCVs. There is a tradeoff between the amount of productivity a vehicle provides and the costs associated with the use, durability, and modification of the roadway infrastructure. This appendix summarizes the work that needs to be done with regard to safely accommodating LCVs, in terms of three types of activities: (1) evaluations of vehicle performance characteristics at Michigan highway sites, (2) evaluations based upon previous research, and (3) subjects that need to be addressed but which are beyond the resources (time and money) available to this study.

The next section provides a background which puts this study in the context of an overview of how the truck transportation system evolves and a list of issues concerning heavy trucks and highway design. Then subsequent sections describe the vehicle types selected and discuss the performance situations to be addressed in this study.

Overview of the context of the study

This study pertains to a small piece of the overall system that acts in developing truck transportation. Figure A-1 is a characterization of a part of the overall system. The system is envisioned as operating as follows. Size and weight policies are established. Then truck designers (assemblers, specifiers, etc.) plan vehicles that will be productive and meet the rules in the policies. In a parallel effort, highway designers build roads using highway design policies that employ design-vehicles including trucks. To some extent the highway

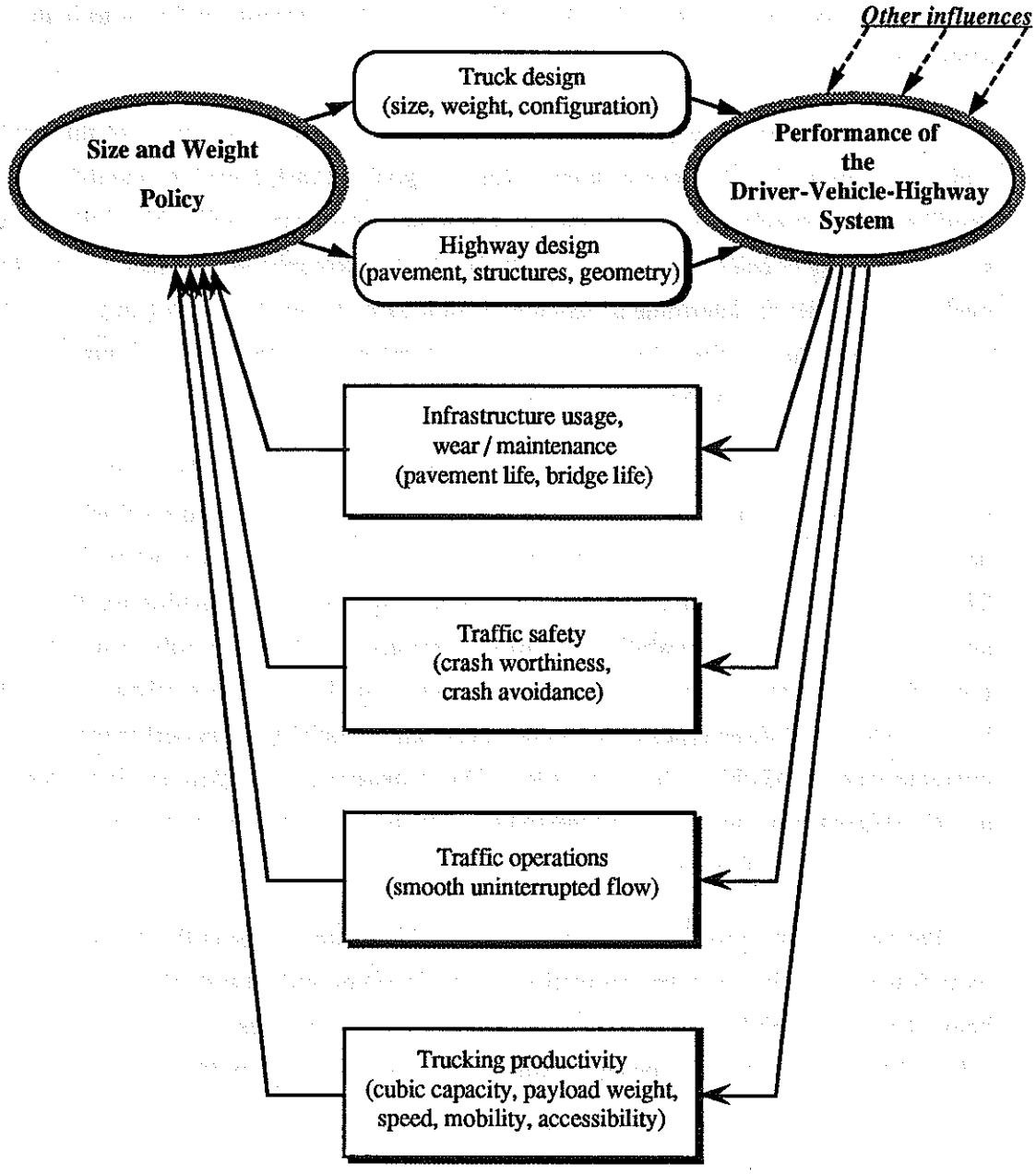


Figure A-1. An overview of the evolution of the truck transportation system

and vehicle designers work independently (within the rules). However, truckers may observe that, if some length or weight restriction could be relaxed a little bit, they could assemble vehicles that would serve their needs more efficiently and more profitably. In that case, highway designers may be asked by policy-makers if it would not be alright to relax the rules. In this way, a feedback process is started and the size and weight policies are re-examined.

The diagram (figure A-1) shows feedback mechanisms through which the performance of the system is evaluated. In addition to trucking productivity, there are feedback mechanisms involving traffic operations, traffic safety, and infrastructure preservation. The trucking community continuously strives to be able to carry more goods to more places at a higher speed. The weight and volume of traffic moving on a road cause wear and accumulated damage to the infrastructure. Pavements and bridges need to be replaced or rehabilitated. The users and designers of the highway are concerned with safety and they know that crashes involving trucks tend to have severe consequences. The users and designers of highways are also concerned with smooth, pleasant trips to allow people, goods, and equipment to reach their destinations without untimely delays. These evaluations may influence policy and hence start another development cycle involving new trucks and possible needs for changes in highway designs.

Here are some subjects where truck and highway designers might work together to develop a better system for highway transportation of goods and services. These subjects derive from traffic and safety issues primarily. However, they have infrastructure usage and trucking productivity aspects in terms of costs and benefits.
(Note: The page numbers (for example, pp. 12-17) refer to the ITE report listed as reference [1]. References to other reports in the bibliography are indicated by square brackets.)

(1) low speed offtracking at intersections and tight ramps (pp. 12-17)
(2) acceleration from a standing start (transit time across intersections) (pp. 17-19), [2], [3], [4]
(3) sight distance for crossing an intersection or turning left (p. 51), [3], [4]
(4) sight distance along railroad tracks (pp. 55-58), [3], [4]
(5) acceleration from an initial to a final velocity on an entrance ramp (traffic merge compatibility)
(6) maintaining speed on upgrades (pp. 39-41), [2], [5]
(7) passing-sight distance for being passed and passing on two-lane roads (p. 66), [2], [5]

(8) median opening and U-turns (p. 51), [2], [5]
(9) roll stability on ramps (superelevation, radius, side friction, velocity) (pp. 23, 28-31), [6]
(10) high-speed offtracking on ramps (curbs, lane widening and width) [5], [7], [13]
(11) friction demand at intersections (low-speed, tight turn on a slippery surface) [5],[7]
(12) yaw stability and directional control on turns and curves on the highway (p. 25), [7], [20], [22]
(13) speed control on downgrades [14], [18], [19]
(14) obstacle evasion at highway speeds (rearward amplification, alternative hitch devices, backing up) (p. 23), [6], [7], [15], [21]
(15) rear-end crashes due to speed variations [8]
(16) traction for low speed mobility on slippery surfaces [7], [11]
(17) stopping sight distance for horizontal and vertical curves (pp. 20-22, 33-38), [2], [4], [9]
(18) decision sight distance for signalized intersections (p. 63), [2], [4]
(19) deceleration from an initial velocity to a speed appropriate for an exit ramp (p. 47), [6], [9]
(20) effects that pavement rutting has on directional stability
(21) implications for safety imposed by a negative superelevation at the outside shoulder of highway ramps (cross slopes) (p. 44)
(22) performance of multiaxled vehicles in offtracking, obstacle avoidance, and friction demand situations
(23) various scenarios of merging
(24) effects of LCVs on traffic flow (p. 59)
(25) impacts on design and operations in work zones (p. 69-71)
(26) sign visibility

Clearly, pavement- and bridge-loading issues need to be considered in resolving costs and benefits. The Turner truck study [11] is an example of an attempt to improve productivity while preserving the infrastructure. The principal idea behind the Turner truck is that you can have more productive trucks that do less pavement damage if you have more lightly loaded axles. (The Turner idea is like the weight and axle loading rules that have been in effect in Michigan for many years.)

Truck designs selected

Review of technical and statistical information concerning the variety of heavy-duty trucks used in the U.S. reveals a considerable number of truck configurations. Nevertheless, by examining the various combinations (excluding the oddball ones), certain combinations can be identified and categorized as distinct types.

For the purpose of this study, the pertinent truck designs are classified as (1) STAA vehicles, (2) LCVs in use, and (3) Optimization type LCVs. The different types are portrayed in figures A-2 through A-4. Length and weight dimensions specified for the various truck combinations are based on statistical data from TIUS [10], 1980-1986 TIFA and NTTIS [16], [17], FHWA studies (e.g., [5]), and design vehicles used in AASHTO's "Green Book." The dimensions for the optimization type LCVs are based on the Turner truck study [11]. The following items provide further definition of the selected vehicle types.

1. STAA type — Configuration options allowed by the Surface Transportation Assistance Act. These configurations are a 48' tractor-semitrailer and a double with twin 28' trailers, commonly known as the western double (see figure A-2). As these combinations are allowed nationwide, the STAA vehicles will serve as reference points for evaluating the safety-related and operational performance of other types of LCVs.

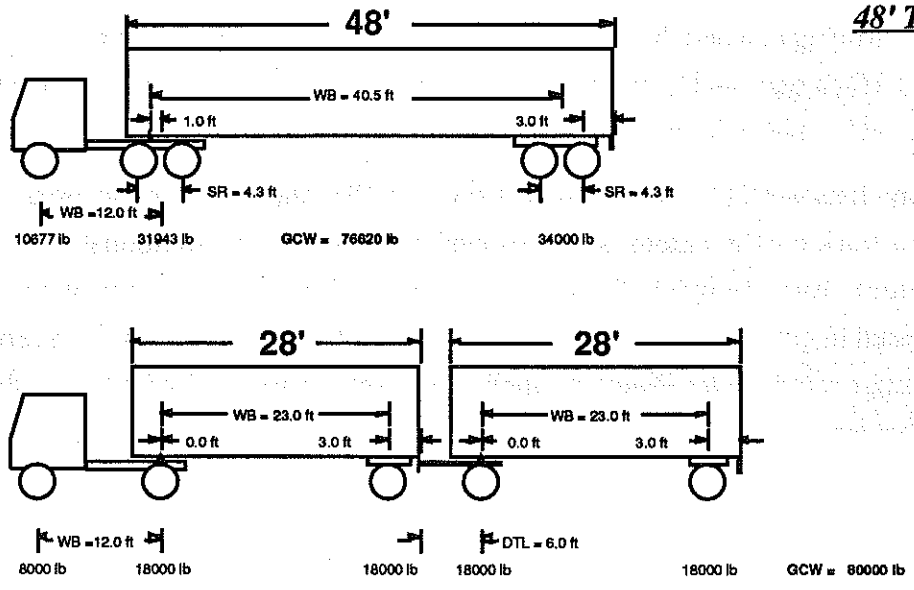


Figure A-2. STAA type vehicles

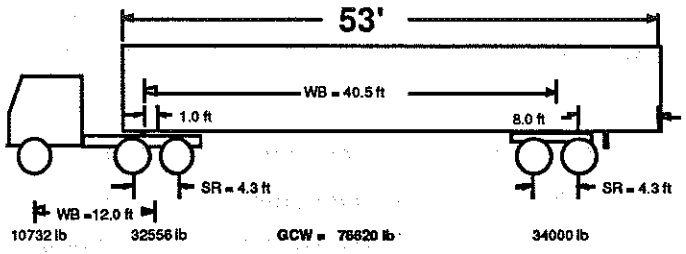
2. LCV type — Longer combination vehicles might be defined as commercial vehicle combinations that, due to length, are subjected to operational restrictions and limited to certain road types. Under the present regulations, they typically require a special permit. Based on the data sources listed above, LCVs in use encompass a few popular, well defined configurations (see figure A-3). In this study, the following configurations will be considered: 53' and 57' tractor-semitrailers, a Rocky Mountain double, a turnpike double, and a triple.

As implied by the name and the above definition, the pertinent mechanical properties that distinguish LCVs from the other types of commercial vehicles, are primarily associated with length. These properties are identified as follows:

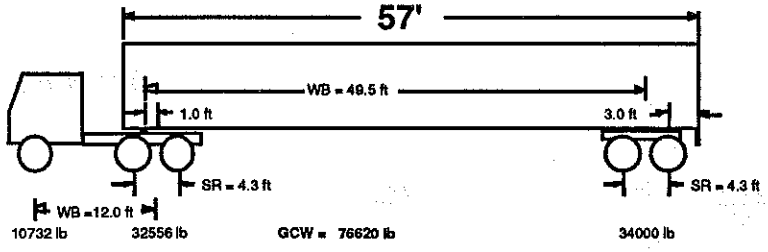
A. Number of units — One of the LCV configurations is a triple, where three trailers are attached to the leading tractor.
B. Unit lengths — Semitrailers might be significantly longer than what is commonly used and regulated.
C. Overall length — Due to longer and/or additional units, the overall length of the LCV is increased (hence, the name).
D. Overhang length — The distance between the rearmost axle of each unit and its rear end is an important factor, more so in LCVs than in the standard commercial vehicle configurations.
E. Number of axles and spacing — It might be expected that operators will be motivated to mount additional axles under the longer units in places like Michigan where heavier gross combination weights are allowed.
F. Hitch type — The use of innovative dollies with special hitch arrangements offer means for improving the performance of LCVs.

In a previous work [5], Fancher and Mathew studied the safety implications of various truck configurations, as determined by the above and additional mechanical properties. Even though LCVs in use were not evaluated in particular, it was suggested in general that when the issue of longer trucks is considered, pavement and bridge related rules should be applied, and rules associated with length should be considered.

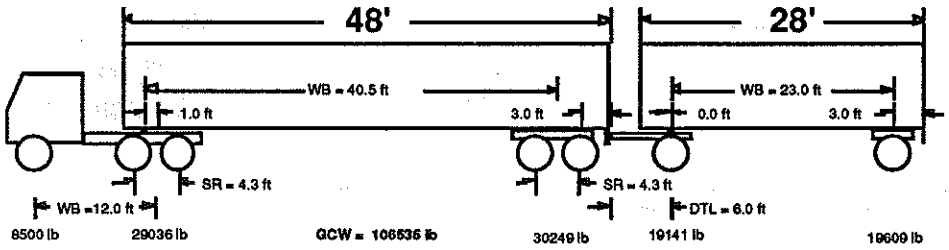
53' Tractor-Semitrailer



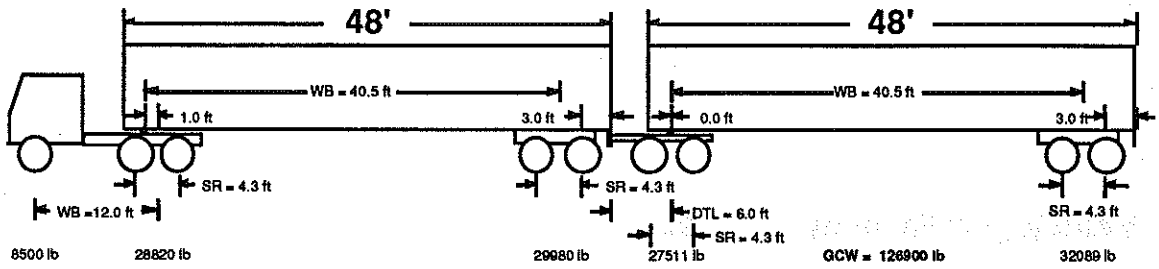
57' Tractor-Semitrailer



Rocky-Mountain Double



Turnpike Double



Triple

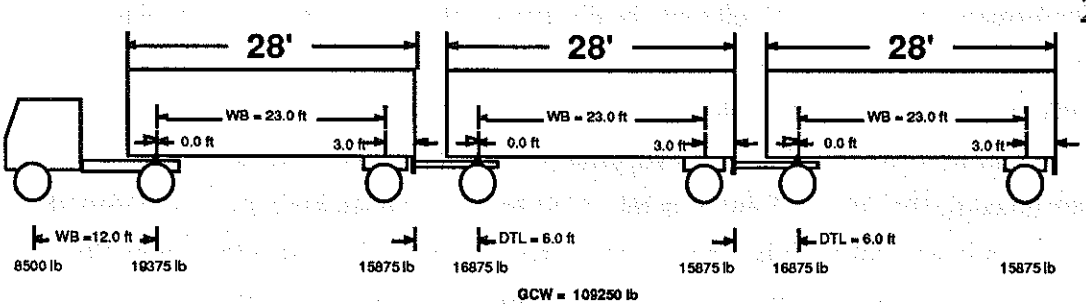


Figure A-3. LCVs-in-use

3. Optimization type — Truck configurations which are longer and bigger than those approved by the STAA, and therefore might be classified as LCVs (see figure A-4). These are proposed vehicles that are intended to optimize productivity and safety, while making efficient use of the roadway infrastructure. For the purpose of this study, the Turner truck (twin 34' trailers with tandem axles) and a similar combination with single axles will serve as representatives of this type.

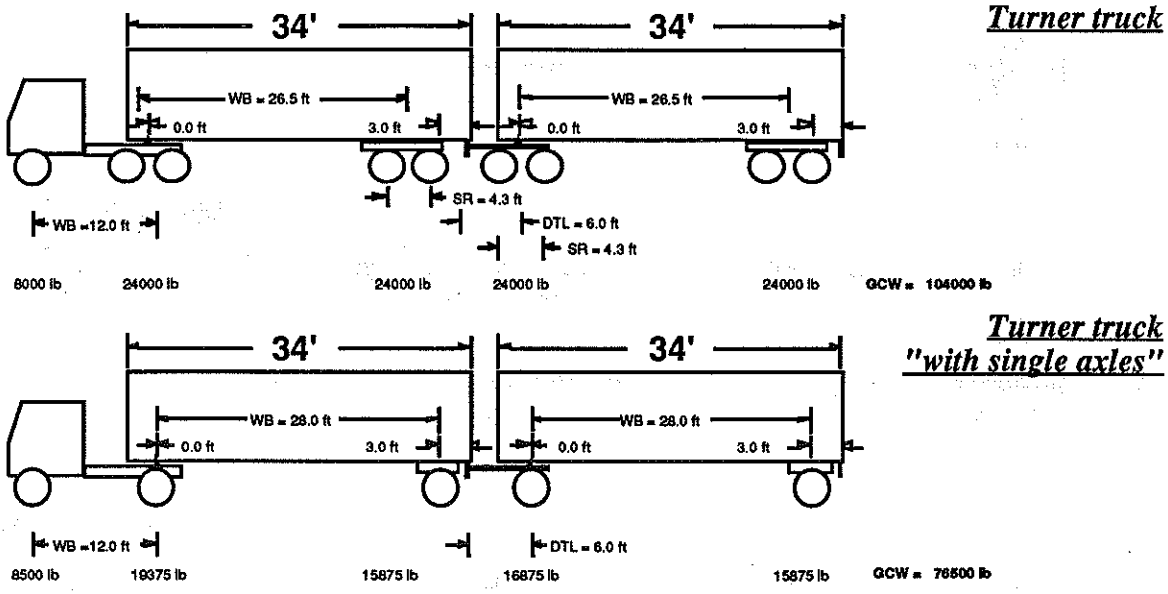


Figure A-4. Optimization type LCVs

Vehicle performance modes

Performance modes of vehicles can be classified into three categories associated with (1) traffic safety, (2) traffic operations, and (3) mobility. Traffic safety pertains to the dynamic characteristics of the vehicle and its crash-avoidance capabilities. Traffic operations deal primarily with those properties that are associated with smooth uninterrupted traffic flow. Mobility is related to traction and backing up. It involves the ability to get in and out of tight places without getting stuck. To assess the compatibility between the vehicle and the roadway, all three categories should be evaluated.

In general, the different performance modes that should be considered under each of the three categories specified above are:

Traffic safety	• Static roll stability • Dynamic roll stability • Obstacle evasion (rearward amplification) and alternative coupling devices • Braking performance and brake timing • High-speed offtracking • Path-curvature gain (cornering at highway speeds) • Directional stability and transient response to steering
Traffic operations	• Low speed offtracking (intersection turns, maintaining the vehicle within lane boundaries) • Power requirements (acceleration and merge maneuvers, maintaining speed on upgrades) • Braking requirements (deceleration going into curves on interchange ramps)
Mobility	• Backing up and the influence of alternative coupling devices • Traction on slippery roads • Friction demand in tight turns

Traffic Safety

In many ways the safety properties of LCVs are similar to those of other heavy trucks. In a recent study, UMTRI developed testing and screening procedures for certifying the static roll and obstacle evasion performance of longer and heavier vehicles [15]. Specifically, a rollover threshold of 0.35g was selected as the performance target for static roll performance (such as that measured in a tilt-table test). A rearward amplification of 2.0 was selected as a performance target for obstacle evasion maneuvers. The LCVs studied here will be configured to meet these performance specifications. If at all possible, LCVs should be required to meet these specifications if they are to operate safely on Michigan roads.

This will mean, for example, that C-train triples employing innovative dollies will be considered. The lengths and hitching arrangements specified in [15] for satisfactory

performance in obstacle avoidance maneuvers will be considered in defining vehicle properties.

Vehicles meeting the requirements for static roll stability and obstacle evasion can be expected to have satisfactory performance with respect to dynamic roll stability except for tankers and possibly other vehicles with shifting loads. There is a need for further study of tankers to explain their propensity to roll over as evidenced in the crash (accident) data files [11]. This subject could constitute a research project on its own, and it is viewed as requiring efforts beyond the constraints on this study. In this study we will not be giving special treatment to tankers but the optimum tanker is a subject that has been addressed previously [12] and that subject is in need of further investigation with regard to LCVs.

Braking performance of LCVs is much like that of other trucks except that the control signals need to travel a long way to reach the rear axles. Booster relay valves provide means for speeding up the initiation of braking at rear axles. On the other hand, in cases where the number of axles is almost doubled (from five to nine axles) with a much lower weight increase, a better braking ability is attained. With respect to emergency braking, antilock braking systems provide improved stability during braking on slippery surfaces. Like many of the other safety issues, the requirements for LCVs are pretty much the same as those for other trucks. The idea supported here is that these longer vehicles should have at least the same safety-related braking qualities as those of the vehicles that they would replace.

High-speed offtracking and path-curvature gain refer to steady turning maneuvers. Path-curvature gain is a measure of the sensitivity of the tractor response to changes in steering wheel angle. High-speed offtracking measures the ability of the back end to follow the front end. At highway speeds the rear end may track to the outside of the path of the tractor. When this happens, there is a possibility for the trailer to trip on curbs or other road edge features. High-speed cornering, being a directional stability mode, depends on the lateral forces generated by the tires during high-speed turns. It is influenced by the qualities of the tires and the vehicle weight. Longitudinal dimensions are of importance and their impact on the LCV in high-speed cornering has been quantified using simplified models to examine high-speed cornering performance [13].

Directional response and transient response times are subjects that have been analyzed in the past, but their influences on the accident (crash) record is not well understood. This is an important subject that needs a great deal of study to resolve for all trucks, not just

LCVs. We do not believe that this project has the resources in time or budget to address this safety-related aspect of truck performance. Nevertheless, the lateral acceleration and yaw-rate-response times of trucks could be important in crash-avoidance situations.

Given that there is a body of knowledge on the safety-related (crash avoidance) performance of large trucks, the results of existing work will be applied to the maximum extent possible in this study.

Traffic Operations

Each of the baseline combinations that were identified above will be investigated to determine a range of values for their pertinent mechanical properties. The performance modes, under which these configurations will be evaluated, are primarily based on considerations associated with those properties that distinguish LCVs from other heavy trucks. The following performance modes will be addressed, as their level is expected to be peculiar to LCVs, and to be directly influenced by their unique properties:

1. Low-speed offtracking — As an LCV turns around an intersection corner or on a highway ramp, offtracking is the most prominent problem such a vehicle is expected to have. This performance mode is influenced by most of the mechanical properties that distinguish LCVs. Unit lengths, axle locations and their spread, and hitch location and type are the primary parameters determining the level of the offtracking. Since, by definition, LCVs have longer units than other heavy-duty trucks, they are expected to constitute a unique class in the sense of low-speed cornering performance.

   Using a number of short trailers rather than one long trailer is a means for reducing low-speed offtracking. When there are several units, the offtracking of each unit is added to the total inbound encroachment of the vehicle, causing an increased offtracking at the last trailer. The manner by which each unit's offtracking is "added" is influenced by its tongue connection and the overhang length of the preceding unit. The inside of the last trailer, at a point above its rear suspension, will determine the inner bound of the swept path established by the truck as it turns.

2. Power requirements — This mode assesses the requirements from the prime mover's power train to ensure a sufficient longitudinal acceleration performance level, so that it is compatible with road restrictions. Even without increasing the weight cap to which LCVs might be subjected, the time to cross intersections with

their existing power trains is going to be longer. If the weight cap is raised, maintaining speed on uphill grades and acceleration on merging lanes onto highways might be degraded to a point of hazard.

The performance modes associated with traffic operations can be studied in the context of vehicle performance in site-specific situations existing on Michigan roads. We feel that this project should emphasize operational considerations since many of the safety issues have been examined in other work.

Mobility

Under the heading of mobility three issues will be addressed, namely, friction demand in tight turns, traction for moving on upgrades, and backing up. This discussion emphasizes the friction demand performance mode.

Friction demand — Evaluates the friction required by the tires on the driving axle(s) of the leading unit during turning, to maintain a controllable yaw rate. When the friction demand level is too high, an articulated vehicle is susceptible to an imminent jackknife when driven on slippery roads — even without applying the brakes at all. During a turn, some lateral force must act on the front end of the semitrailer in order to maintain directional stability. As a reaction, a lateral force is generated on the fifth-wheel hitch at the rear of the tractor, and its magnitude increases with the articulation angle. That force is supported by the tires of the axle below it — the driving axle of the tractor. The influence of this performance mode might be prominent on LCVs, because both the increased trailers length and the prospect of additional axles directly impact the level of aligning moment imposed by the semitrailer on the tractor, and hence the friction demanded to support it.

This evaluation will be carried out using methods employed in the study of vehicles for interprovincial use in Canada [7]. However we believe that there is need for further investigation of this subject, especially because Michigan rules promote the use of vehicle units with multiple axles. Perhaps the Canadian rules are overprotective and they have decided unfairly against vehicles with multiple axle suspensions. We believe that friction demand in a tight turn will require a separate research project in order to make satisfactory progress on the issues involved.

Traction may be an issue for vehicles with light loads on the drive axles compared to the gross combination weight of the vehicle. STAA doubles have a low ratio of drive axle

load to GCW. These vehicles may have problems on steep grades when the road is slippery. Vehicles with greater GCW but with drive-axle loads similar to the STAA double will have even more trouble with steep slippery grades.

Backing up is a problem for A-train combinations. However the use of alternative hitching arrangements makes backing up possible for doubles and perhaps for triples. For vehicles that are to have access to terminals removed from main roadways, there may be justification for requiring the ability to back up to get out of unexpected situations.

The mobility issues could probably be put in with traffic operations, and, like traffic operations, they could have safety implications if they result in obstructions to the smooth flow of traffic. Nevertheless, the mobility issues are mainly vehicle dependent matters and they tend to have less connection with highway design than the traffic operations issues.

Relationships between vehicle characteristics and roadway design elements

Several official and organizational publications list and discuss requirements and recommendations pertaining the relationships between vehicles (characteristics and performance levels) and elements of the roadway. AASHTO policy on geometric design sets standards on the aspects of roadway design that concern sight distance, horizontal and vertical alignments, layout of cross section elements, road types, intersections on grades, grades separations, and interchanges. Studies that are under way also address these issues — for example, ITE's "Geometric Design and Operational Considerations for Trucks" [1] or TRB's synthesis project on "Truck Operating Characteristics" [24].

The vehicle performance situations that are of concern to this study are reflected below with relation to the various pertinent roadway features:

1. low speed offtracking at intersections (turning templates for specific situations) (e.g., 37 ft radius, 90 degrees)
2. acceleration from a standing start across an intersection
3. acceleration from an initial to a final velocity on an acceleration lane on an entrance ramp
4. deceleration from an initial velocity to a speed appropriate for negotiating an exit ramp

5. roll stability on ramps (superelevation, radius, side friction, velocity)
6. high-speed offtracking on ramps (curbs, lane widening and width)
7. friction demand at intersections (a low-speed, tight turn on a slippery surface)
8. yaw stability and directional control on turns and curves on the highway (highway speed, superelevation, radius)
9. speed control on downgrades
10. speed maintenance on upgrades
11. obstacle evasion at highway speeds (rearward amplification, alternative hitch devices, backing up)
12. rear-end crashes due to the need to change speed for vehicles, intersections, etc.
13. traction for low-speed mobility on slippery surfaces (drive axle loads for heavy vehicles)
14. stopping-sight distance for horizontal and vertical curves
15. passing-sight distance for being passed and passing on two lane roads
16. decision-sight distance for signalized intersections

Roadway design varies according to its nature of use and landscape environment. For the purpose of evaluating performance levels and compatibility of the various truck configurations under different roadway conditions, three types of roads will be considered: freeways, rural (county) roads, and urban (city) roads. For each of these types, the following vehicle performance situations from the above list should be considered as candidates for evaluation:

Freeway — 1, 3, 4, 5, 6, 8, 9, 10, 11, 12, 14

Rural — 1, 2, 7, 9, 10, 12, 13, 14, 15, 16

Urban — 1, 3, 7, 13, 14, 16

Summary of preliminary interpretations and recommendations

Compatibility between heavy-duty trucks and the roadway on which they travel is a continuously changing issue. Both trucks and roads undergo ongoing improvements and modifications that constantly require evaluation: on one hand, the desire for increased

safety and productivity of the trucks, and on the other hand, the capability of the roadway infrastructure to handle the weight and dimensions of these vehicles. As described in the preceding sections, there is an elaborated list of performance modes and scenarios that needs to be evaluated to assess the capability of the roadway to accommodate LCV trucks safely without disrupting traffic operations. Since some of the associated issues have been studied before, and since some of the safety and operational aspects of accommodating heavy trucks on the roadway system are beyond the scope of this work, the following approaches are recommended:

1. Modes that have been previously studied and will not be analyzed in this work:

   The influence and safety implications of these performance modes have already been evaluated in previous studies. Results of these studies can be directly used to assess the ramifications of those modes on traffic safety and operations of large trucks in Michigan:

   (a) roll stability on ramps (superelevation, radius, side friction, velocity)
   Ref. [6]

   (b) high-speed offtracking on ramps (curbs, lane widening and width)
   Ref. [5], [7], [13]

   (c) friction demand at intersections (low speed tight turn on a slippery surface)
   Ref. [5], [7]

   (d) yaw stability and directional control on turns and curves on the highway
   Ref. [7], [20], [22]

   (e) speed control on downgrades
   Ref. [14], [18], [19]

   (f) obstacle evasion at highway speeds (rearward amplification, alternative hitch devices, backing up)
   Ref. [6], [7], [15], [21]

   (g) traction for low-speed mobility on slippery surfaces
   Ref. [7], [11]

   (h) stopping-sight distance for horizontal and vertical curves
   Ref. [2], [4], [9]

   (i) decision-sight distance for signalized intersections
   Ref. [2], [4]

(j) deceleration from an initial velocity to a speed appropriate for an exit ramp Ref. [6], [9]

2. Modes that will be addressed and studied in this work:

The following modes appear to have a unique and direct influence on operation of LCVs in the State of Michigan, and they will be evaluated in conjunction with standard as well as actual roadway layouts supplied by MDOT:

(a) low-speed offtracking in intersections and on ramps

(b) acceleration from a standing start across an intersection and sight distance

(c) acceleration from an initial to a final velocity on an entrance ramp

(d) passing-sight distance for being passed and passing on two-lane roads

(e) speed maintenance on upgrades

(f) median opening and U-turns

3. Modes that are suggested to be addressed separately in future studies:

Some of the performance levels that are used to evaluate safety and operational limits of heavy trucks, are not peculiar to the LCV category, which is the population targeted for assessment in this study. Still, they affect the entire population of trucks on the road—those that are currently allowed and regulated, as well as those that require special permits to operate. An example might be the effects that pavement rutting has on directional stability. For the purpose of enhancing the safety of highway operation of heavy-duty trucks, these topics should be addressed in the future. Other issues, such as prospective multiaxle trailers (even though they might be peculiar to LCVs) are positioned beyond the scope of this work, due to their broad implications. Further study is required to assess the influences of such operational modes, and it is suggested that they will be addressed separately in the future.

The following subjects appear to be candidates for individual studies:

(a) impacts of pavement rutting on the directional stability of trucks

(b) implications on safety imposed by a negative superelevation at the outside shoulder of highway ramps

(c) performance of multiaxle vehicles in offtracking, accident avoidance, and friction demand situations

(d) various scenarios of merging

(e) effects of LCVs on traffic flow

(f) impacts of LCVs on design and operations in work zones

(g) rollover propensity of tankers (including LCVs)

(h) the dynamic stability and response times of trucks (LCVs) in steering maneuvers

(i) friction demand for multi-axle vehicles as configured under Michigan rules

(j) rear-end crashes due to the need to change speed for vehicles, intersections, etc.

Clearly there are many ways that truck characteristics influence the policies, plans, designs, and operational characteristics of roads. Often it is the largest trucks that have the most influence on highway issues. Hence it is not surprising to find that LCVs will challenge highway capabilities more than smaller trucks. Nevertheless, LCVs are not recommended as design vehicles for general use. For example, the ITE Informational report [1] states: "Design vehicles based on LCVs are not appropriate for general use at this time, but should be considered on highways where they are permitted." The selected approach involving specific highway sites is in keeping with this philosophy.

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APPENDIX B

HIGHWAY FEATURES AND EXPECTED PERFORMANCE OF LCVS

This appendix provides a summary of the highway features that are expected to have an important effect on the performance of LCVs in Michigan. The principal results presented here pertain to the work done in Task 2 of this study, and are based on drawings and data provided by MDOT.

Overview of typical Michigan highway features

This section summarizes the roadway features that represent the Michigan highway system. For the purpose of this study, the typical highway features are assumed to be characterized by the geometric attributes as reflected in construction drawings and geometric standard guides. This section lists the highway sites for which a cluster of construction plans was supplied by MDOT, and those roadway elements included in the standard design guides are also provided. These two sets are viewed as representing the Michigan highway system.

Content of the drawings

The highway drawings are grouped according to the locations they describe. Ten different sites were identified, and they are listed below. Interchange drawings contain detailed information about the associated ramps and intersection geometry, including curvature, superelevation and merging lanes. Drawings of urban and arterial intersections, on the other hand, are less detailed. In some cases pertinent information needs to be extracted based on scaling. In the following sections, reference to a specific set of drawings as a site number is in accordance with the following list:

Site 1. Freeway interchange — I-94 (used to be US-12) and US-23 (see figure B-1)

Site 2. I-94 south of Ypsilanti: from Huron Street exit in the West to the Willow Run Airport exit in the East. This set of drawings appears to be instructions to road crews. It provides a great deal of information about signs, guardrails, and water piping, but only very little information about the geometry of the road. It also describes alternate routing of traffic through Ypsilanti to avoid the working area (see figure B-2)

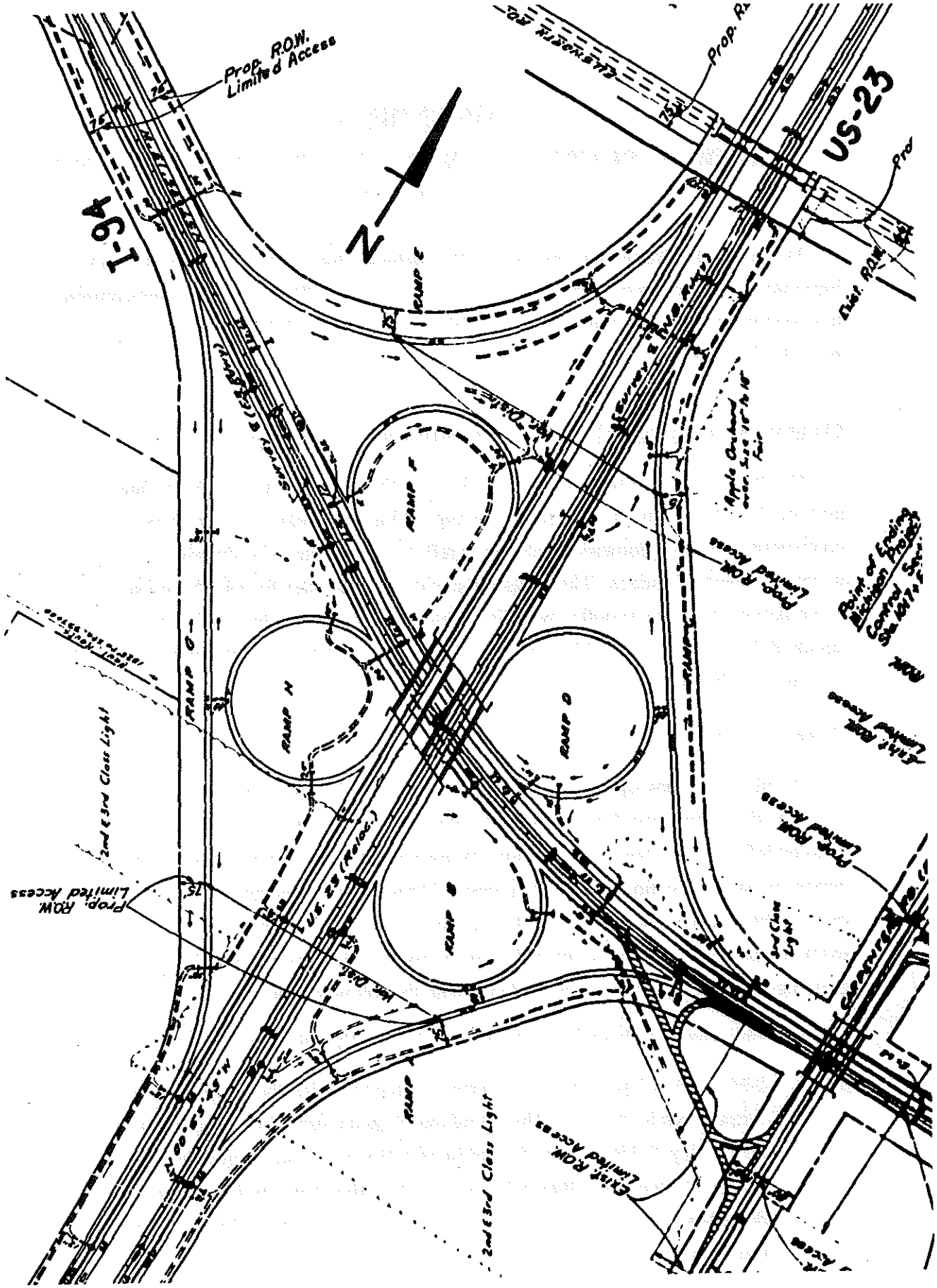


Figure B-1. Site 1: I-94 and US-23

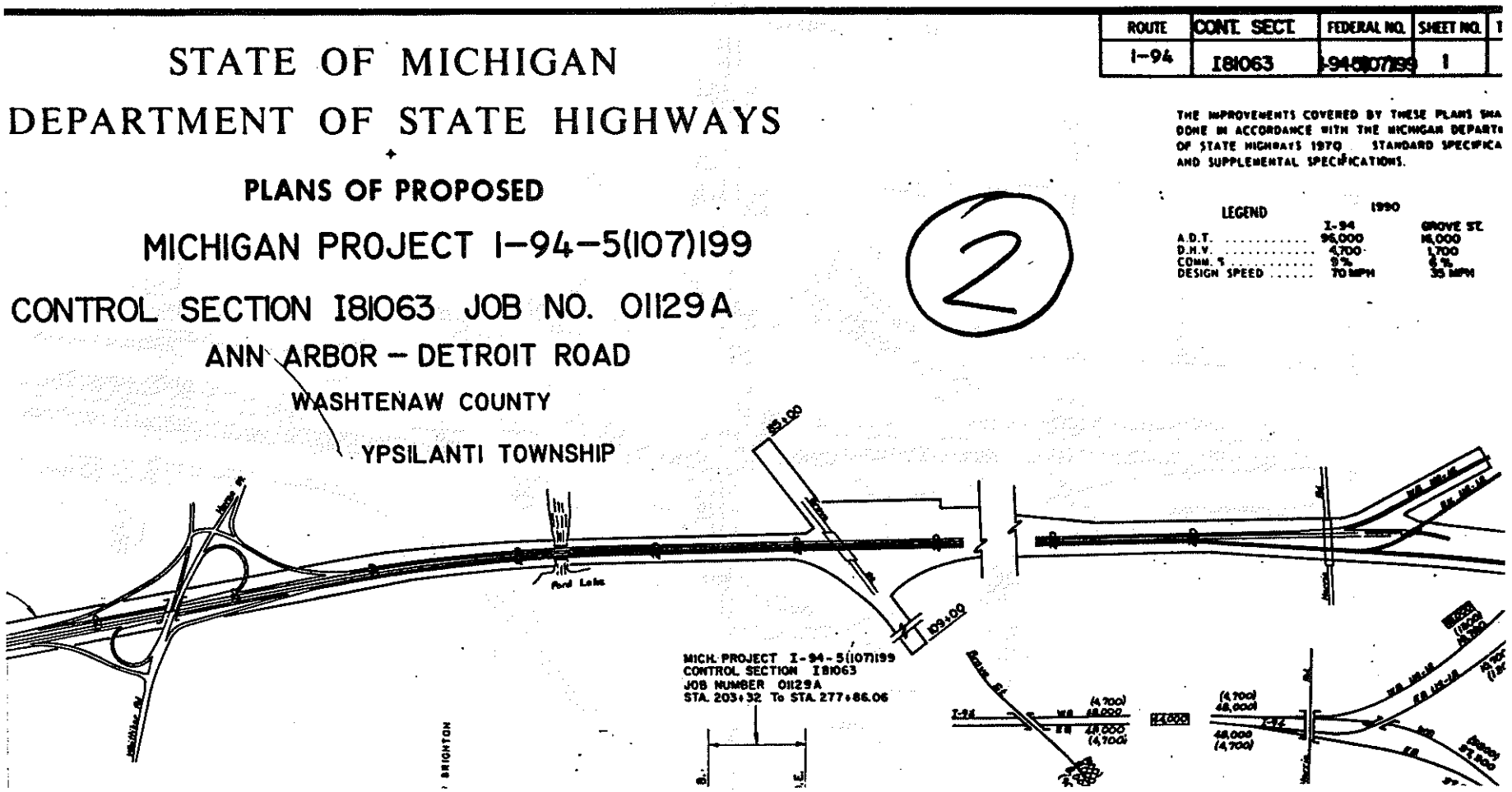


Figure B-2. Site 2: I-94 along Ypsilanti

Site 3. Freeway interchange — I-94 and Belleville Rd. (see figure B-3)

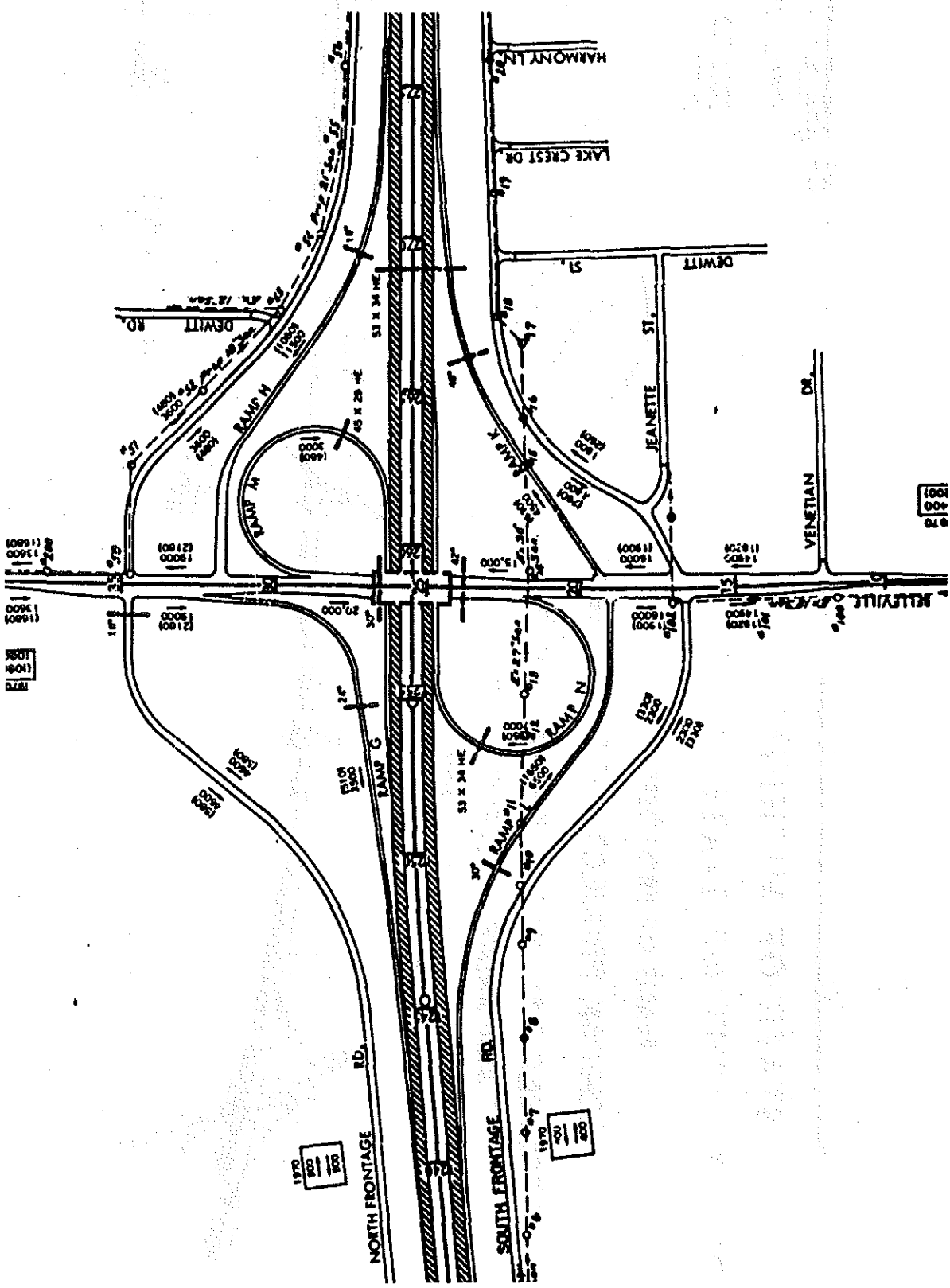


Figure B-3. Site 3: I-94 and Belleville Rd.

Site 4. Arterial road — Individual junctions along US-12 (Michigan Avenue) from Saline in the West to Pittsfield in the East. Junctions included: Austin Road, Mills Street, Monroe Street, Lewis Street, Ann-Arbor Road, Harris Street, Davenport Street, Maple Street and Bemis Street, Moon Road and relocated State Road, Fosdick Road, Warner Road, Campbell Road This set also describes the curvature moderation of US-12 as it passes the railroad tracks in Saline. (see figure B-4)

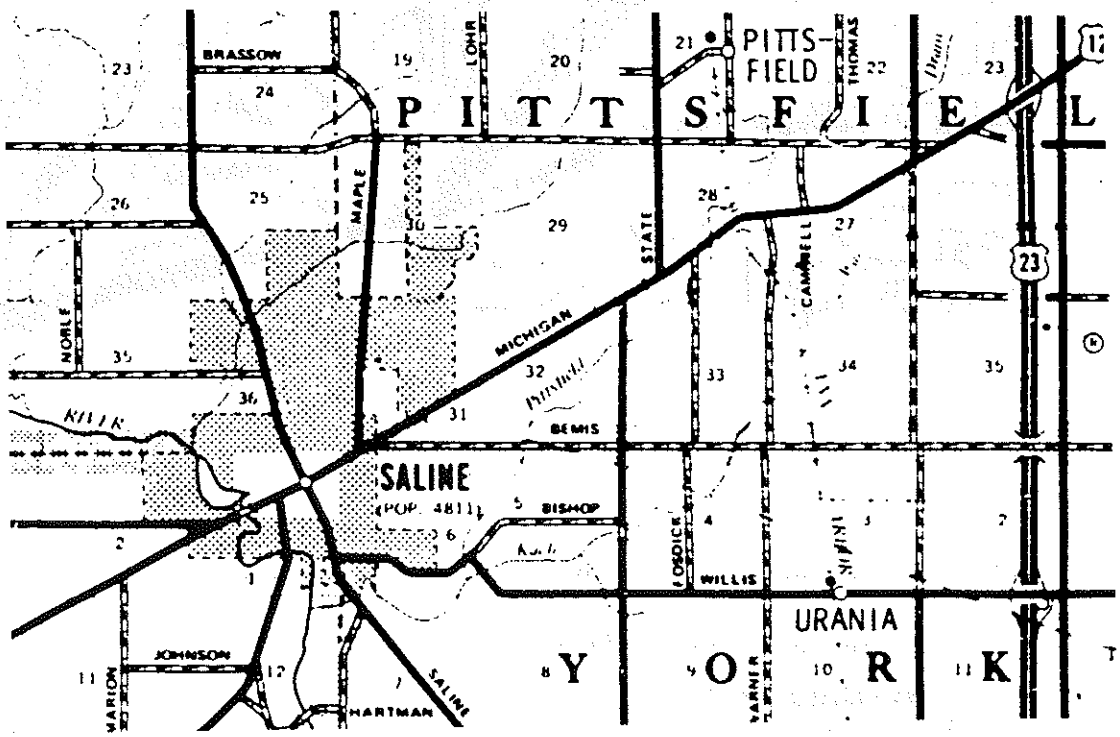


Figure B-4. Site 4: Arterial road, US-12 (Michigan Avenue)

Site 5. Arterial roads — Individual junctions along Washtenaw Avenue in Ann Arbor. From Stadium Boulevard in the West to Yost Boulevard in the East (before US 23). Junctions include: Tuomy Road, Arlington Boulevard, Glenwood Avenue, and Platt Road, Huron Pkwy., and Pittsfield Boulevard (see figure B-5).

Site 6. Freeway interchanges (assorted)— General layout of I-94 and Jackson Road (see figure B-6). This seems to be a preliminary design of I-94 and US-23. It is different from the existing roadway. Ramps of US-23 and the old US-112 (Michigan Avenue, now US-12.) (see figure B-7); A preliminary layout of I-94 and US-23.

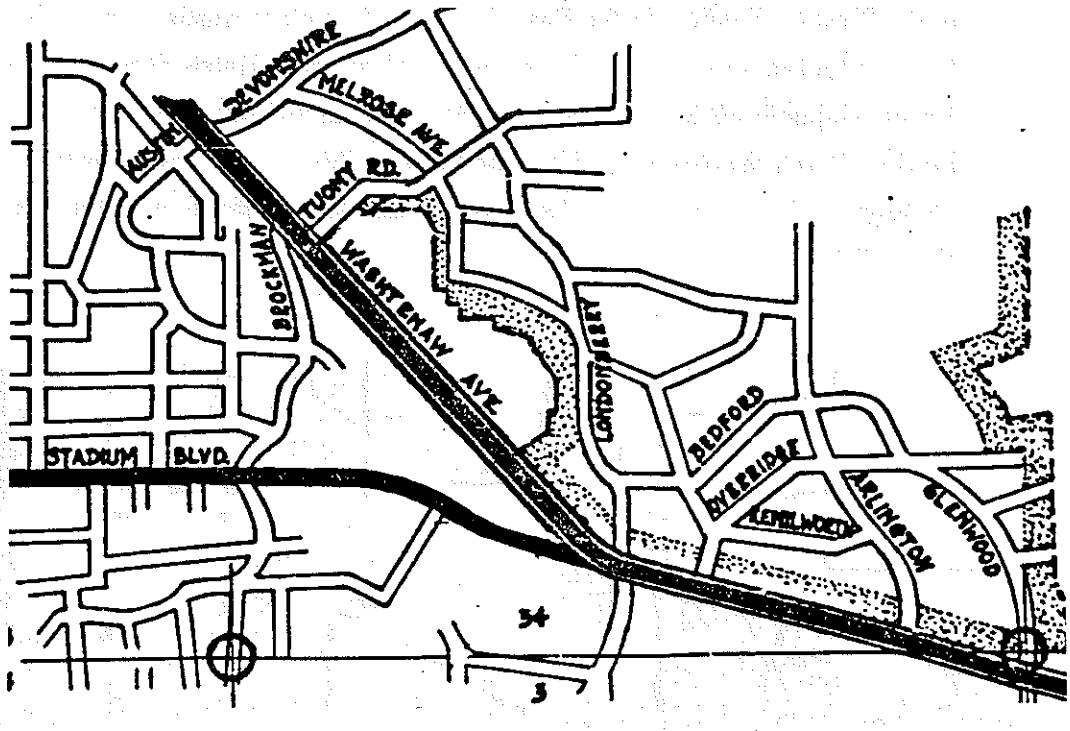


Figure B-5. Site 5: Arterial road, Washtenaw Ave.

Site 7. Freeway interchange — I-94 and Rawsonville Rd. (see figure B-8)

Site 8. Freeway interchange — Details of I-94 and Jackson Rd. (in addition to those provided in site 6).

Site 9. Freeway interchange — I-94 and Huron / Whittaker Rd. (see figure B-9)

Site 10. Freeway interchange — I-94 and Haggerty Rd. (see figure B-10)

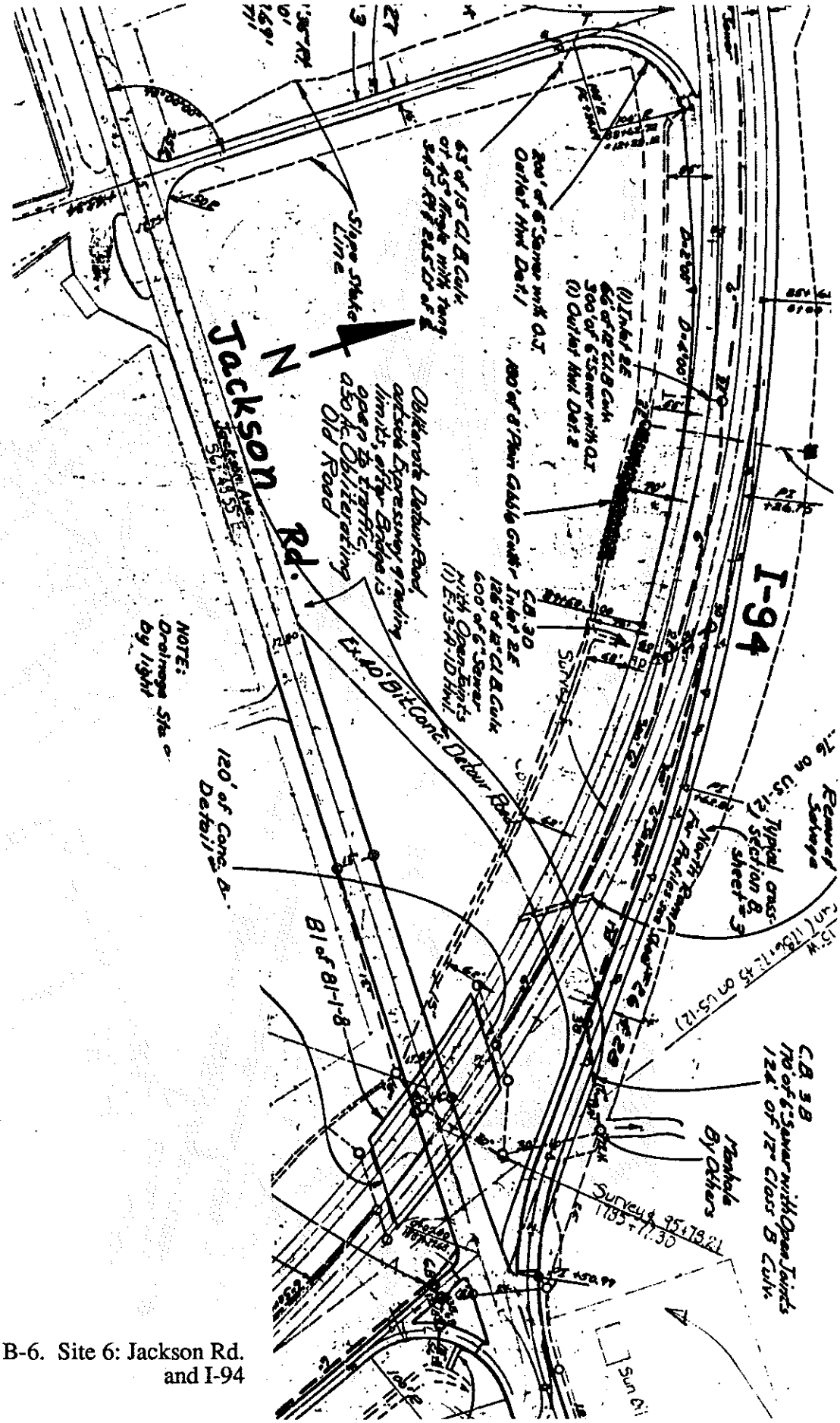


Figure B-6. Site 6: Jackson Rd. and I-94

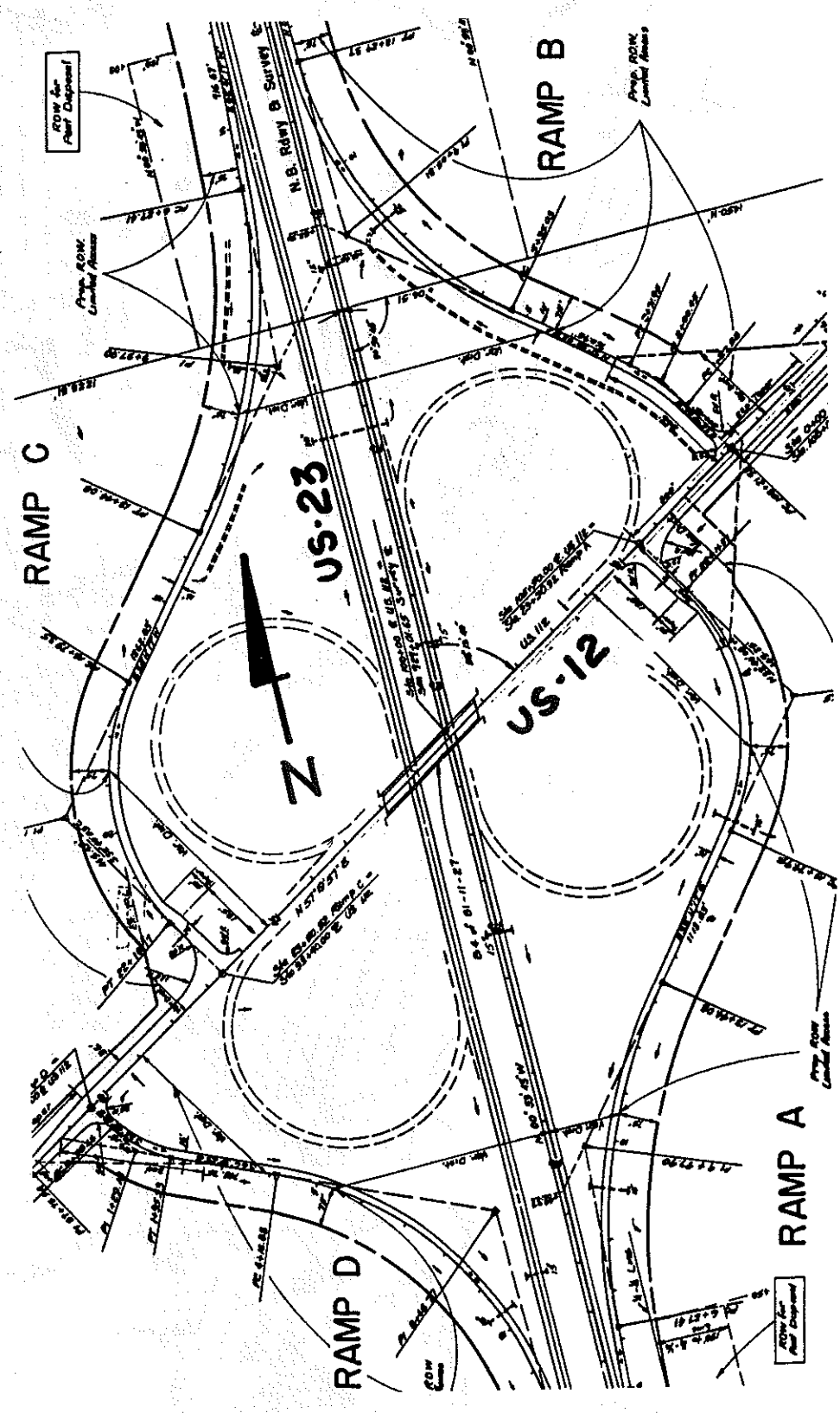


Figure B-7. Site 6: US-23 and US-12

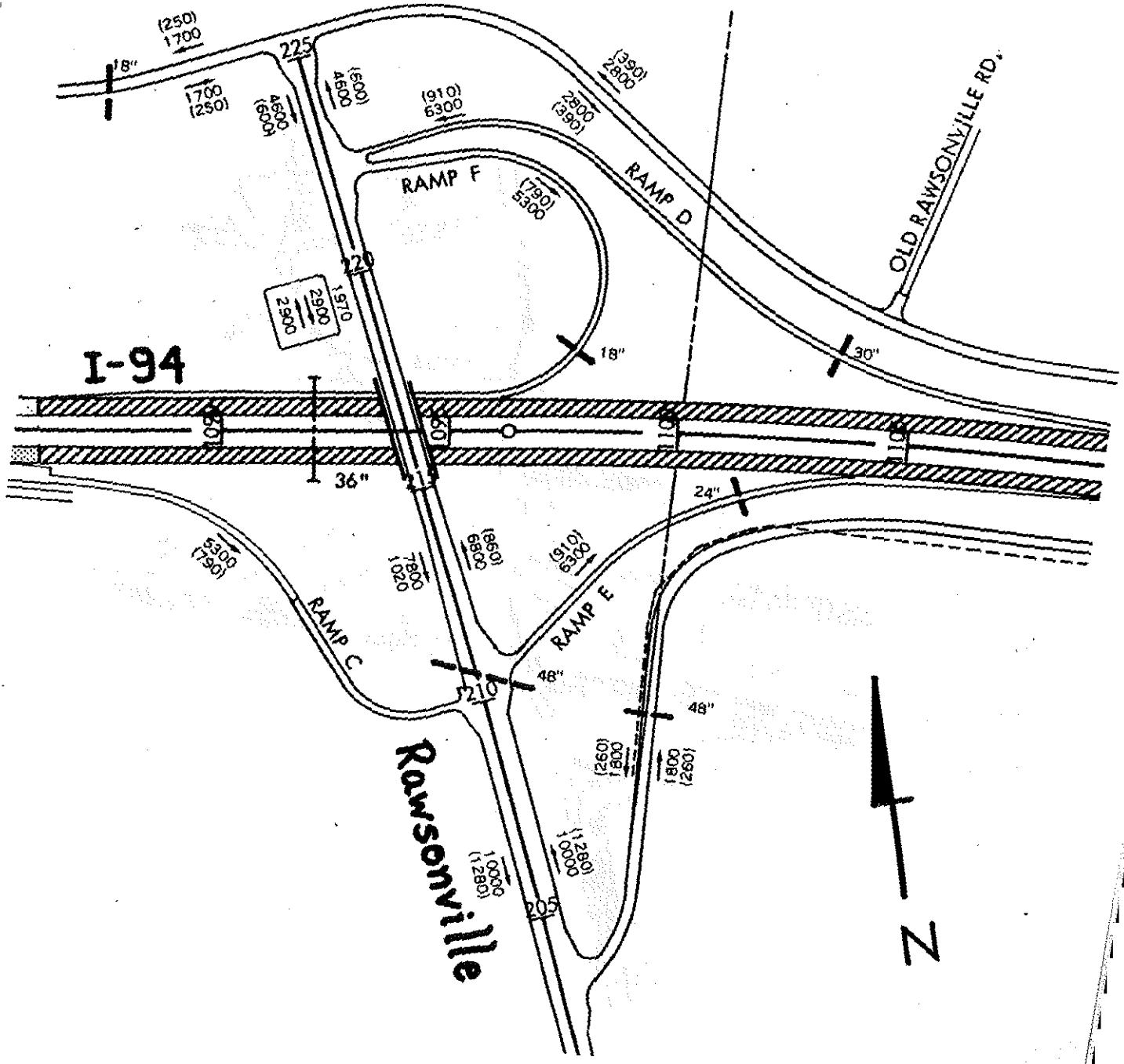


Figure B-8. Site 7: Rawsonville Rd. and I-94

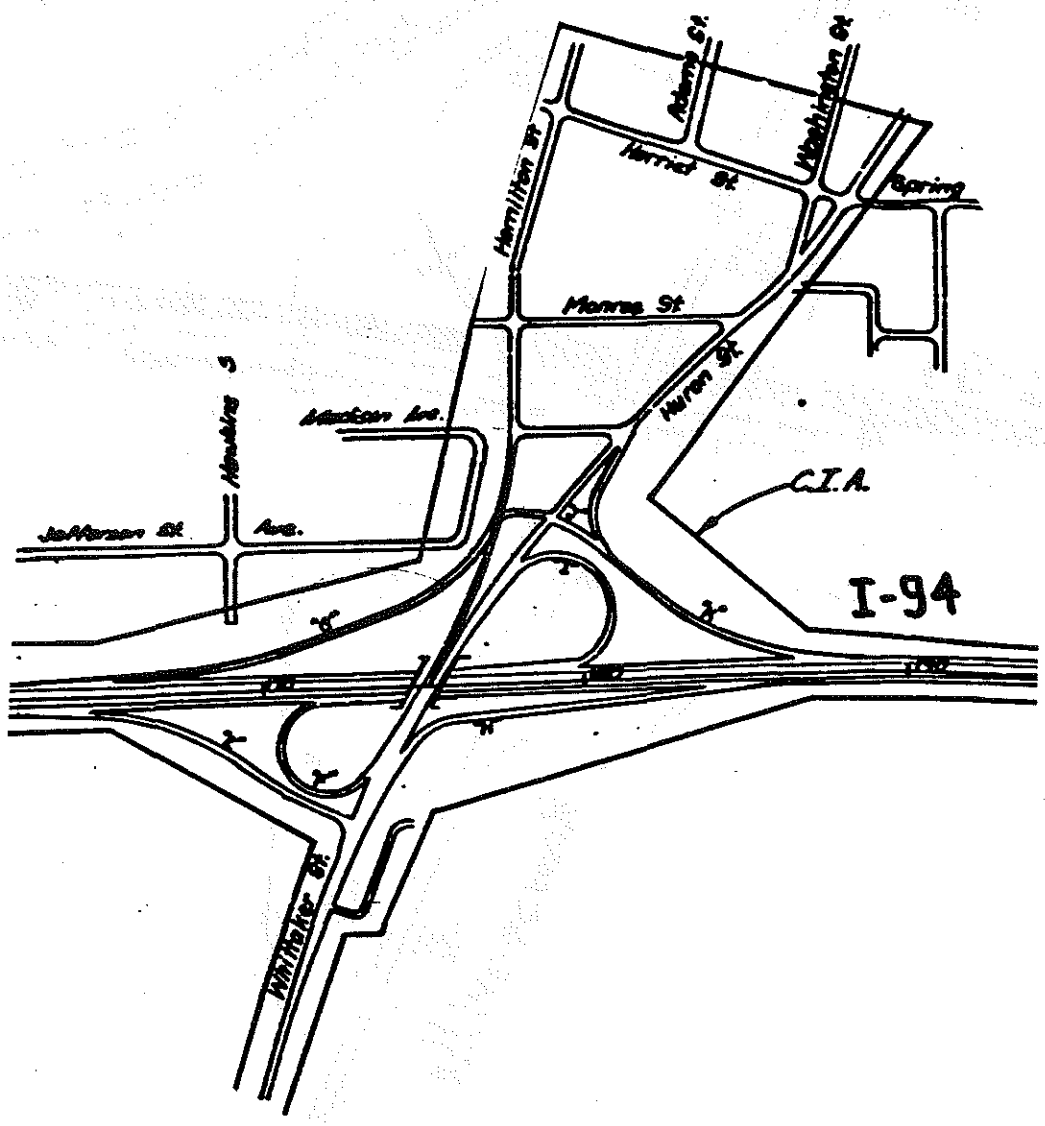


Figure B-9. Site 9: Huron / Whittaker Rd. and I-94

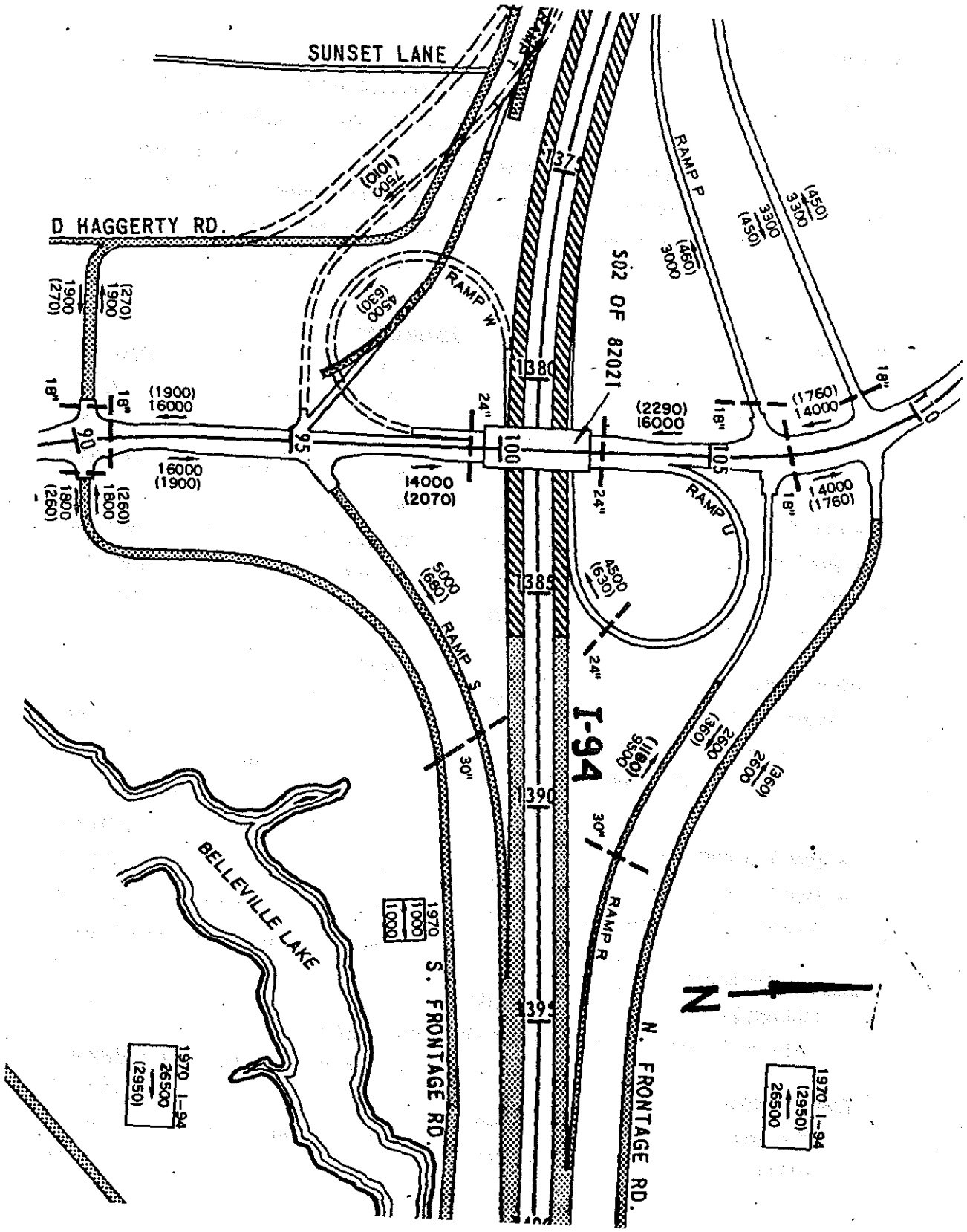


Figure B-10. Site 10: Haggerty Rd. and I-94

Standard design guides

The second group of geometric information about typical Michigan highway features was provided as a bound set of Michigan Department of Transportation Bureau of Highways standard design guides. That set contains drawings to be used as standard guides for designers of various roadway elements at different areas. Standard guides to the following elements are included, and they are referred to in the course of this work:

Rural ramps:

- One lane tapered entrance (VII-100)
- Parallel entrance (VII-101)
- Two-lane entrance (VII-110)
- Successive entrance (VII-120)
- One-lane exit (VII-130)
- Parallel exit (VII-131)
- Two-lane exit (VII-140)
- Successive exit (VII-150)

Urban ramps:

- Entrance and exit (VII-202)
- Parallel entrance and exit (VII-203)
- Entrance and exit for crossover (VII-204)
- Two-lane entrance (VII-210)
- Two-lane exit (VII-24-)
- Junction of major roadways (VII-260)

Urban interchanges:

- Diamond (VII-400)
- Collector-distributor road (VII-410)

Limited access:

- Rest area (VII-500)
- Weigh station (VII-510)

Rural interchanges:

- Diamond (VII-300)
- Collector-distributor road (VII-310)
- Parclo - A - 4 - quad (VII-320)
- Parclo - B - 4 - quad (VII-330)
- Parclo - A - B - 2 - quad (VII-340)
- Trumpet type (VII-350)
- Cloverleaf type (VII-360)
- Ramp terminal details (VII-370)

Free access:

- Two-to-four-lane transition (VII-610)
- Turned-in roadway (VII-640)
- Flares and intersection details (VII-650)
- Crossovers (VII-670)
- Commercial driveways (VII-680)
- Temporary runaround and crisscross (VII-690)

Sight distance:

- Determining stopping sight distance (VII-700)
- Determining passing sight distance (VII-710)

Highway features likely to affect LCV's

This section discusses those roadway elements mentioned previously that are most likely to influence the safe operation of LCVs. For each of the highway sites described in the drawings, those performance modes most likely to be affected are identified, and they are associated with the pertinent truck types.

The maneuverability of heavy duty articulated trucks is rather limited. The increased length of the LCVs is expected to have operational effects on both the LCVs and on the other traffic. Performance modes associated with offtracking can limit turning capabilities, while those modes associated with engine power might cause the LCV to become a more pronounced traffic obstruction (e.g., when crossing intersections or when passing).

After examining the geometric data of the sites described in the previous section, several potential problems were identified. Certain situations might pose obstacles for LCVs negotiating these roadways; other situations might cause LCVs to become obstructing or hazardous elements to the other drivers. As a preliminary approach, observations were made for each site, and the potential problems are identified below (refer also to figures B-1 through B-10).

Site 1. Offtracking on ramp H (southbound US-23 to eastbound I-94), which represents the tightest curve (same as ramp D): 16 ft wide, 290° turn, R_i=230.7 ft.
Rollover on ramp E, and accelerating onto I-94 westbound (short acceleration lane and sight distance).

Site 2. Offtracking on alternate routing of traffic through Ypsilanti to avoid the working area, maintaining speed.

Site 3. Offtracking on ramp M (Belleville Road northbound to I-94 westbound). 16 ft wide, 263° turn, R_i=230 ft.
Offtracking in the intersections of ramps H and L with Belleville Road, due to a 90° tight turn. The offtracking problem might be amplified entering ramp K to I-94 eastbound from Belleville Road southbound where there is a 120° turn.
Acceleration limits should be considered when exiting ramps H and K onto Belleville Road due to slope and visibility.

Site 4. That section contains no ramps or freeway interchanges. It is approximately six miles of arterial road with urban junctions. Turning off US-12 (Michigan Avenue) onto any of the side roads, LCVs are expected to have offtracking problems such that they will be unable to execute the maneuver.

Site 5. An arterial road similar to site 4. Curbed median in the junction of Washtenaw Avenue and Stadium Boulevard is not expected to raise an offtracking problem. Turning onto any of the side roads is expected to pose problems similar to those in site 4.

Site 6. This site is evaluated here in conjunction with the additional information provided in drawings set 8.

Jackson Avenue onto I-94 eastbound:

- Offtracking while negotiating the turn from Jackson Avenue to Lakeview Drive, and from Lakeview Drive to I-94;
- Acceleration problem when merging with I-94 eastbound due to the combination of sight distance, uphill slope, and a short acceleration lane;

Jackson Avenue onto I-94 westbound:

- Acceleration problem when entering the north ramp due to an uphill slope;

I-94 westbound onto Jackson Avenue (eastbound and westbound):

- Offtracking in both directions, as the turning radii (especially eastbound) are tight;
- Possible acceleration problem when turning westbound on Jackson Avenue, as the vehicle starts from a complete stop (traffic lights and uphill slope);
- Since the exit ramp is downhill, the braking issue should be addressed;
- Rollover limits should be evaluated as the vehicle turns eastbound on Jackson Avenue from the exit ramp. The tight turn and the downhill slope might serve as rollover propagating factors;

US-23 and US-12:

- Accelerating uphill and visibility from ramps A through D onto Michigan Avenue (US-12);
- Prospective offtracking problem when entering and exiting the ramps to US-12;

Site 7. Rawsonville Road and I-94. Rawsonville northbound ends in a 'T' junction with a local road (North Frontage Road). It is not considered a highway beyond that junction.

Offtracking:

- Turning through the 'T' junction (all directions) at the north side of Rawsonville Road;
- Entering ramp E (northbound/southbound Rawsonville to I-94 eastbound);
- Entering ramp F (northbound/southbound Rawsonville to I-94 westbound);

- Exiting ramp C or ramp D to Rawsonville Road (from I-94 eastbound and westbound);

Startability and acceleration:

- Exiting ramp C or ramp D to Rawsonville Road;

Site 9. I-94 and Huron / Whittaker Road at Ypsilanti. This intersection does not resemble a typical "Cloverleaf" layout commonly found on freeways. The rather sharp angle between I-94 and the intersected road, combined with utilization of existing pavement, forge a peculiar design of freeway interchange. As is, LCVs are probably not capable of negotiating this site in all directions. In an itemized manner, the following details of the interchange should be assessed:

Ramp I (Whittaker Road northbound to I-94 westbound):

- Offtracking. It is a tighter ramp than ramp H on site 1 (R_j=200 ft);
- Acceleration and merging onto I-94 might be difficult due to an uphill slope and perhaps insufficiently long acceleration lane;

Traffic from Ypsilanti via Huron Street cannot access directly to I-94 westbound. The access to ramp G (that leads to I-94 westbound) is possible only from Hamilton Street Getting to that street requires maneuvering through down-town roads, which is neither desirable nor feasible for LCVs. Once on ramp G, due to varied curvature, rollover risks should be evaluated at its apex.

Ramp K (exit from I-94 westbound):

- Braking and slowing down while entering the ramp might pose a problem; therefore, it might be desired to study it in combination with the increased curvature and limited sight distance at that point;
- Limited sight distance to the left at the end of this ramp might also present problems while merging onto Huron Street;

Ramp J (starting from ramp K, ramp J crosses Huron Street and turns onto Whittaker Road southbound):

- Limited sight distance might present a problem while crossing Huron Street;
- Turning onto Whittaker after crossing Huron, the ramp goes through a radius of 80 ft. For most LCVs offtracking performance will be marginal, but some LCV configurations will not be able to execute this maneuver at all;

Ramp F (Whittaker Road southbound to I-94 eastbound):

- Offtracking. It is the tightest ramp in this interchange (R_j=175 ft);
- A priori, acceleration and merging with I-94 eastbound does not seem to pose a problem since I-94 eastbound is downhill. Once some acceleration

performance levels for LCVs are established, this assessment should be verified;

Ramp E (I-94 eastbound to Whittaker Road):

- The offtracking performance mode should be evaluated when turning right onto Whittaker Road southbound;
- Acceleration during the turn to Whittaker Road northbound might be a problem due to limited sight distance and an uphill slope;

Site 10. Haggerty Road and I-94. This intersection is very similar to the one of I-94 and Rawsonville Road Pertinent details that should be considered:

Ramp R (I-94 westbound to Haggerty Road northbound and southbound):

- Acceleration and sight distance while turning onto Haggerty Road;

Ramps U and W (loops to I-94):

- Acceleration when merging with I-94;
- Offtracking. These are the tightest turns in this interchange (R_i=200 ft). It should be noted that similar (ramp I in site 9) and tighter ramps (F in site 9) were discussed before, and their results might be implemented here;

Ramp T (I-94 eastbound to Haggerty Road):

- Offtracking could pose a problem when turning to Haggerty southbound;
- Acceleration and limited sight distance during the turn to Haggerty Road northbound or southbound might be a problem;

Ramp P (Haggerty Road southbound to I-94 westbound):

- The issue of offtracking in the turn from Haggerty Road (northbound or westbound) to the ramp should be looked into due to lane restrictions;
- A priori, acceleration and merging with I-94 westbound does not seem to pose a problem since I-94 is downhill in the merging section. However, once some acceleration performance levels for LCVs are established, this assessment should be verified;

Decelerating while entering a ramp from the freeway, or accelerating while leaving the ramp (onto the freeway or the crossing road,) are two performance modes that cannot be easily evaluated from the drawings. Under some desirable rate of deceleration, different slopes (uphill or downhill), and different design speeds will require different lengths for the deceleration lane.

Pragmatic acceleration requirements are also difficult to evaluate from the drawings, since they incorporate sight distance considerations that are landscape dependent. Like the deceleration lanes, they are also grade dependent. After visiting some of the sites, those

with the worst combinations of sight distance, slope, and startability conditions were selected as benchmark sites to be used in the simulations.

In Task 1 (see appendix A), three distinct truck designs were identified and selected to be used in this study: (1) STAA type, (2) LCVs-in-use type, and (3) optimization type LCVs. Generally speaking, each roadway element can be associated with some particular performance modes. For example, turns might be related to offtracking, while straight multilane highway sections might be related to passing sight distance considerations. In addition, the sensitivity of different performance modes to various truck parameters is also different. For example, when evaluated for the capability to maintain speed on upgrades, weight and engine power are the most sensitive parameters; but, for offtracking, length is the determining parameter. Multiunit trucks (i.e., triples) are expected to perform better than the long semitrailers (i.e., 53 ft or 57 ft) for offtracking. On the other hand, when evaluated for the required sight distance across an intersection, the semitrailer will perform better. Table B-1 provides cross references between the various sites, the various truck types, and the particular performance modes that might potentially pose a problem. The list of performance modes is according to the one determined in appendix A as needed to be addressed in this study.

(a) Low speed offtracking in intersections and on ramps.
("L.S. Offtracking")

(b) Acceleration from a standing start and sight distance across an intersection.
("Accel. from 0")

(c) Acceleration from an initial to a final velocity on an entrance ramp.
("Accel. from V")

(d) Passing sight distance for being passed and passing on two lane roads.
("Passing")

(e) Speed maintenance on upgrades.
("Upgrade speed")

(f) Median opening and U-turns.
("U-Turns")

Site	Benchmark Truck Designs							
	LCVs						Reference Trucks	
	53' Tractor Semitrailer	57' Tractor Semitrailer	Rocky Mountain Double	Turnpike Double	Triple	Turner Truck	48' Tractor Semitrailer	Western Double
1	L.S. Offtracking	Accel. from speed	L.S. Offtracking	L.S. Offtracking Accel. from speed	Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed
2		Upgrade speed		L.S. Offtracking Upgrade speed		L.S. Offtracking Upgrade speed	L.S. Offtracking Upgrade speed	L.S. Offtracking Upgrade speed
3	L.S. Offtracking	Accel. from speed	L.S. Offtracking	L.S. Offtracking Accel. from speed	Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed
4	L.S. Offtracking	Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns
5	L.S. Offtracking	Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns	L.S. Offtracking Accel. from 0 Passing U-Turns
6	L.S. Offtracking	Accel. from speed Upgrade speed	L.S. Offtracking	L.S. Offtracking Accel. from speed Upgrade speed	Accel. from speed	L.S. Offtracking Accel. from speed Upgrade speed	L.S. Offtracking Accel. from speed Upgrade speed	L.S. Offtracking Accel. from speed Upgrade speed
7	L.S. Offtracking	Accel. from speed	L.S. Offtracking	L.S. Offtracking Accel. from speed	Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed
8	L.S. Offtracking	Accel. from speed	L.S. Offtracking	L.S. Offtracking Accel. from speed	Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed
9	L.S. Offtracking	Accel. from speed	L.S. Offtracking	L.S. Offtracking Accel. from speed	Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed
10	L.S. Offtracking	Accel. from speed	L.S. Offtracking	L.S. Offtracking Accel. from speed	Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed	L.S. Offtracking Accel. from speed

Table B-1. Performance modes, sites, and truck configurations

In addition to the sites listed in the Table B-1, compatibility of each truck configuration with the appropriate roadway elements from the standard geometric design guides should also be evaluated using the pertinent performance mode.

Some highway elements of the ten sites, or those in the standard guides, have the same geometric characteristics (e.g., radius of ramp). For other elements, required guidelines can be established regardless of the present geometry. For example, the length of a merging lane on different grades can be evaluated based solely on the accelerating capabilities and the length of the LCV. In the next section, those elements that are common, or represent the extreme cases, are identified and selected for evaluation.

Selected highway features

Certain highway features from the drawings of the sites and the geometric standard guides were selected as discussed in the previous section. Those elements that were selected (e.g., particular ramps, particular intersections) will be used to evaluated the compatibility of LCVs with the Michigan highway system. The list of selected features described in this section is based on the drawings and some field trips.

Selected sites for low-speed offtracking

Low speed offtracking will be evaluated for road elements that are related to highways and to arterial and urban roads. Three typical scenarios were selected: an urban traffic area, three representative access ramps, and some transitional roadway sections.

Urban traffic — Roads portrayed in site 4 (see figures B-11 through B-13);

Access ramps — Ramp F (R = 175 ft) on site 9 (see figure B-14);

Ramp I (R = 200 ft) on site 9 (see figure B-14);

Ramp M (R = 230 ft) on site 3;

Transitions — Jackson Road to Lakeview to I-94 on drawing sets 6 and 8 (see figure B-15);

I-94 to Jackson Road eastbound (right turn) on drawing sets 6 and 8;

From ramp H to Belleville Road on site 3;

Rawsonville Road (southbound) to South Frontage Road eastbound (site 7) (see figure B-16);

Urban and rural interchanges from the standard design guides.

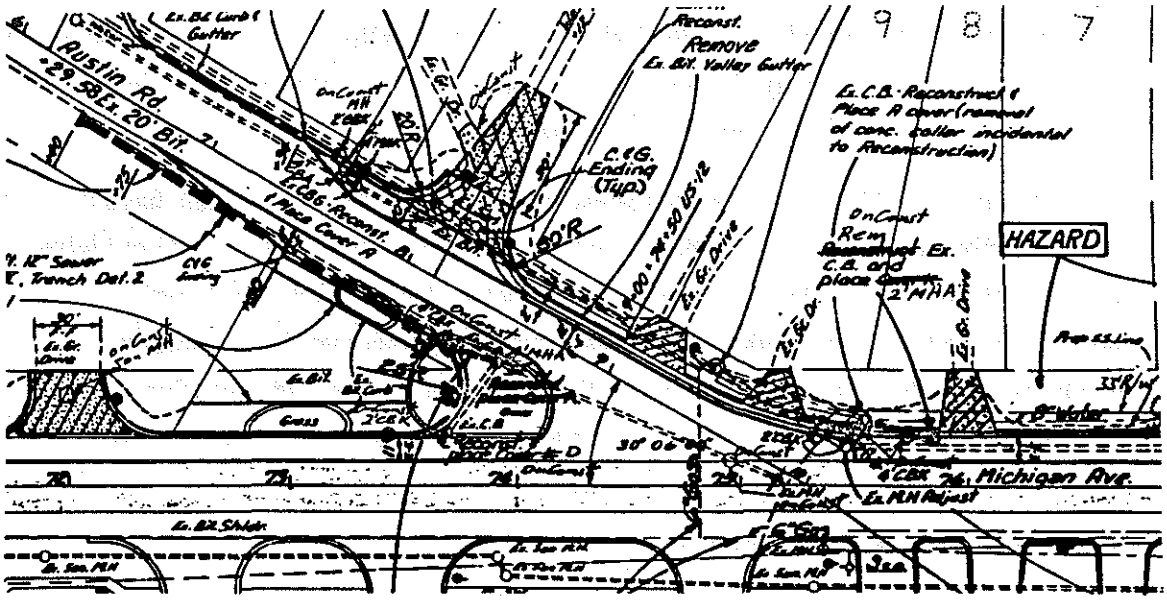


Figure B-11. Austin Rd. at Michigan Ave. from site 4

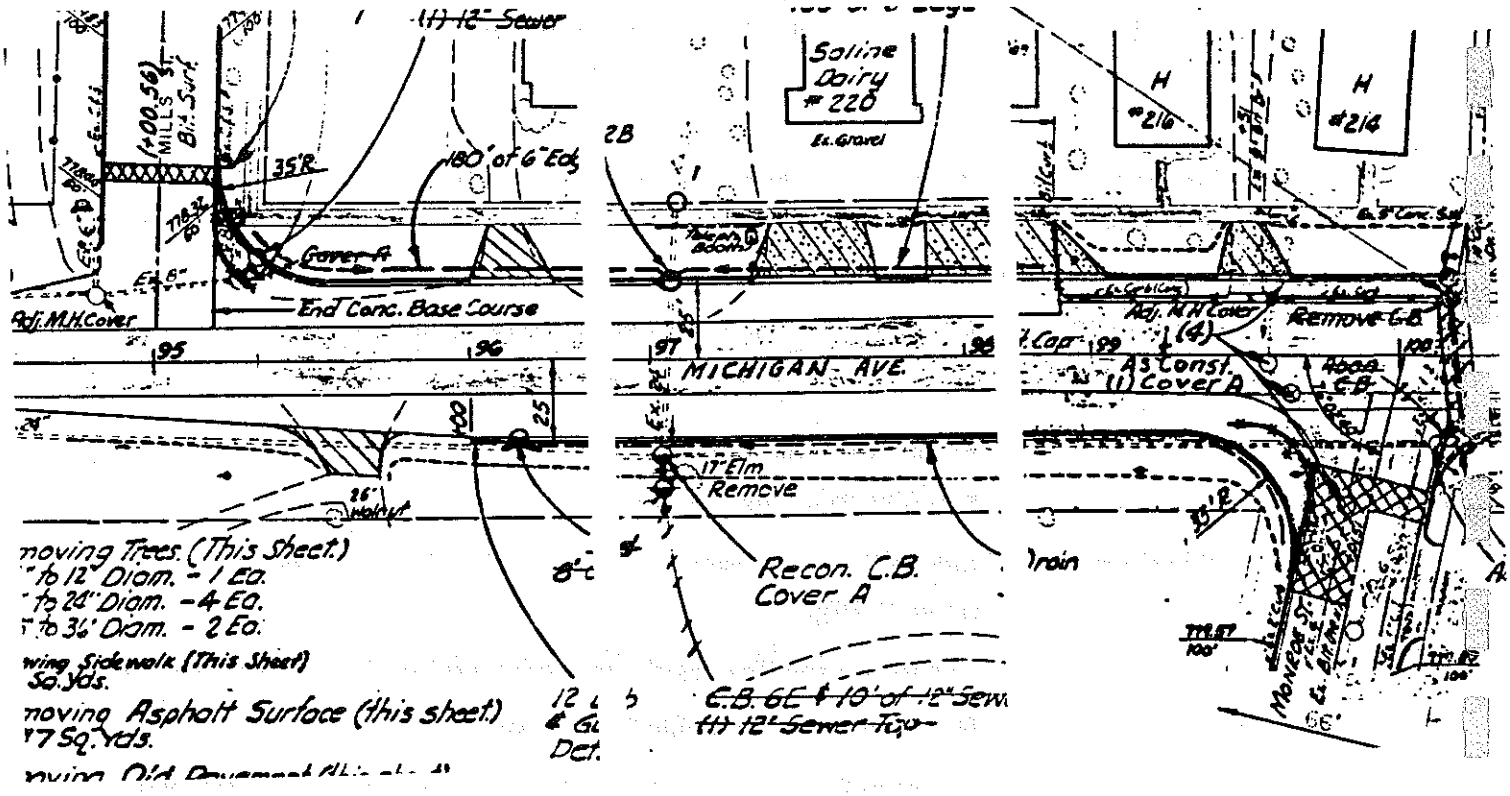


Figure B-12. Mills St. and Monroe St. at Michigan Ave. from site 4

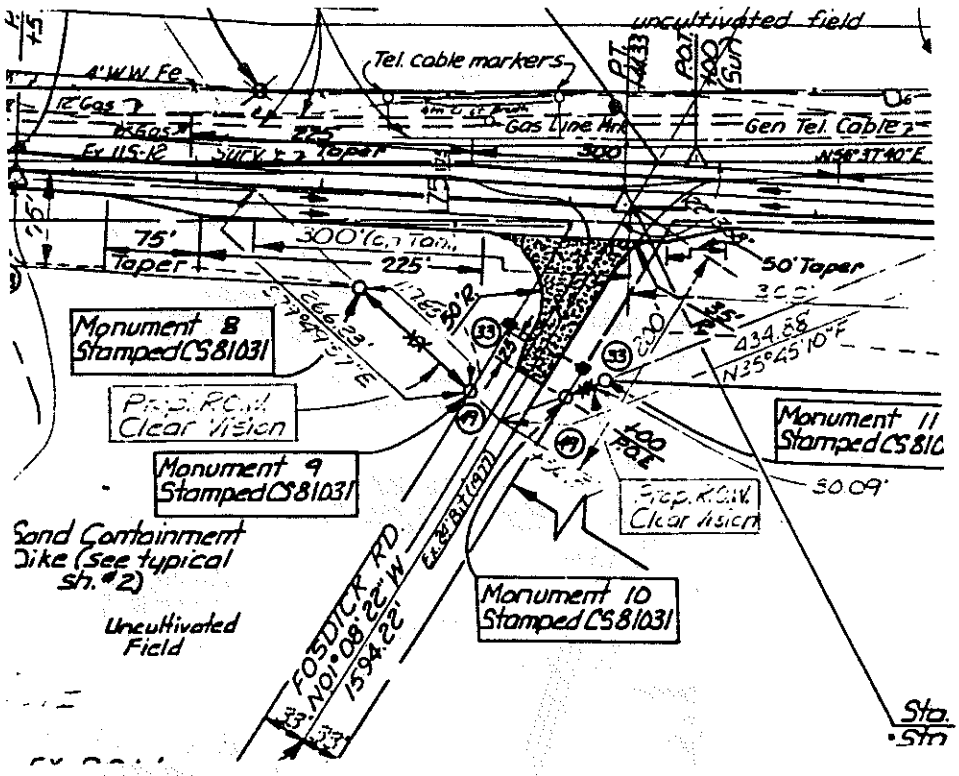


Figure B-13. Fosdick Rd. at Michigan Ave. from site 4

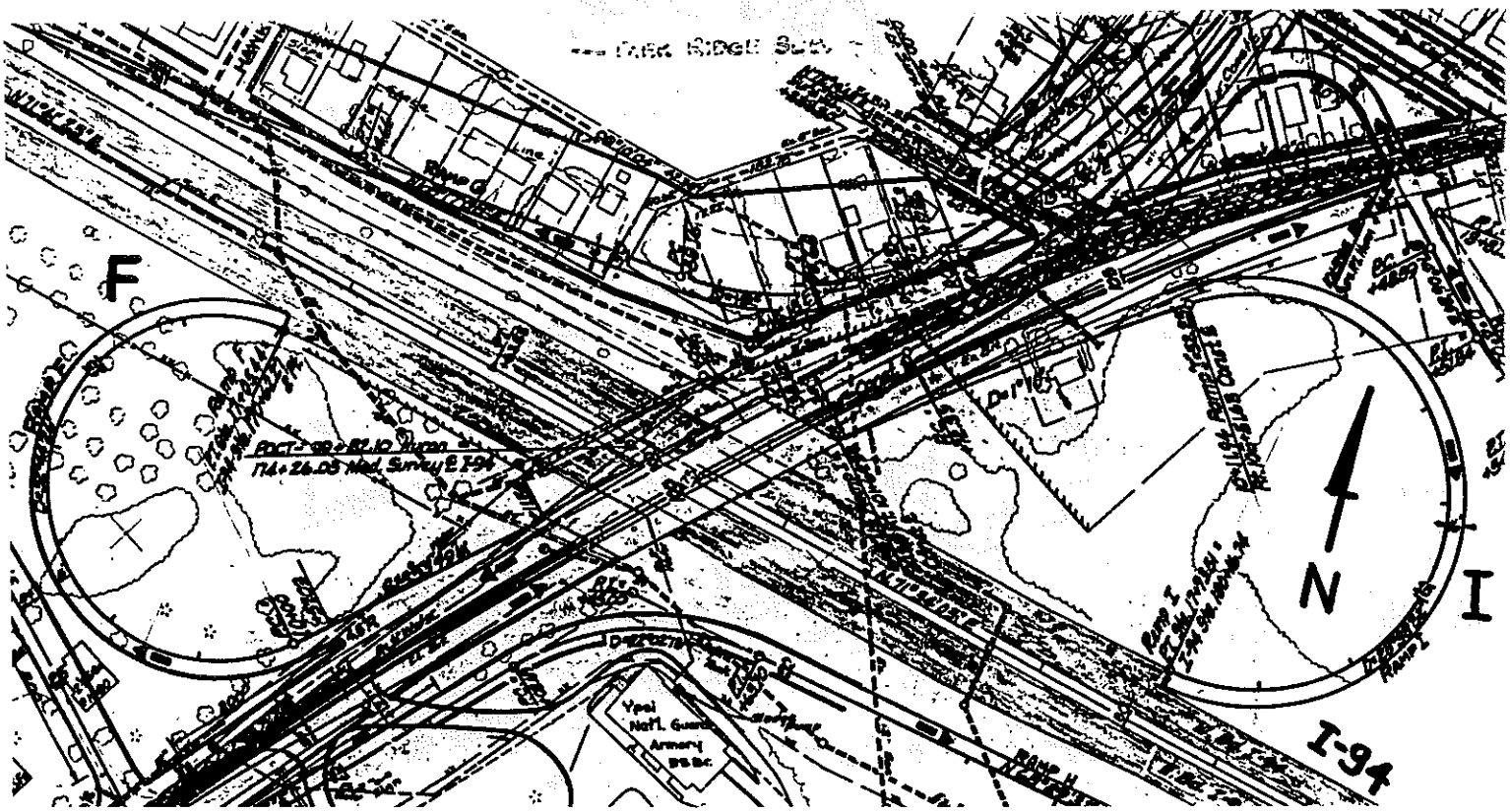


Figure B-14. Ramps F and I at Huron and I-94, from site 4

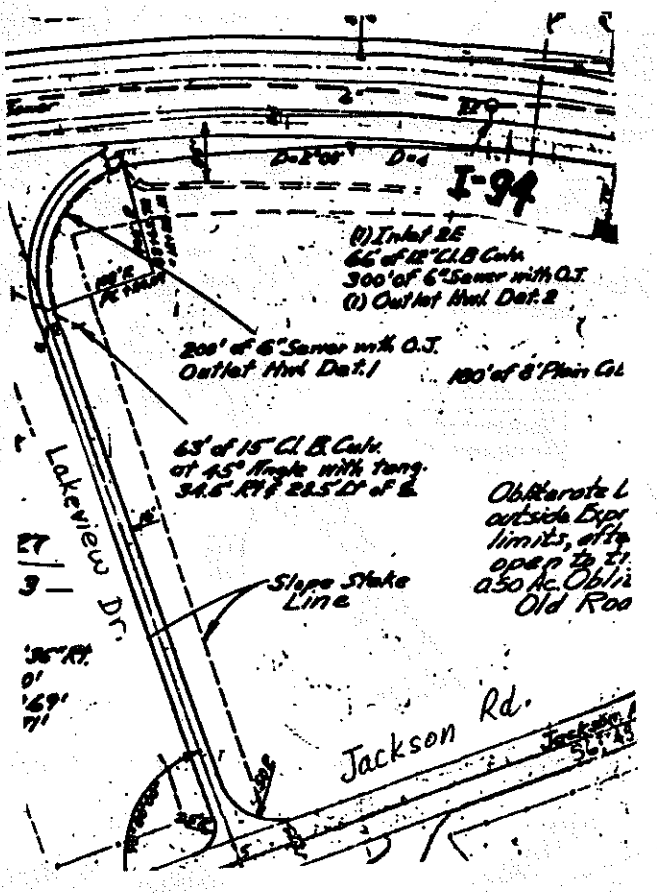


Figure B-15. Jackson Rd. to Lakeview Dr. to I-94, from site 4

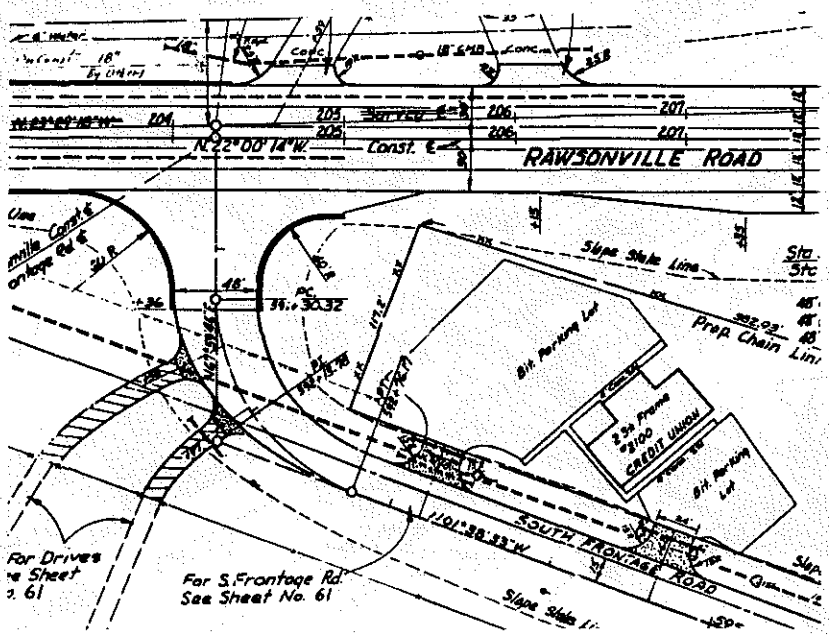


Figure B-16. Rawsonville Rd. to South Frontage Rd., from site 7

Selected sites for acceleration across an intersection

Acceleration across an intersection, or acceleration from a stand still, is a performance mode that evaluates crossing truck as an obstacle to the other traffic. A slow acceleration, combined with a limited sight distance, might force the through traffic to brake or deviate to avoid the truck that has not cleared the intersection. Two typical scenarios were selected: urban traffic and transitioning from the freeway to the arterial road.

Urban traffic — intersections portrayed in site 4 (see figures B-11 through B-13)

Transitions — I-94 to Jackson Road westbound (left turn) on drawing sets 6 and 8

ramp C from US-23 (southbound) onto US-12 (eastbound) in set 6

ramp K from I-94 (westbound) onto Huron Street eastbound in site 9

ramp J from I-94 (westbound) across Huron Street in site 9

ramp E from I-94 (eastbound) onto Whittaker Road northbound in site 9

ramp R from I-94 (westbound) onto Haggerty Road southbound in site 10

Selected sites for merging acceleration

Merging acceleration is a performance mode similar to the acceleration from a stand still, only that in this case the truck is at some initial speed. By nature, the typical scenario for this mode is when a truck leaves the ramp and is attempting to merge with the freeway traffic. Sites include:

Jackson Road to I-94 westbound on drawing sets 6 and 8

Jackson Road to I-94 eastbound (departing Lakeview Drive) on drawing sets 6 and 8

Jackson Road to I-94 westbound (left turn) on drawing sets 6 and 8

departing ramp I from Whittaker Road northbound to I-94 (westbound), in site 9

departing ramp U from Haggerty Road northbound to I-94 (westbound), in site 10

urban and rural ramps from the standard design guides

Selected sites for passing sight distance

Passing sight distance will be calculated independent of site-related geometric characteristics. The calculations will be carried out enabling a comparison between new sight distance values and existing ones. Therefore, no site selection is required for this mode calculation.

Selected sites for speed maintenance on upgrades

The state of Michigan, in general, and the representative sites provided by MDOT, in particular, are not very demanding from a gradeability standpoint. None of the site areas portrayed in the drawing sets incorporated long uphill slopes. For the purpose of this study, uphill slope values from the drawings (even short) are assumed as being kept continuous for a long distance. These include:

working zone on I-94 / Willow-Run exit, site 2

Jackson Road to I-94 eastbound (departing Lakeview Drive) on drawing sets 6 and 8

Jackson Road to I-94 westbound (left turn) on drawing sets 6 and 8

Selected sites for median U-turn

Median U-Turn capabilities or limitations will be calculated based on the standard design guides. Geometric details of crossovers are portrayed in drawing VII-670B (two sheets). No other drawing set provided by MDOT included similar information.

Table B-2 is a rewrite of Table B-1, reflecting the performance modes to be evaluated at the selected sites or under the selected standard geometric design guides. Note that due to the nature of the content of the drawings, sites 6 and 8 are combined. The individual road elements to be used at each site are according to the itemized selections listed above.

Site number or Standard design	Benchmark Truck Designs LCVs						Reference Trucks	
	53' Tractor Semitrailer	57' Tractor Semitrailer	Rocky Mountain Double	Turnpike Double	Triple	Turner Truck	48' Tractor Semitrailer	Western Double
2		Upgrade speed		Upgrade speed		Upgrade speed	Upgrade speed	Upgrade speed
3	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking	L.S. Offtracking
4	L.S. Offtracking	Accel. from 0	L.S. Offtracking Accel. from 0	L.S. Offtracking Accel. from 0	Accel. from 0	L.S. Offtracking Accel. from 0	L.S. Offtracking Accel. from 0	L.S. Offtracking Accel. from 0
6, 8	L.S. Offtracking	Accel. from speed Accel. from 0 Upgrade speed	L.S. Offtracking	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed	Accel. from speed Accel. from 0	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed	L.S. Offtracking Accel. from speed Accel. from 0 Upgrade speed
7	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking	L.S. Offtracking
9		Accel. from speed Accel. from 0		Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0
10		Accel. from speed Accel. from 0		Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0	Accel. from speed Accel. from 0
Urban & Rural Interchanges:								
	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking		L.S. Offtracking	L.S. Offtracking	L.S. Offtracking
Urban & Rural Ramps:								
		Accel. from speed		Accel. from speed	Accel. from speed	Accel. from speed	Accel. from speed	Accel. from speed
VII-710A:								
		Passing sight	Passing sight	Passing sight	Passing sight	Passing sight	Passing sight	Passing sight
VII-670B:								
		U-Turn	U-Turn	U-Turn	U-Turn	U-Turn	U-Turn	U-Turn

Table B-2. Performance modes, sites and MDOT standard design guides, and truck configurations

APPENDIX C

SIMULATION RESULTS

This appendix presents the graphic results of simulations performed in this study. The principal results presented here pertain to the work done in Task 3, where various truck simulation programs were used to evaluate the performance levels of LCVs. The simulated roadway environment for these calculations was determined based on an analysis of highway features identified in Task 2.

A total of six roadway feature elements were selected to be addressed in the framework of this work. These features, and the order in which they are presented in this appendix, are:

- *low speed offtracking*
- *acceleration across an intersection (acceleration from a standstill)*
  - — *acceleration across a four-way intersection*
  - — *acceleration across a three-way intersection*
- *acceleration from an initial speed (merging acceleration)*
- *speed maintenance on upgrades*
- *median U-Turn*

Results of the calculations that were performed to evaluate passing sight distance are not presented here, but are presented and discussed at length in appendix D.

Low-Speed Offtracking

Low speed offtracking was evaluated for road elements that are related to highways, and to arterial and urban roads. Three typical scenarios were selected: an urban traffic area, three representative access ramps, and some transitional roadway sections.

Urban traffic — roads portrayed in site 4;

Access ramps — Ramp F (R = 175 ft) on site 9;

Ramp I (R = 200 ft) on site 9;

Ramp M (R = 230 ft) on site 3;

Transitions — Jackson Road to Lakeview to I-94 on drawing sets 6 and 8;

I-94 to Jackson Road eastbound (right turn) on drawing sets 6 and 8;

from ramp H to Belleville Road on site 3;

Rawsonville Road (southbound) to south Frontage Road eastbound (site 7);

urban and rural interchanges from the standard design guides.

Content of this section

Simulation results of the offtracking runs are included in this section. Turning radii used in the calculations were according to the tightest possible turn of the baseline tractor (40 ft).

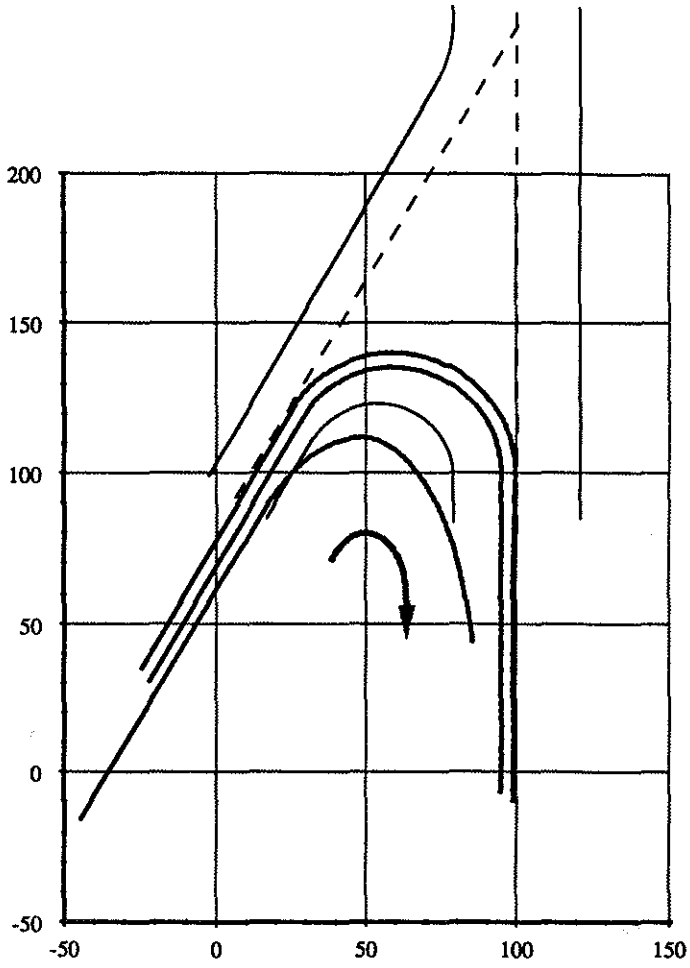
Urban traffic — The geometric layout of each site is provided in the main body of the report. Individual results are provided in this section.

Access ramps — On all ramps, offtracking reaches steady state. Followed by a representative ramp and path sketch, the individual steady state offtracking values are plotted for each combination vs. the ramp's radius.

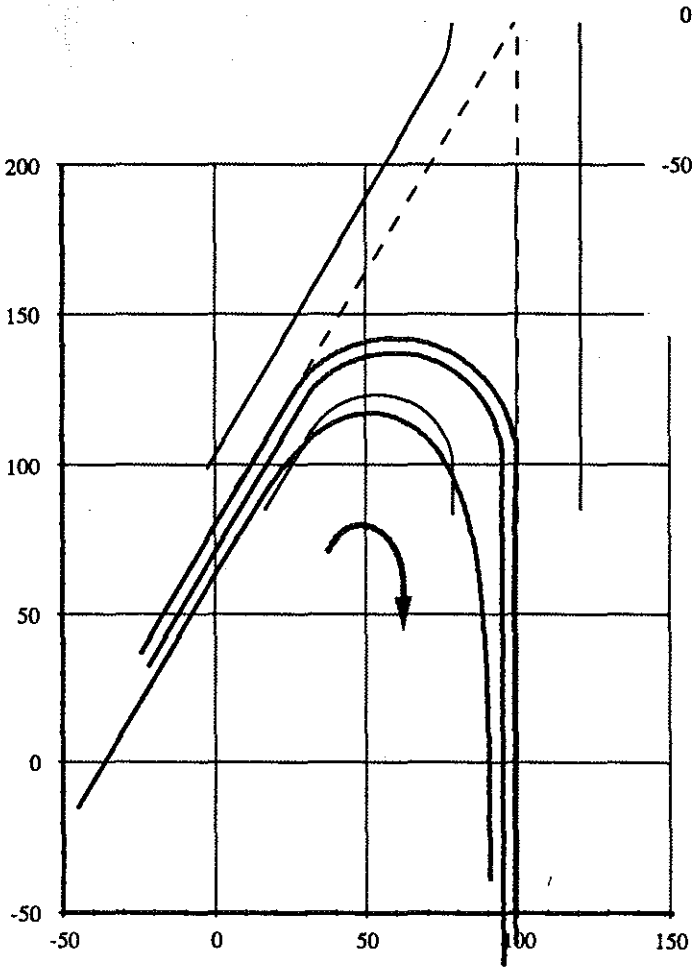
Transitions — Except for the site 7 (Rawsonville Road (southbound) to south Frontage Road eastbound), the results are presented as those for urban traffic. For site 7, a complete path through the required "S" turn is portrayed for the turnpike double. With this worst case being successful, there was no need to examine the other combinations in detail.

Notes:

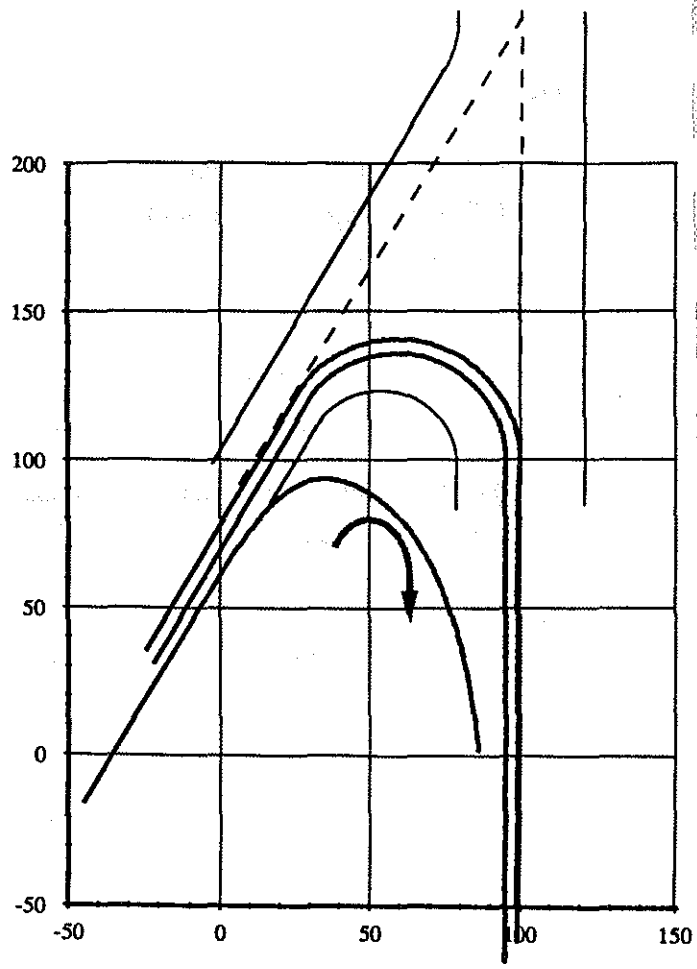
1. Dimensions for the figures in the following pages C-3 through C-11 can be extracted by the scaled mesh (given in feet.)
2. All turns are executed at a turning radius of 40 ft (see 3.1.1 in the report.)
3. Specific roadway dimensions are given in figures 8 through 11 of the report.
4. Tables 3 through 6 summarize the offtracking values.



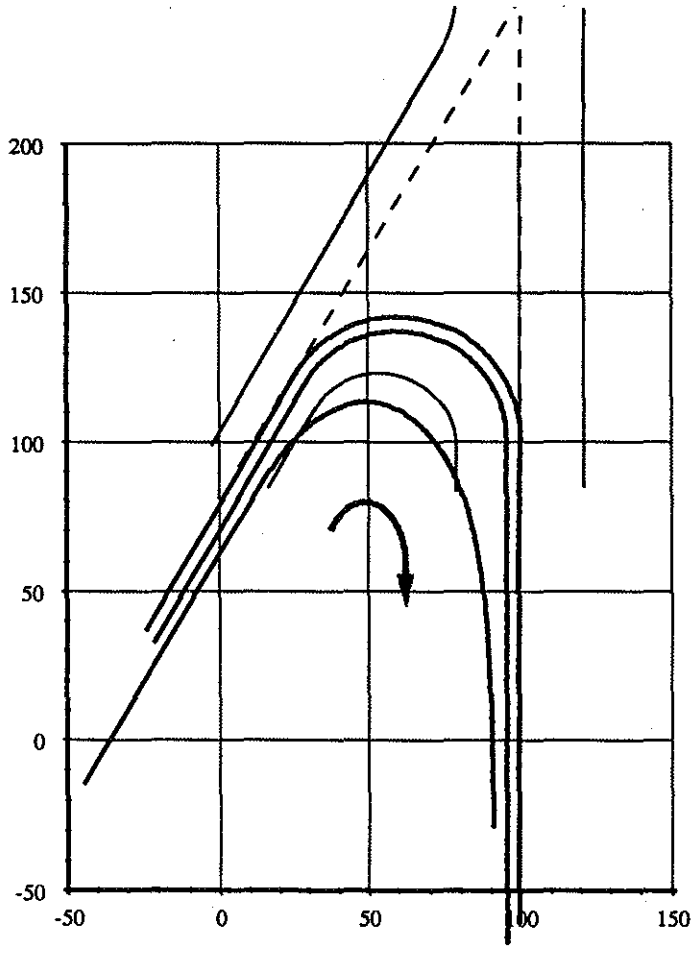
48ft semi at Austin & Michigan ave.



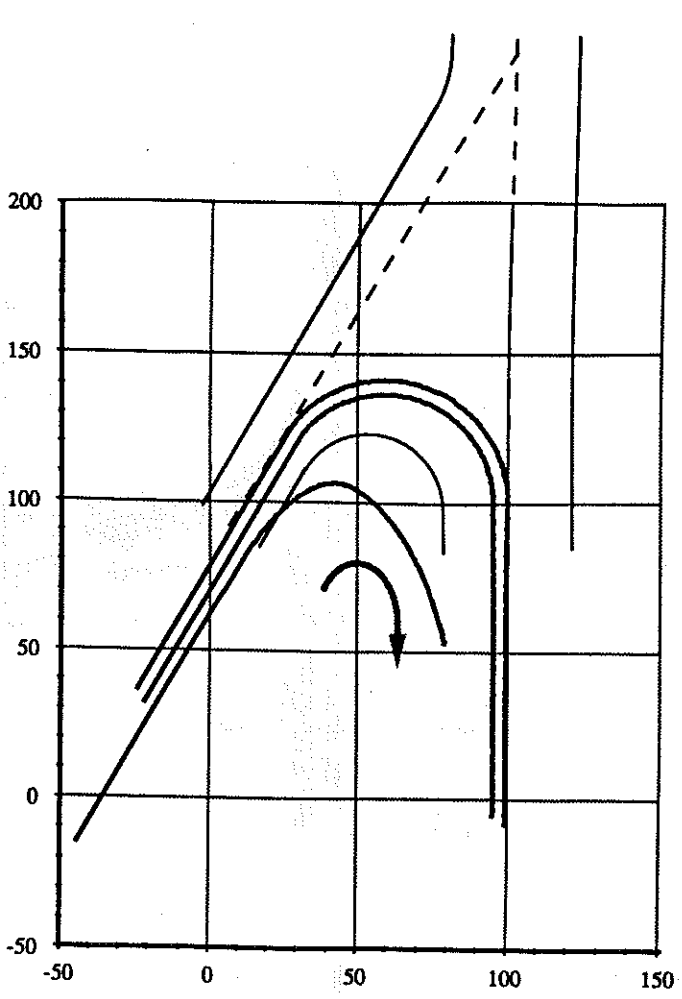
Western Double at Austin & Michigan ave.



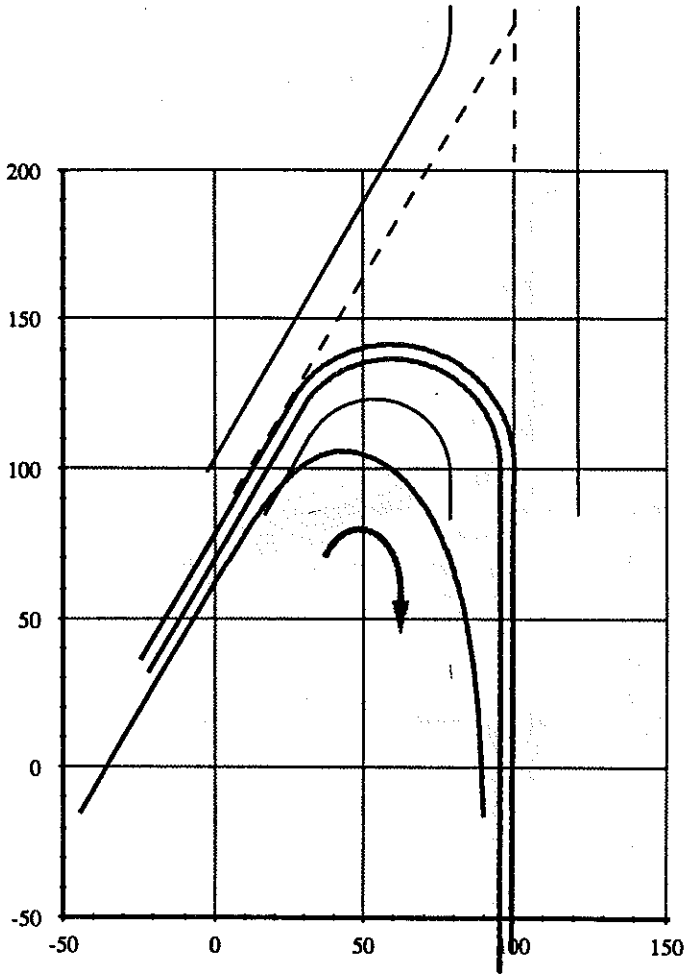
Turnpike Double at Austin & Michigan ave.



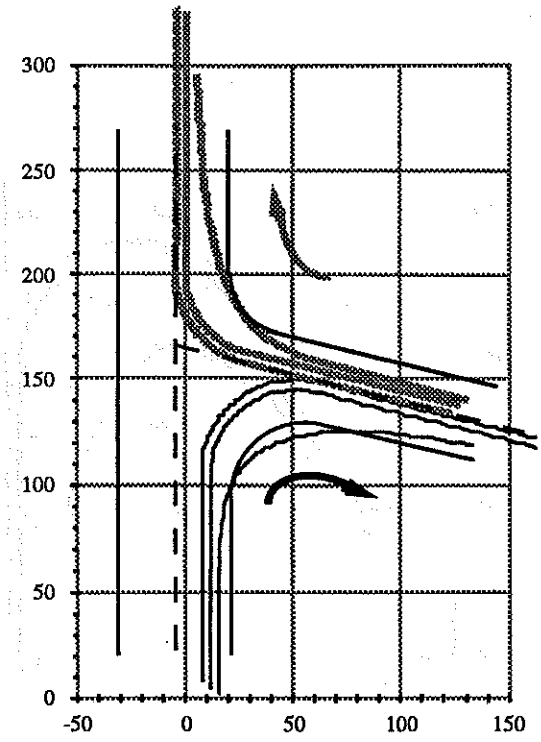
Turner (doubles) at Austin & Michigan ave.



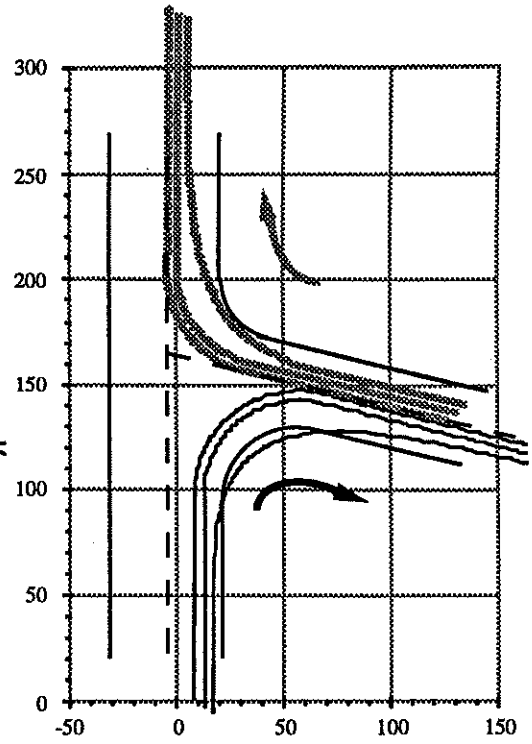
57ft semi at Austin & Michigan ave.



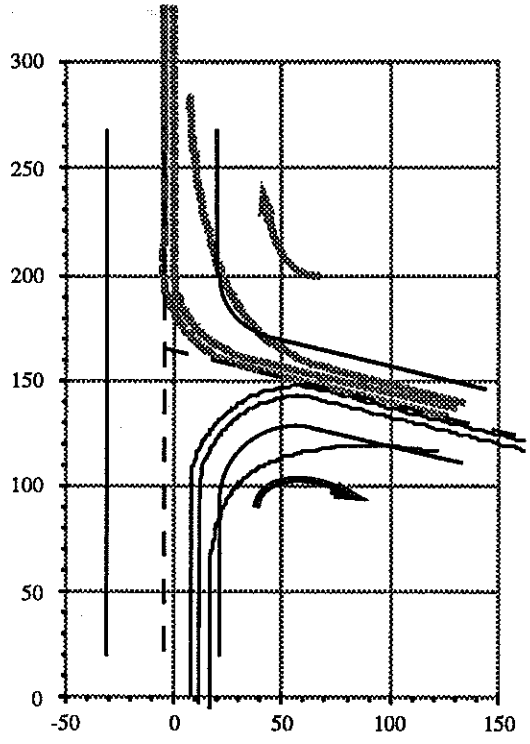
Rocky Mountain Double at Austin & Michigan ave



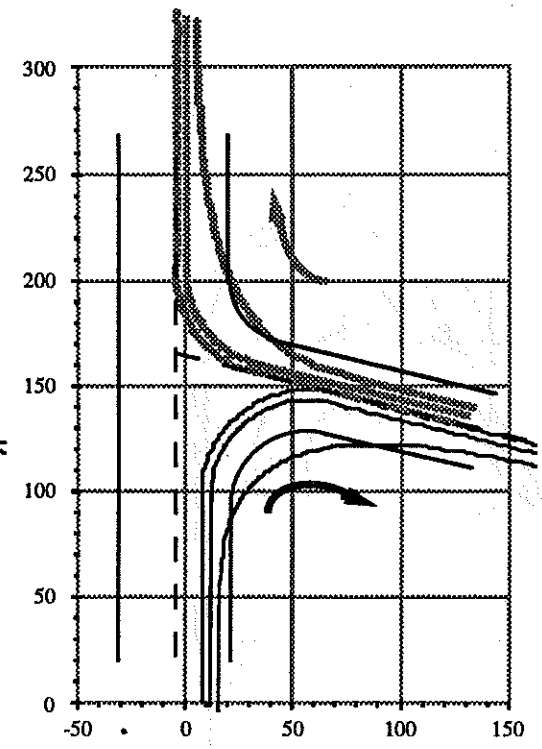
48ft semi at Monroe & Michigan ave.



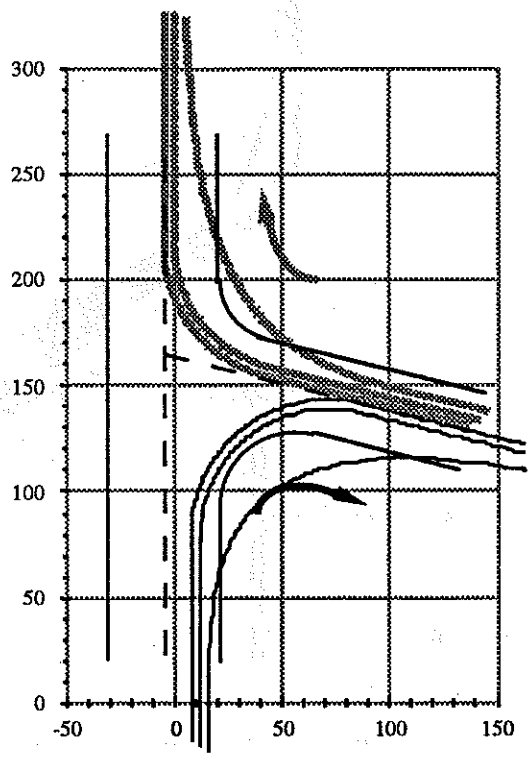
Western Double at Monroe & Michigan ave.



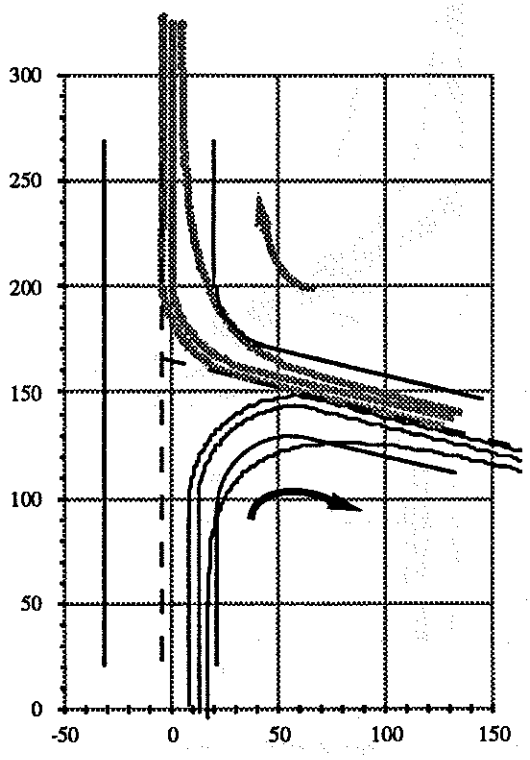
57ft semi at Monroe & Michigan ave.



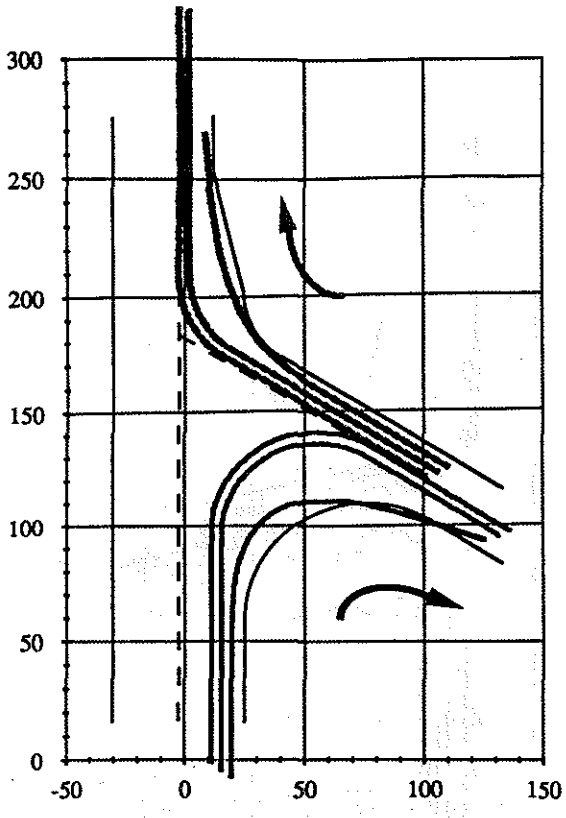
Rocky Mountain Double at Monroe & Michigan ave



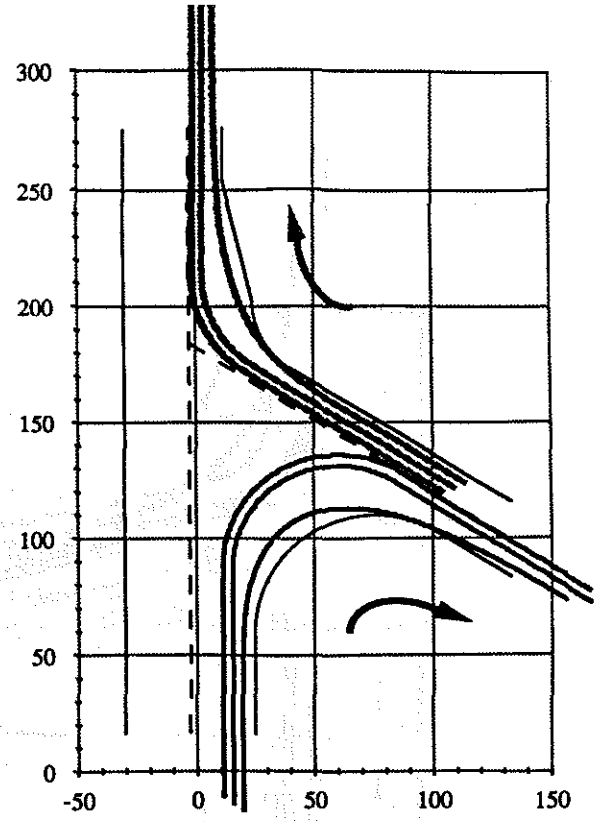
Turnpike Double at Monroe & Michigan ave.



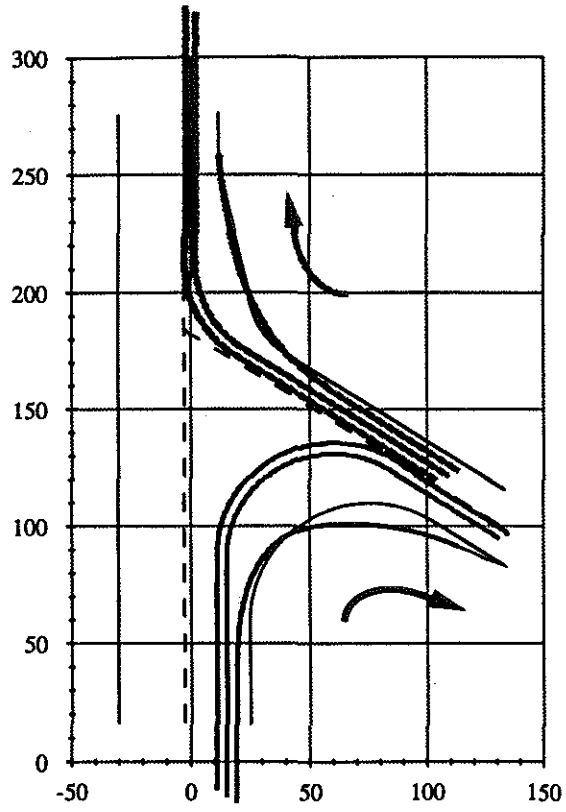
Turner (doubles) at Monroe & Michigan ave.



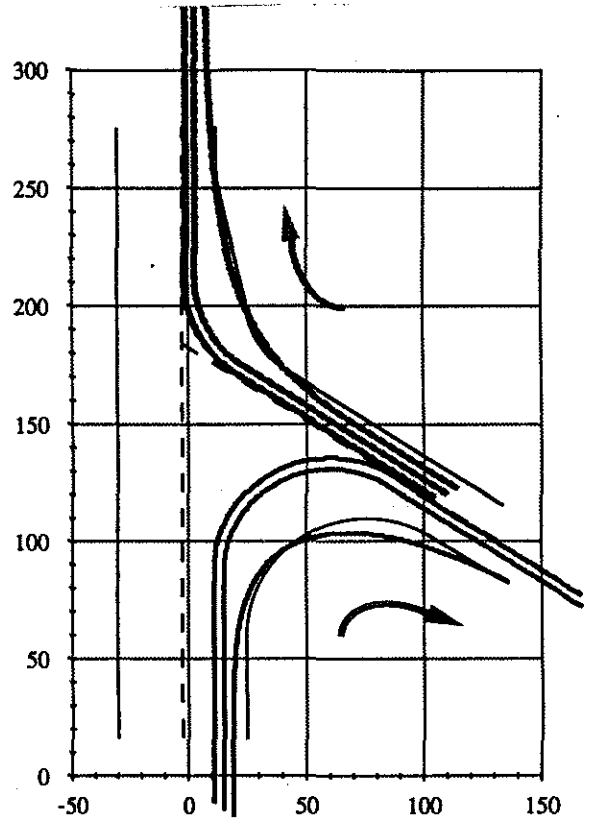
48ft semi at Fosdick & Michigan ave.



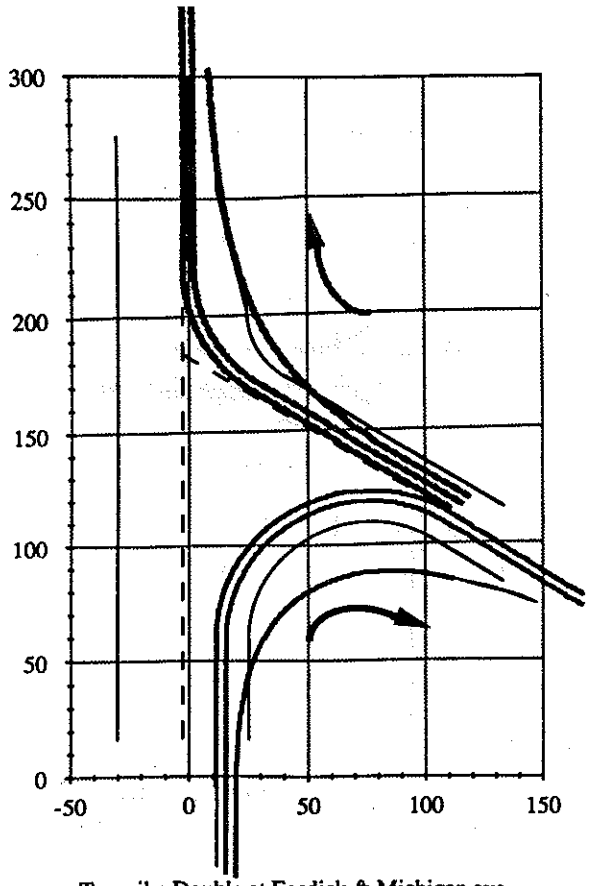
Western Double at Fosdick & Michigan ave.



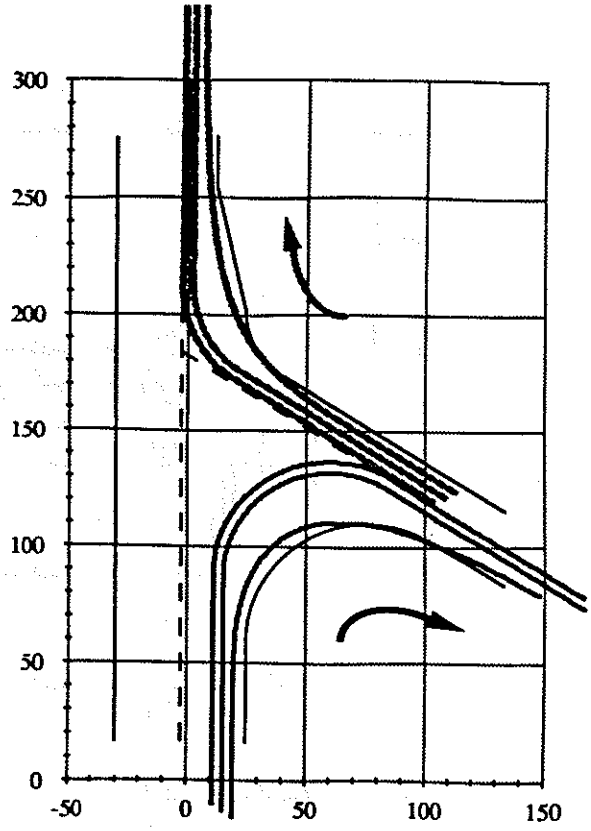
57ft semi at Fosdick & Michigan ave.



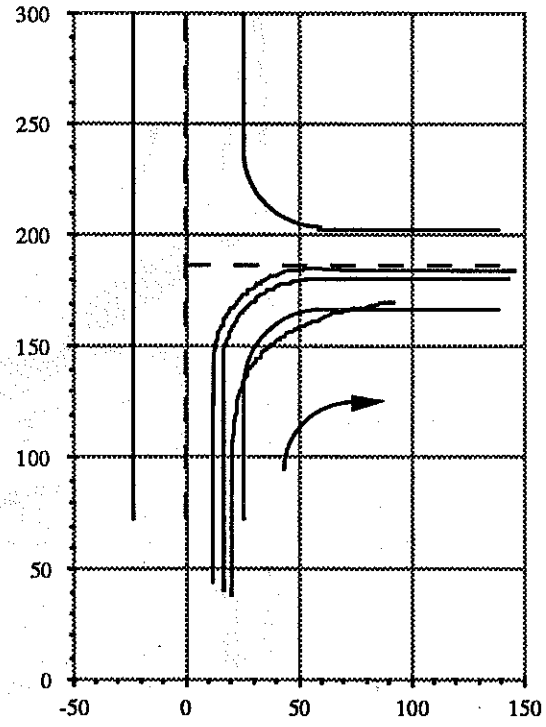
Rocky Mountain Double at Fosdick & Michigan ave



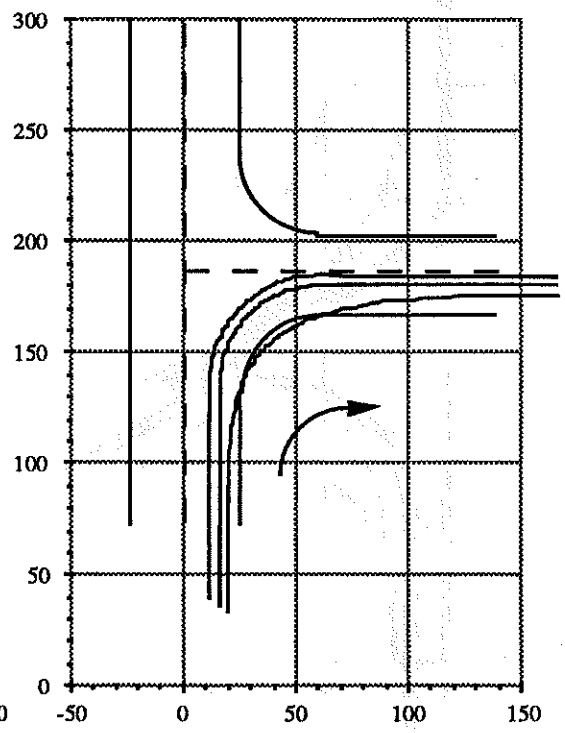
Turnpike Double at Fosdick & Michigan ave.



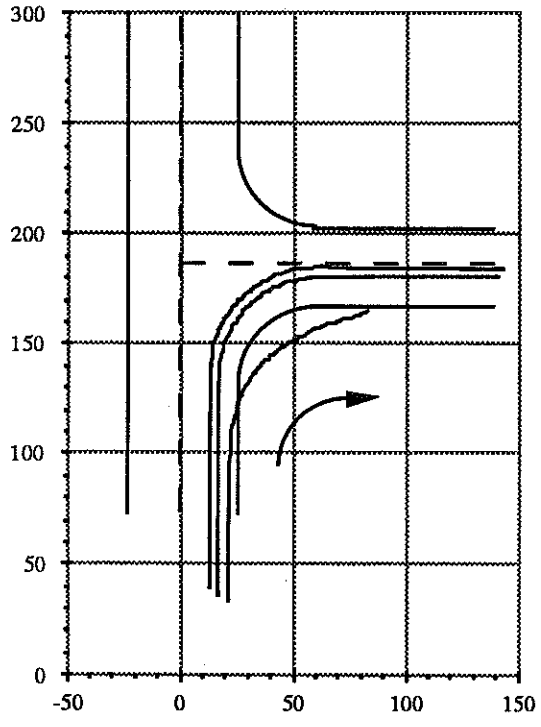
Turner (doubles) at Fosdick & Michigan ave.



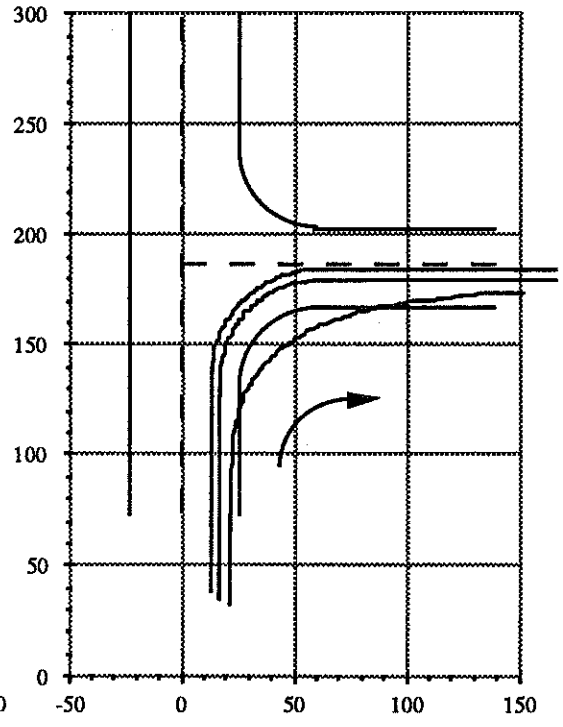
48ft semi at Mills & Michigan ave.



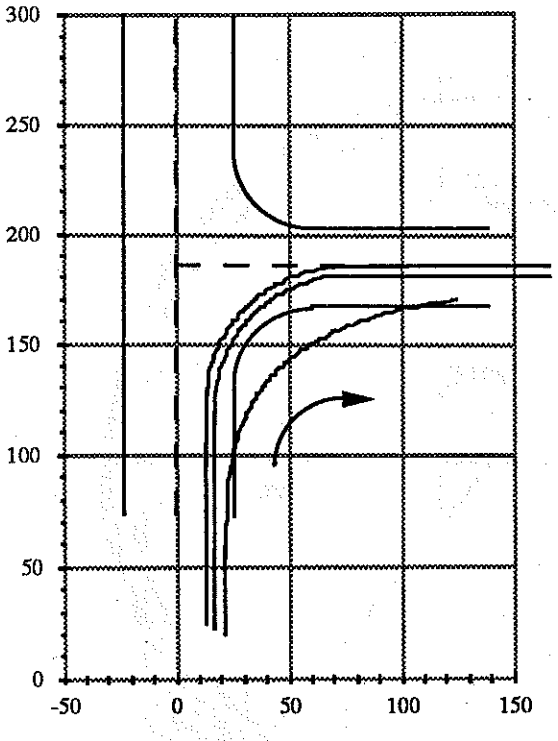
Western Double at Mills & Michigan ave.



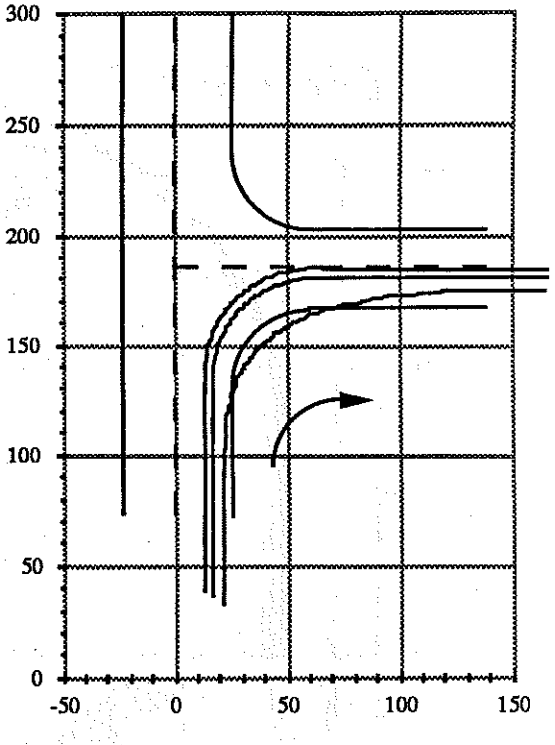
57ft semi at Mills & Michigan ave.



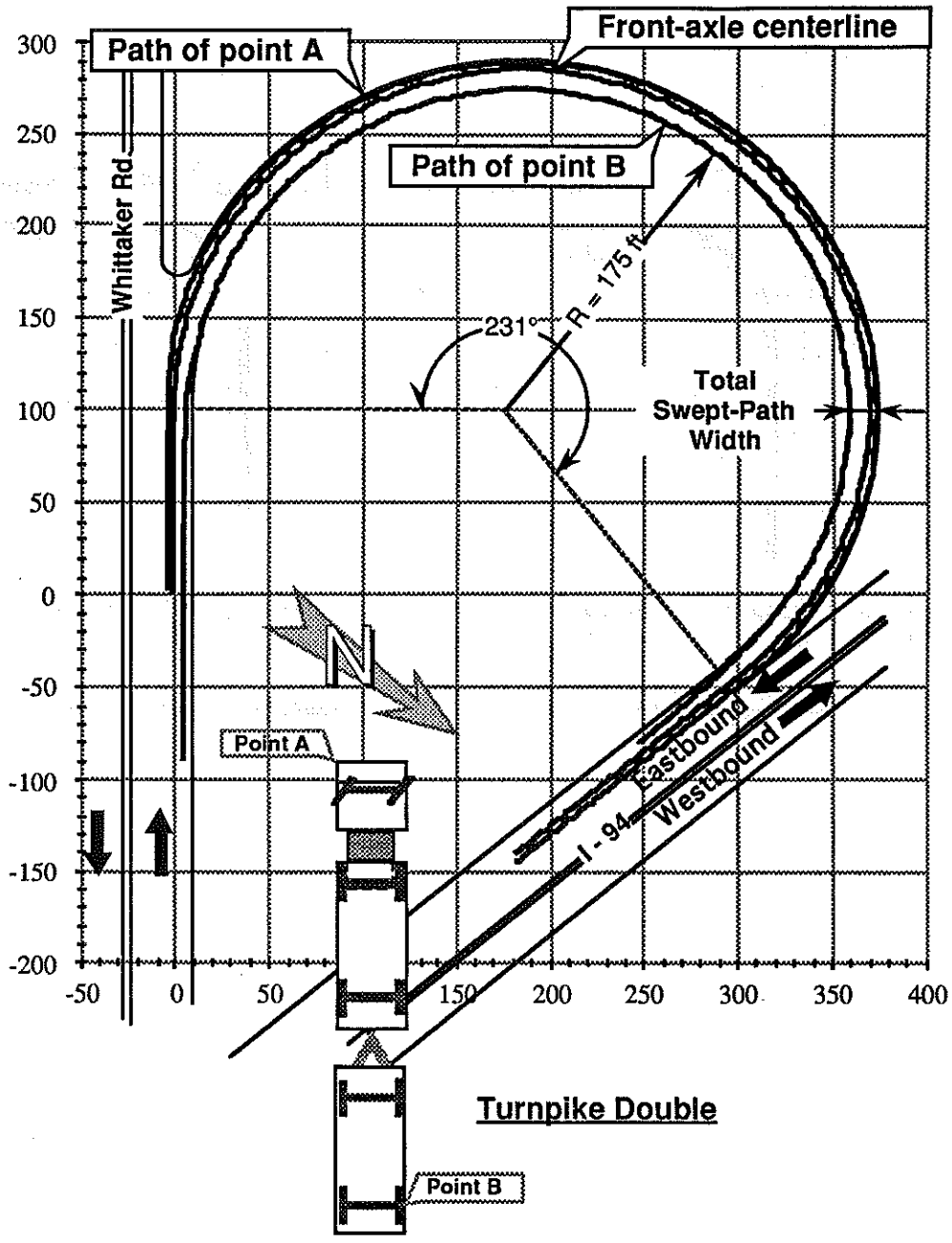
Rocky Mountain Double at Mills & Michigan ave



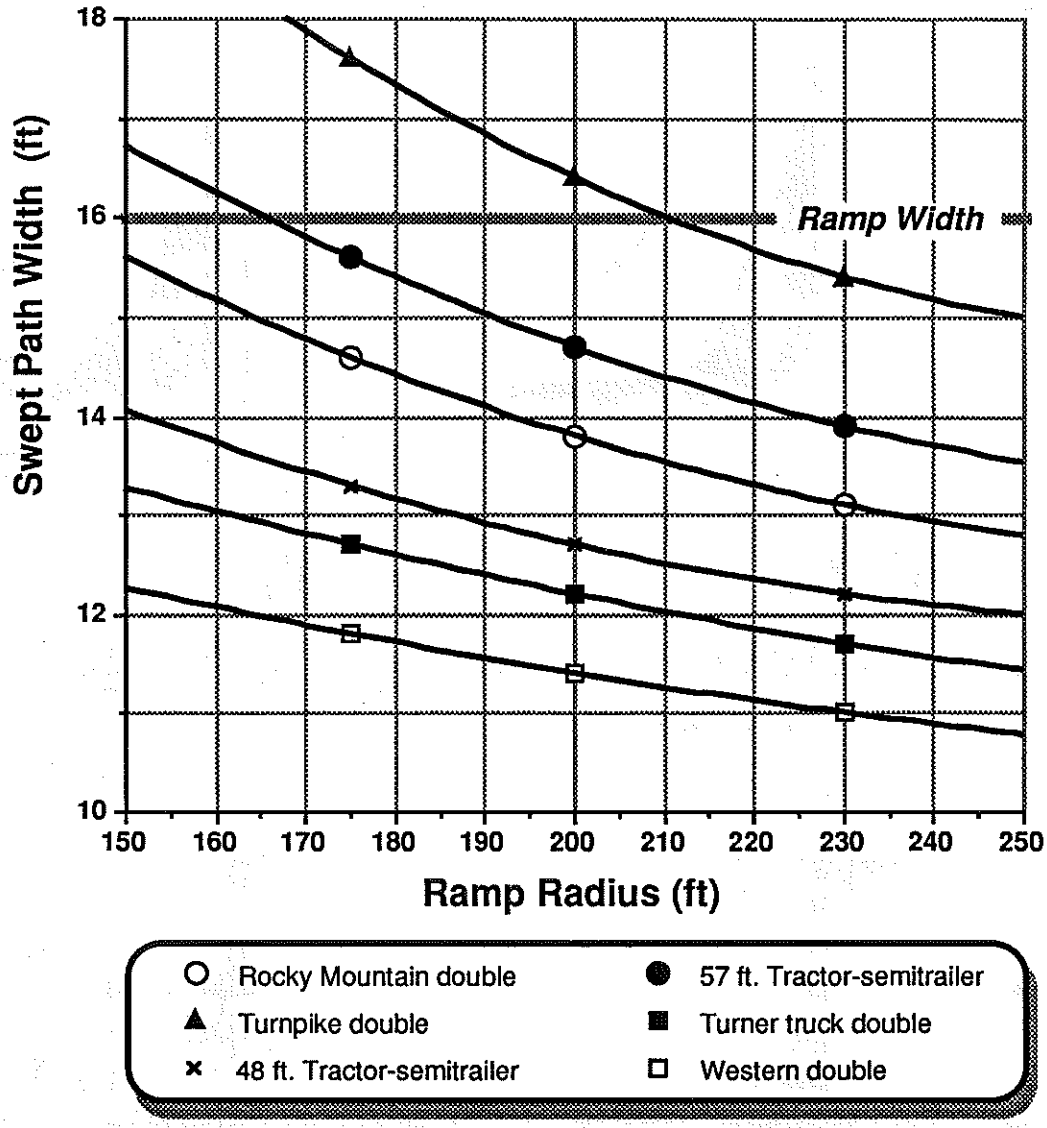
Turnpike Double at Mills & Michigan ave.

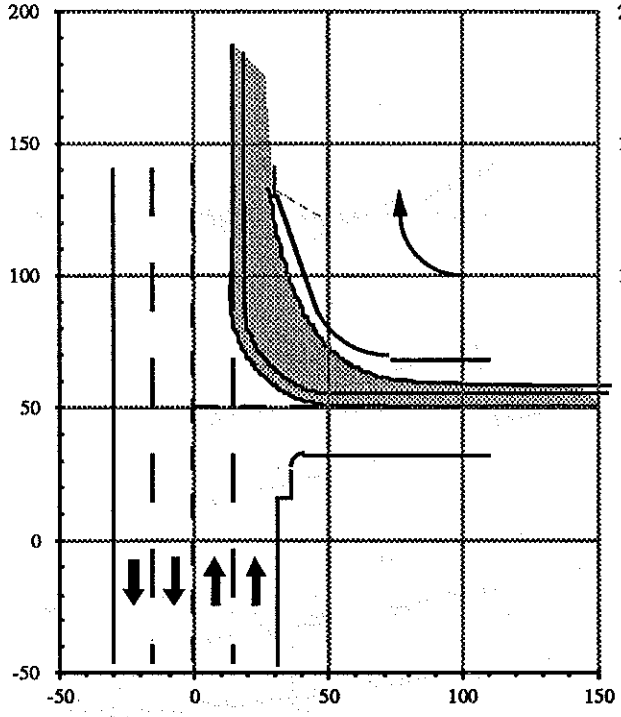


Turner (doubles) at Mills & Michigan ave.

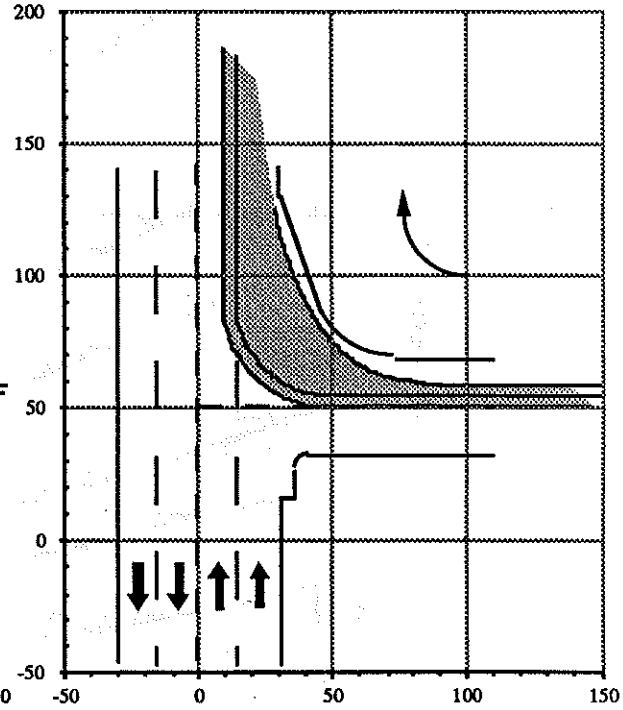


Turnpike Double on ramp F, from Whittaker Road southbound to I-94 eastbound

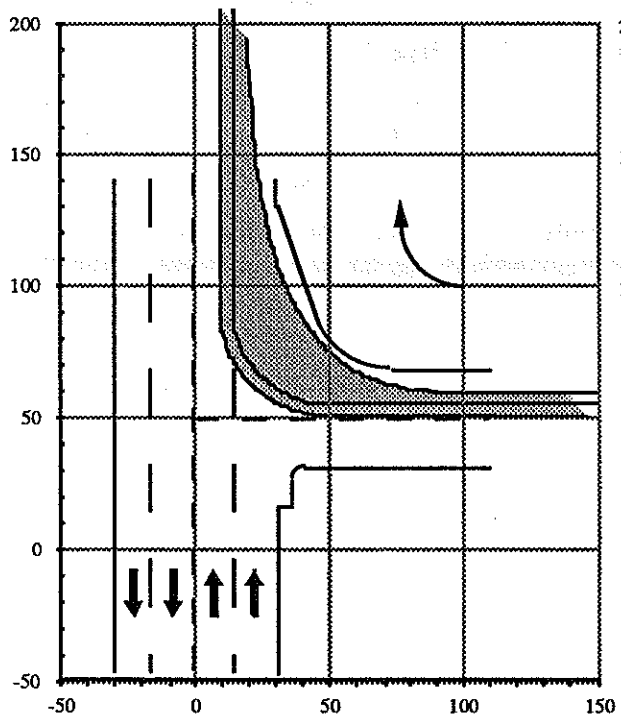

Swept Path Width (ft)
18
16
14
12
10
Ramp Width
150
160
170
180
190
200
210
220
230
240
250
Ramp Radius (ft)
Rocky Mountain double
Turnpike double
48 ft. Tractor-semitrailer
57 ft. Tractor-semitrailer
Turner truck double
Western double



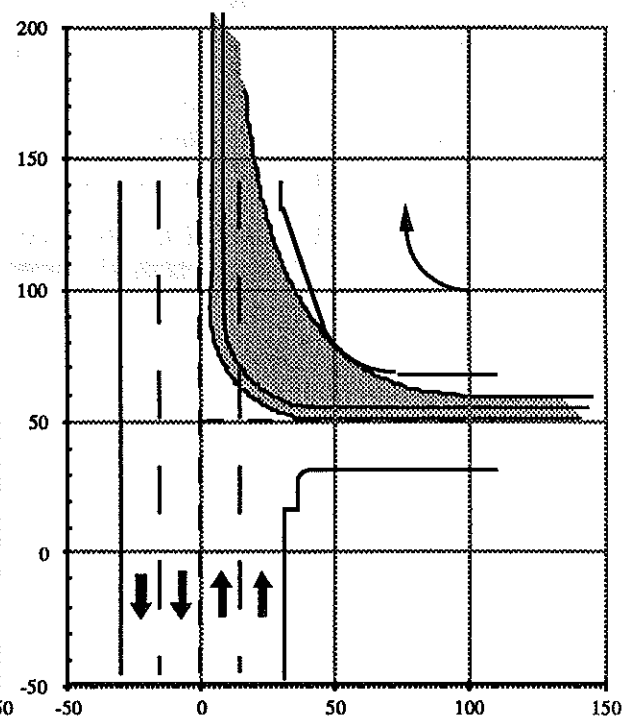
48ft semi from ramp H to Belleville Rd.



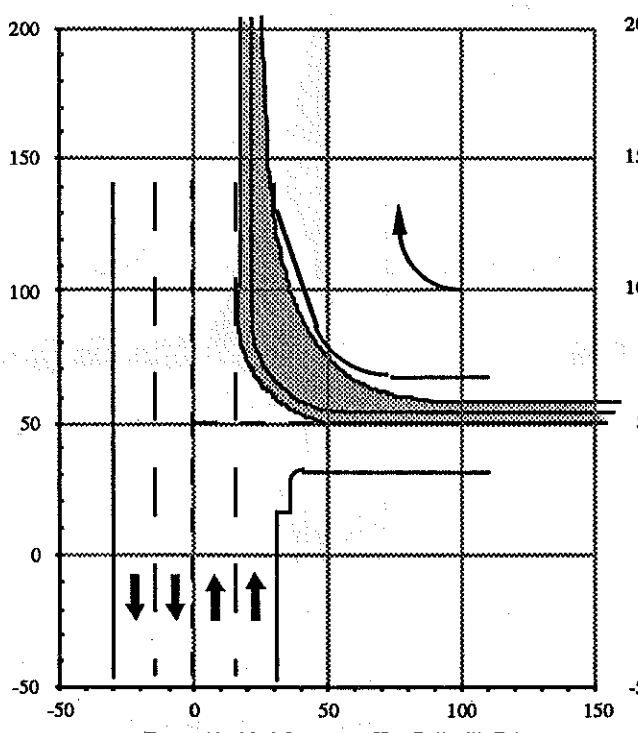
57ft semi from ramp H to Belleville Rd.



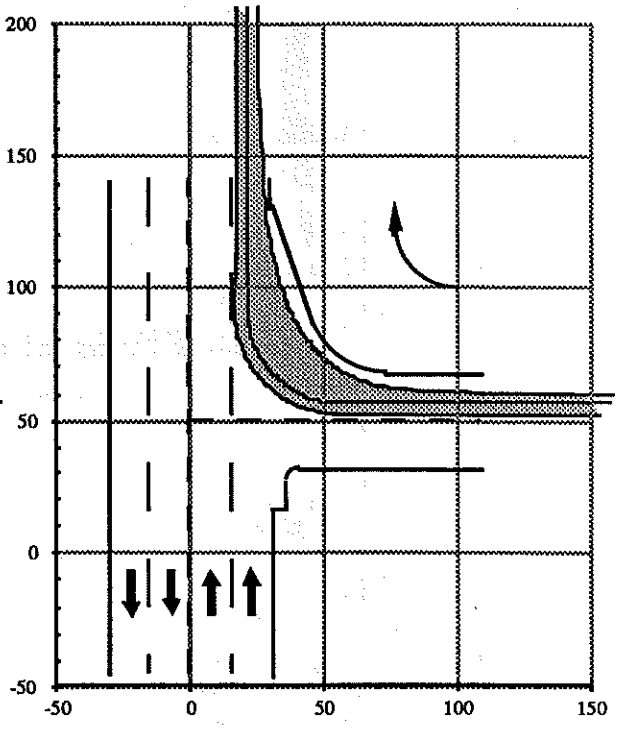
Rocky Mountain Double from ramp H to Belleville Rd.



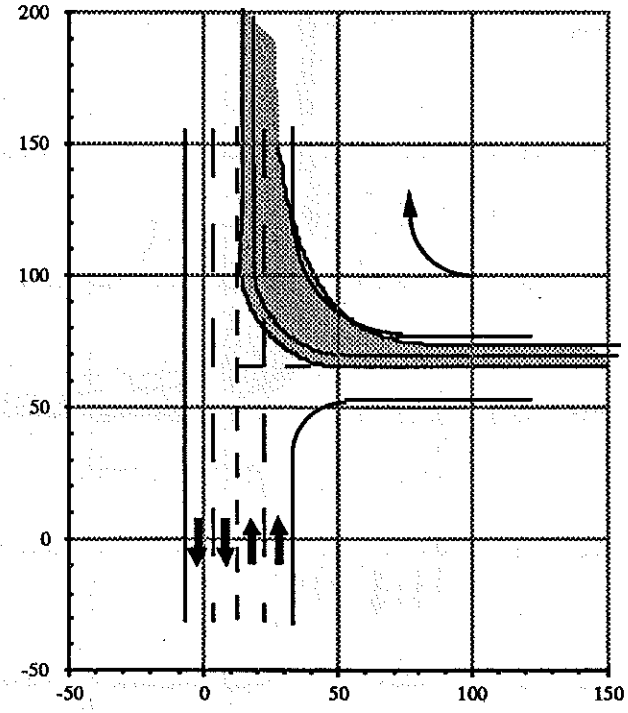
Turnpike Double from ramp H to Belleville Rd.



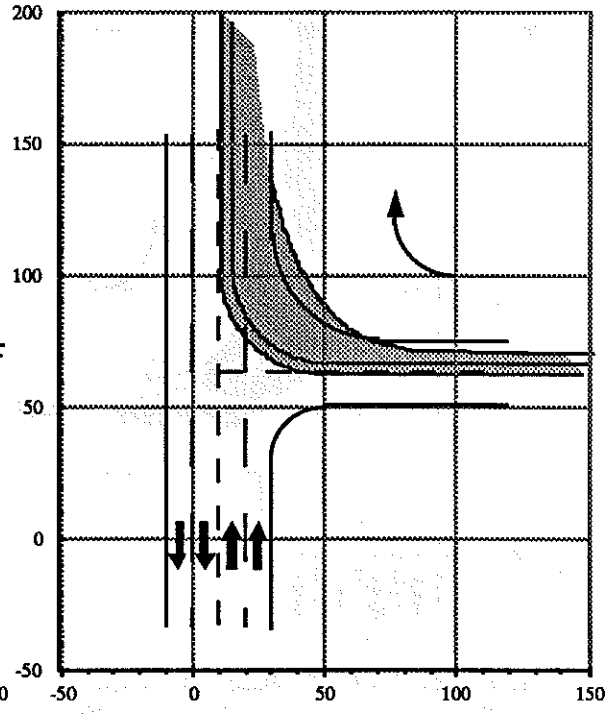
Turner (doubles) from ramp H to Belleville Rd.



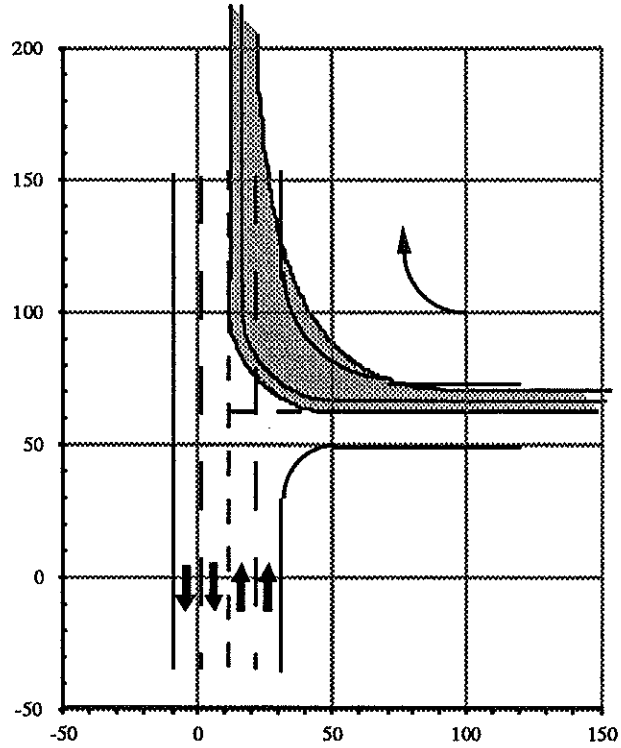
Western Double from ramp H to Belleville Rd.



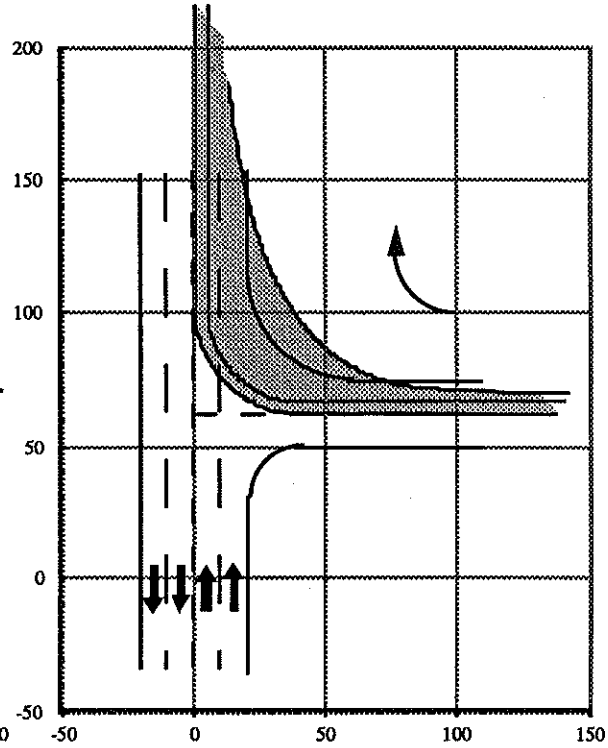
48ft semi from I-94 to Jackson Rd.



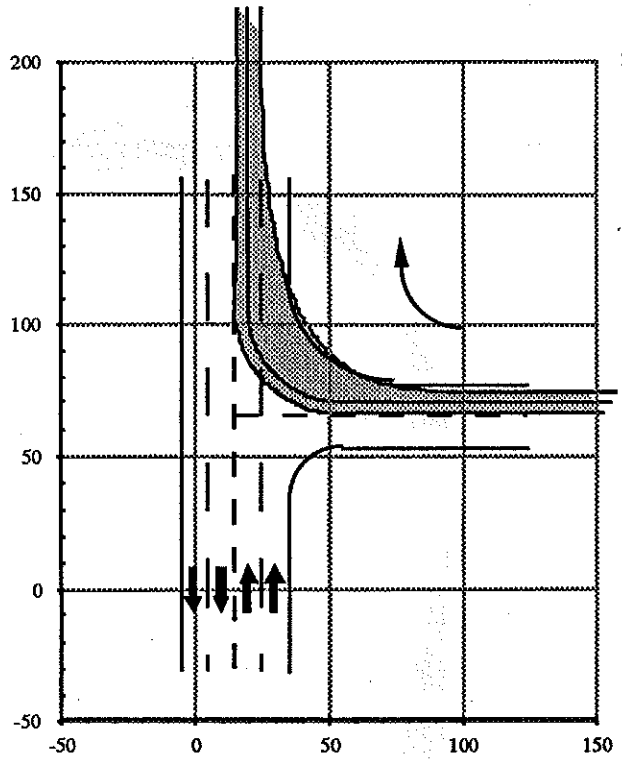
57ft semi from I-94 to Jackson Rd.



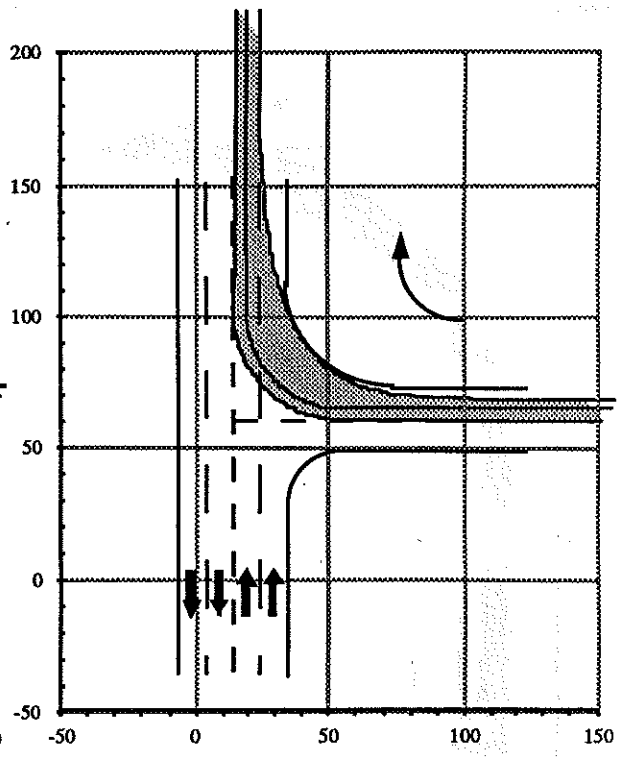
Rocky Mountain Double from I-94 to Jackson Rd.



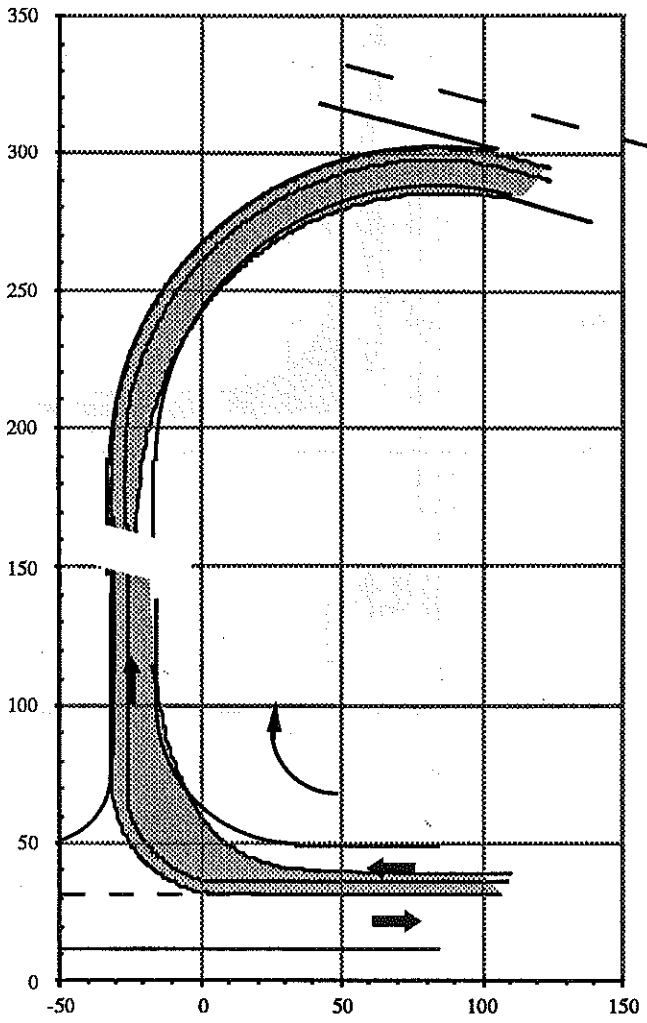
Turnpike Double from I-94 to Jackson Rd.



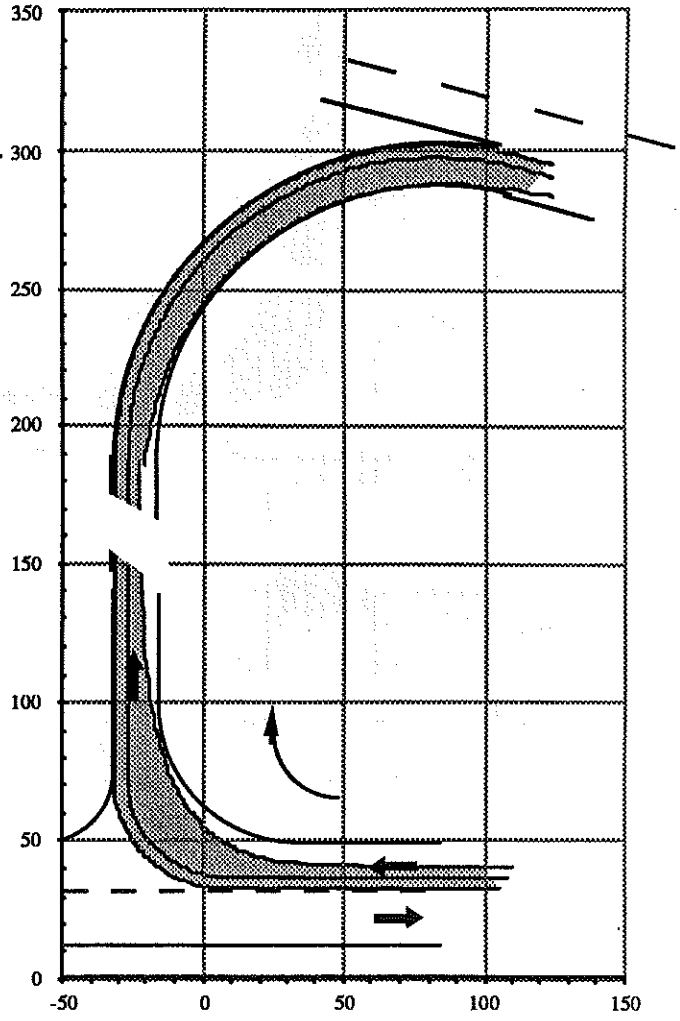
Turner (doubles) from I-94 to Jackson Rd.



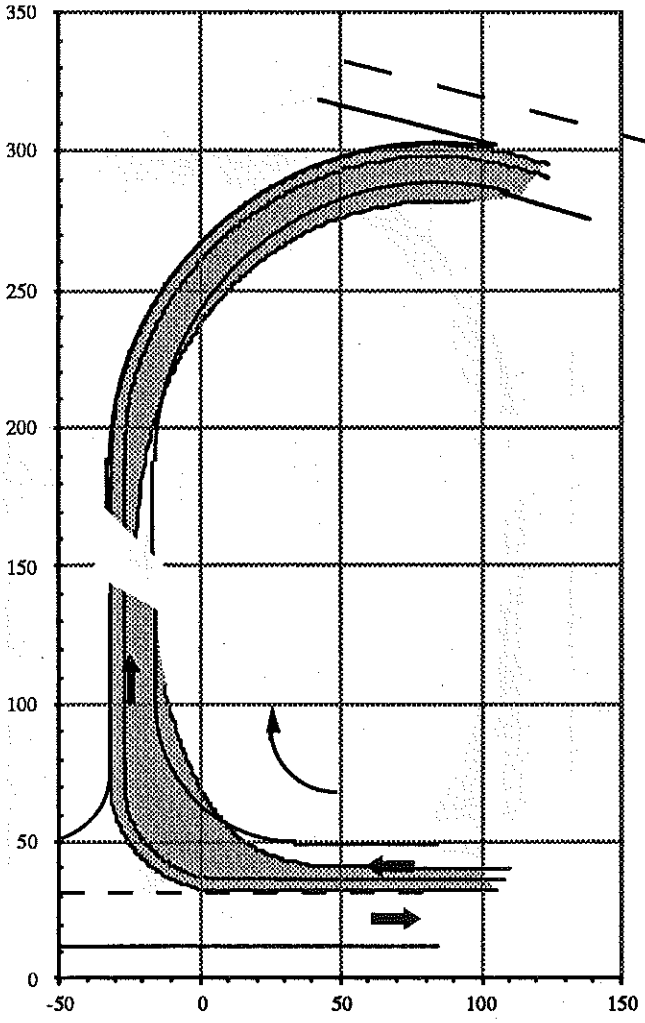
Western Double from I-94 to Jackson Rd.



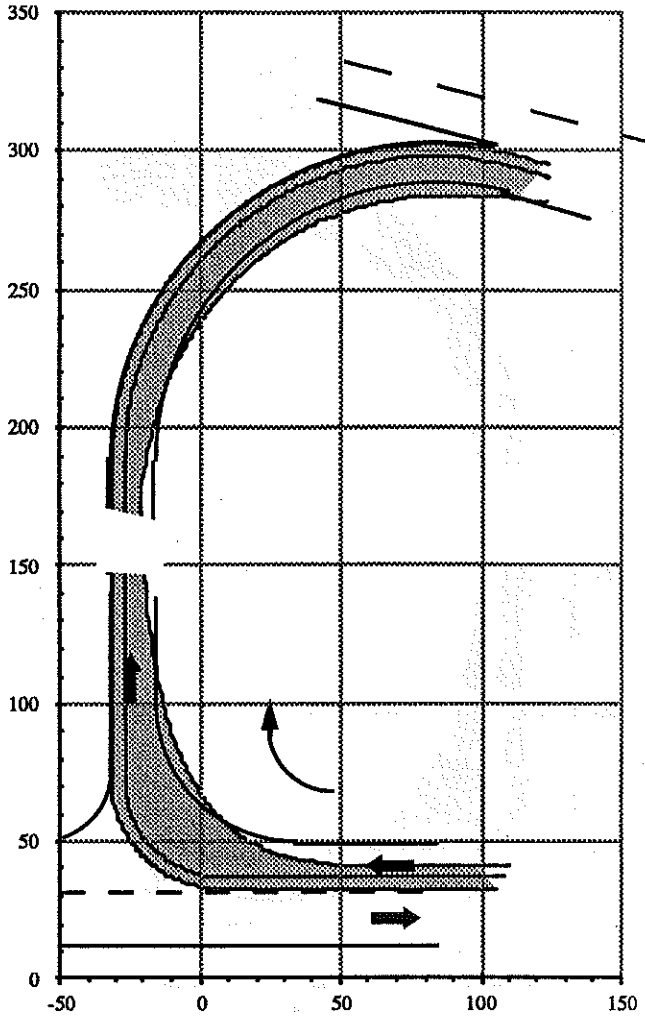
48ft semi at Jackson to I-94 EB



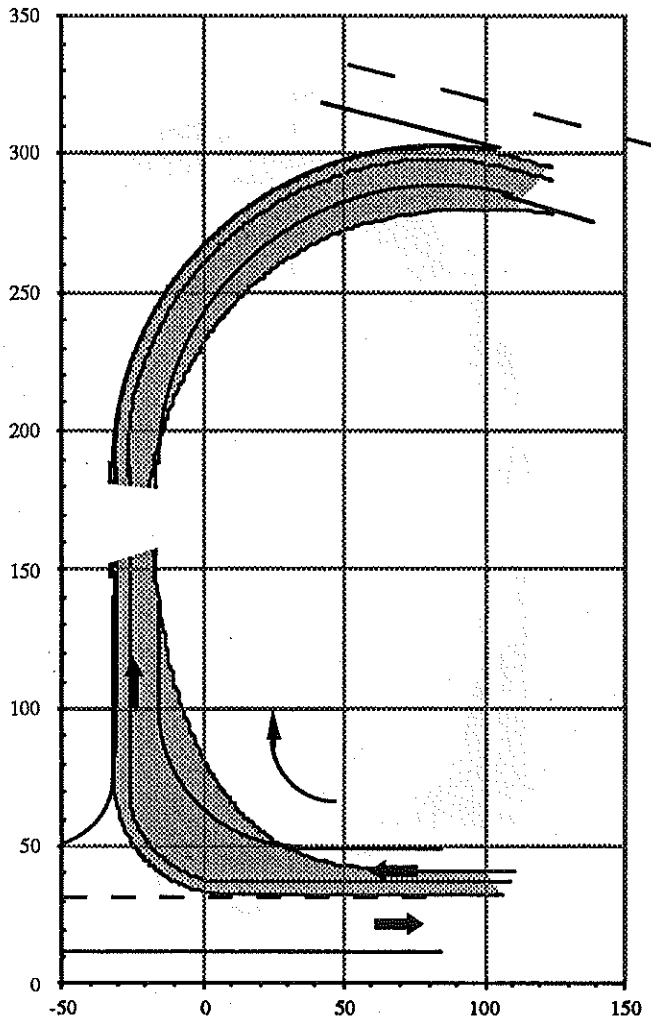
Western Double at Jackson to I-94 EB



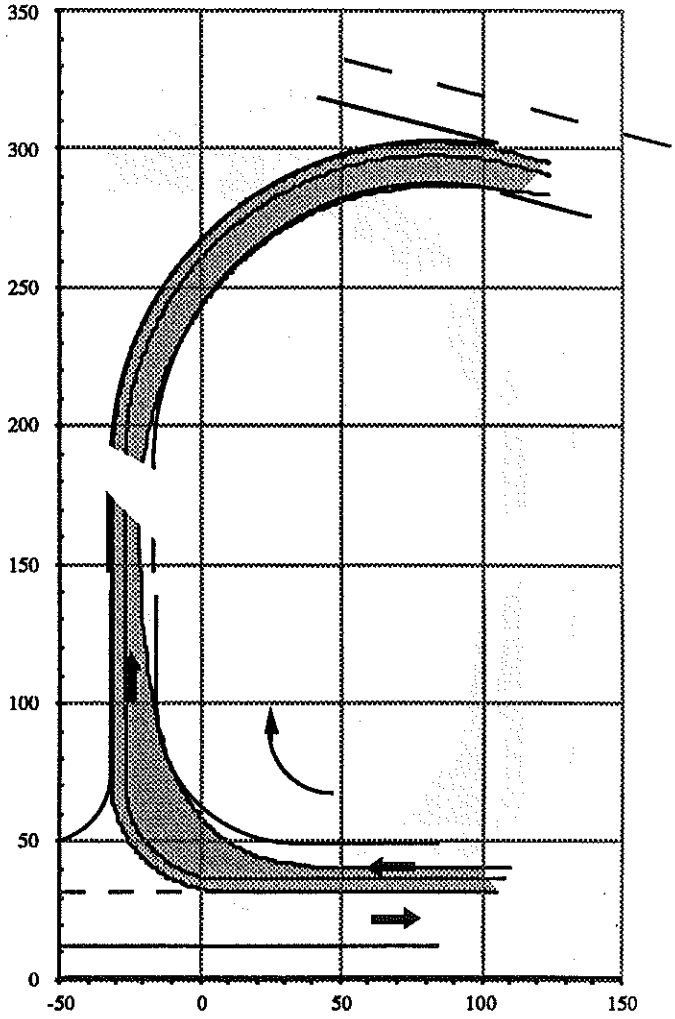
57ft semi at Jackson to I-94 EB



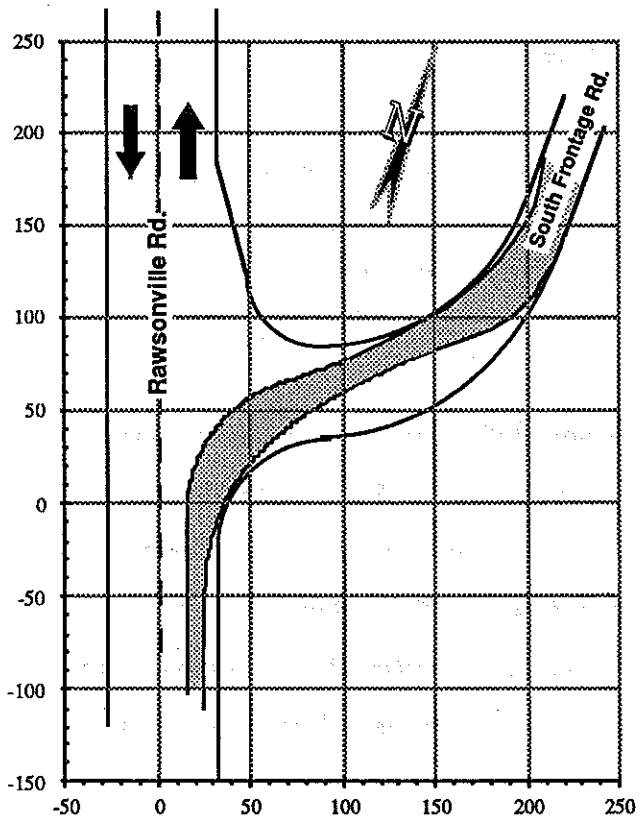
Rocky Mountain Double at Jackson to I-94 EB



Turnpike Double at Jackson to I-94 EB



Turner (doubles) at Jackson to I-94 EB



Turnpike Double at Rawsonville and S. Frontage Rd.

Acceleration Across an Intersection

Two typical scenarios to evaluate acceleration across an intersection, or acceleration from a stand still were selected: urban traffic and transitioning from the freeway to the arterial roads. The first scenario mostly involves four-way intersections, where the truck needs to cross an intersecting road. The second one involves mainly three-way intersections, where the truck needs to merge with the traffic of the intersecting road.

Urban traffic — Intersections portrayed in site 4;

Transitions — I-94 to Jackson Road westbound (left turn) on drawing sets 6 and 8;

Ramp C from US-23 (southbound) onto US-12 (eastbound) in set 6.

Ramp J connector from I-94 (westbound) onto Hamilton Street in site 9;

Ramp J from I-94 (westbound) across Huron Street in site 9;

Ramp E from I-94 (eastbound) onto Whittaker Road northbound in site 9;

Ramp R from I-94 (westbound) onto Haggerty Road southbound in site 10;

Content of this section

The geometric layout of each type of intersection, with an explanation of the criteria used in evaluating truck performance, precedes the plotted results. The results for the four-way intersections are graphically presented as time-to-clear different intersection widths: the road is considered flat (0% slope). All truck combinations are displayed on a single combined plot. The results for the three-way intersections are presented for each truck combination separately. Results are also provided for various grades.

For different truck combinations, the distance to reach a speed on various grades is provided in the following tables (the speed is expressed in mph and the distance in feet):

• On a flat, horizontal road:

Speed to get to:	Truck combination				
	48 ft TST	Western double	RMD	Triple	TPD
10	65	70	68	67	68
15	139	143	140	158	160
20	266	295	291	321	313
25	464	510	506	601	546

• On a 2% upgrade:

Speed to get to:	Truck combination				
	48 ft TST	Western double	RMD	Triple	TPD
10	67	73	70	75	70
15	156	164	167	201	179
20	332	365	369	465	405
25	627	727	746	1042	866

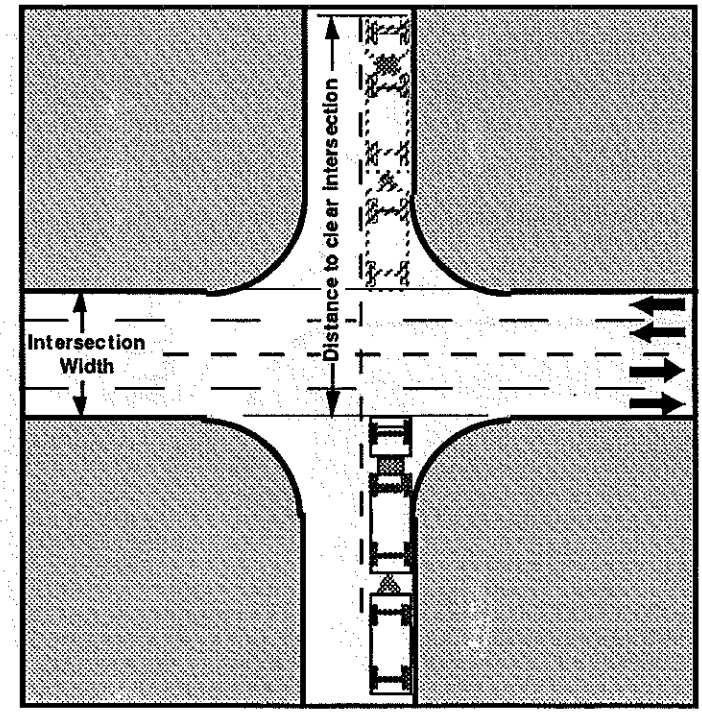
• On a 4% upgrade:

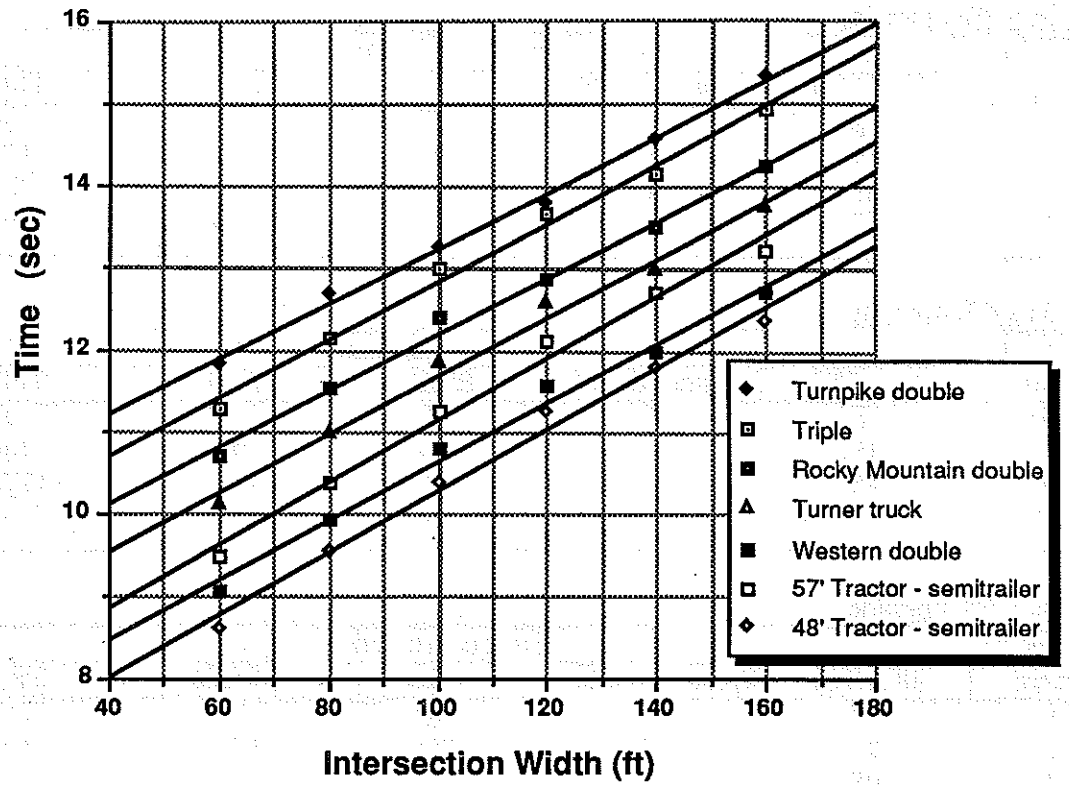
Speed to get to:	Truck combination				
	48 ft TST	Western double	RMD	Triple	TPD
10	67	74	78	82	78
15	187	207	214	270	240
20	452	560	580	1114	1275
25	1163	2109	2197	—	—

• On a 6% upgrade:

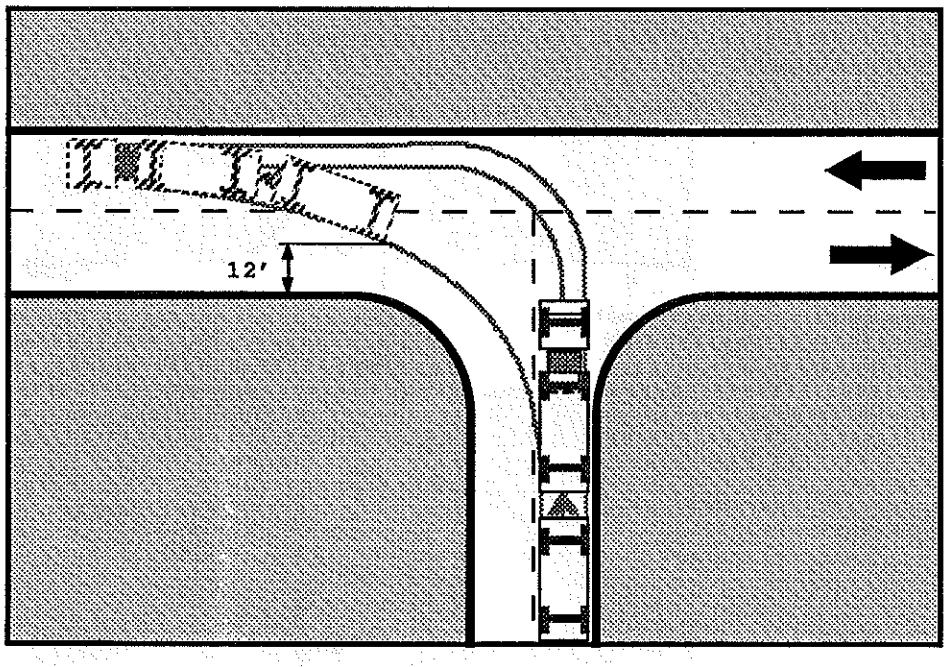
Speed to get to:	Truck combination				
	48 ft TST	Western double	RMD	Triple	TPD
10	78	82	81	107	91
15	239	290	298	1069	426
20	980	—	—	—	—
25	—	—	—	—	—

The following figure pertains to acceleration across a four-way intersection, measured in time required to accelerate the truck from a stand-still position until its rear end has cleared the intersection zone.

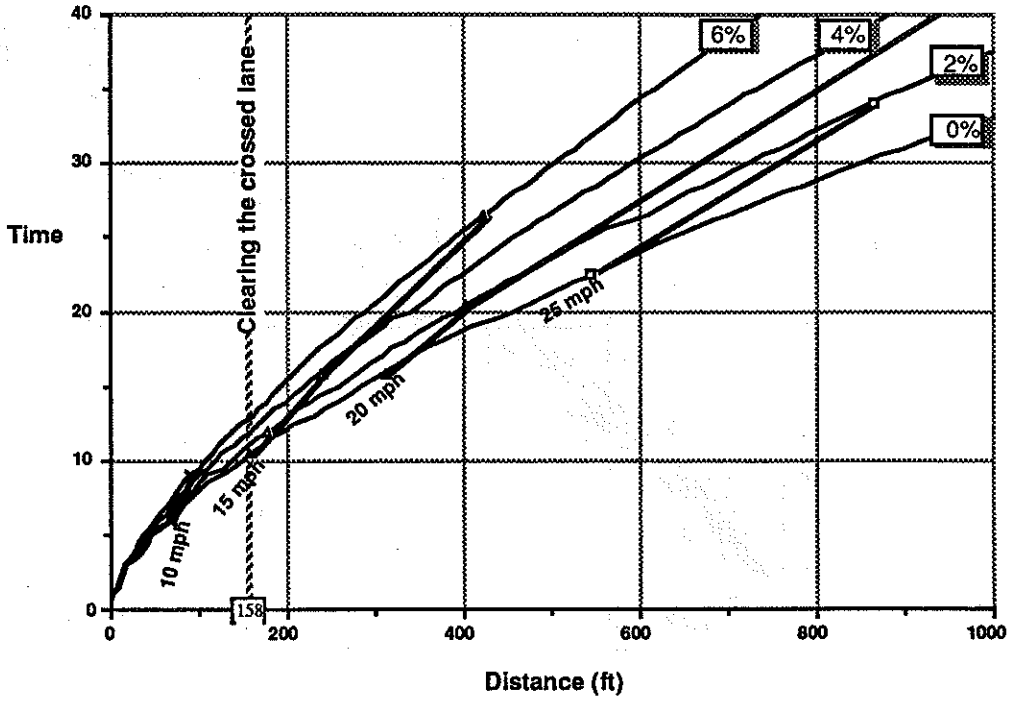




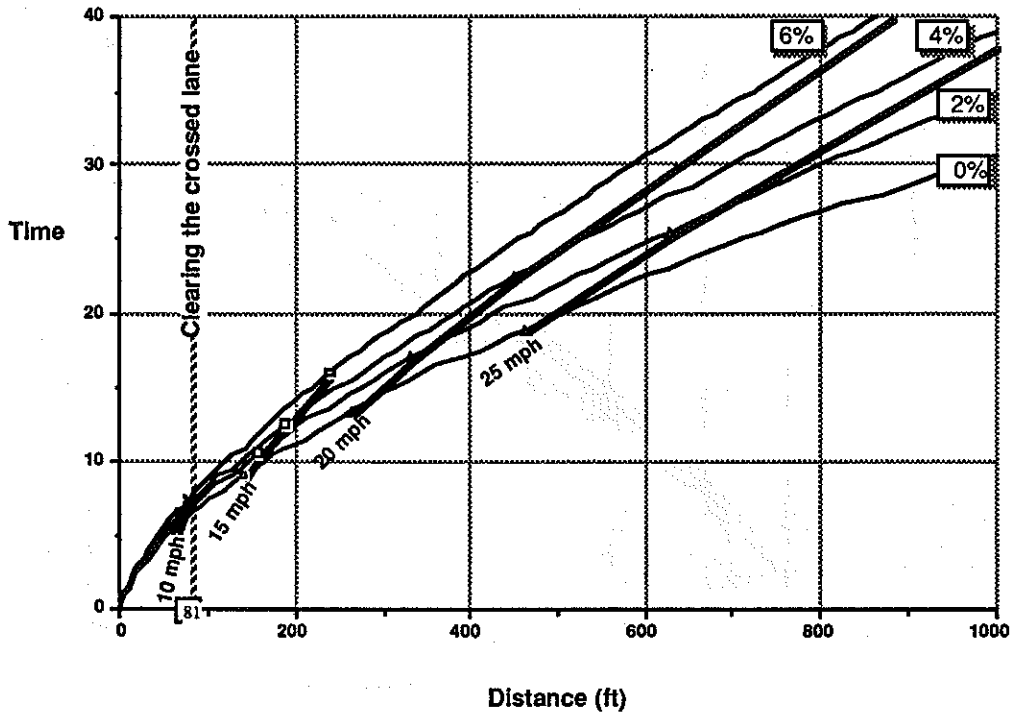
The following figure pertains to acceleration across a three-way intersection, measured in time and distance traveled by the leading unit of the truck combination from a stand-still position until its rear end has cleared a 12 foot path (lane) for the traffic in the opposite direction.



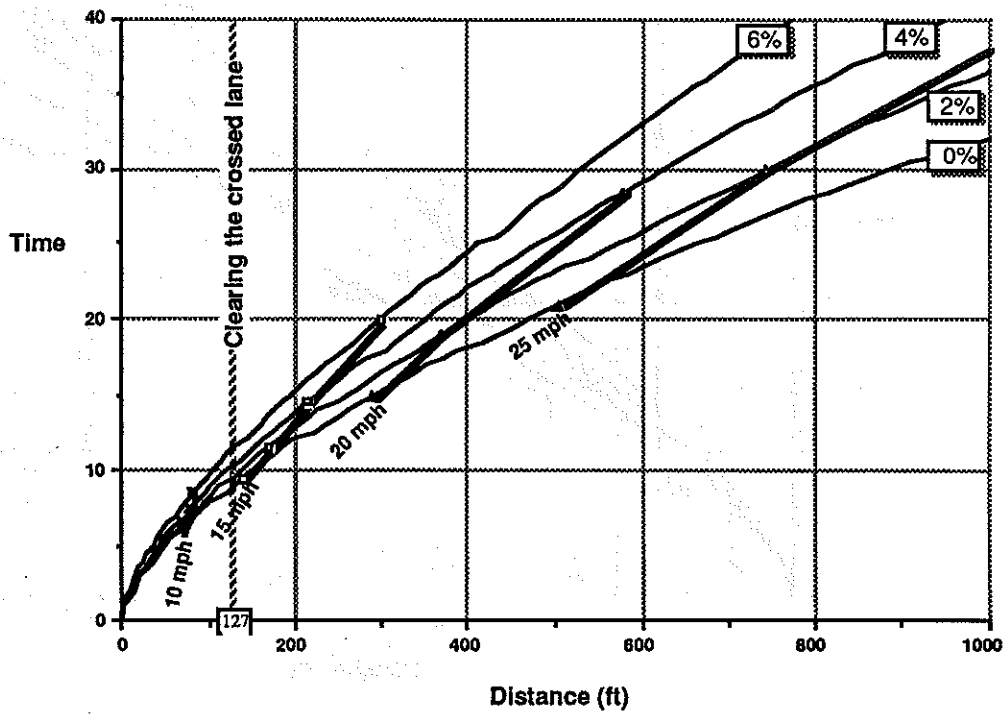
Turnpike Double



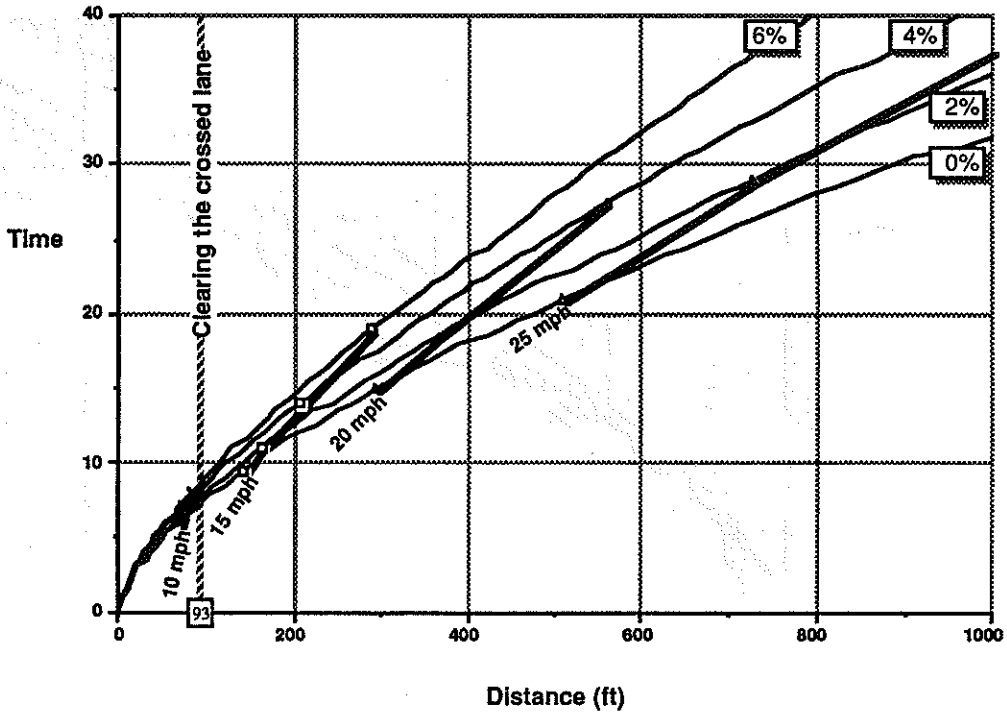
48 ft Tractor Semitrailer



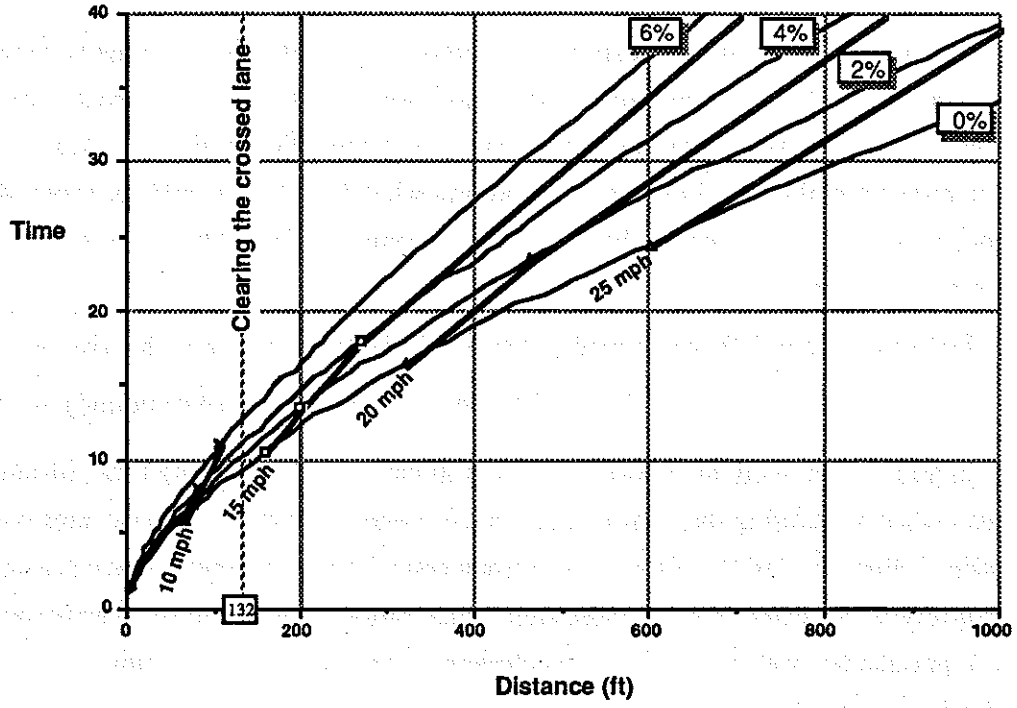
Rocky Mountain Double



Western Double



Triple


Time
Distance (ft)
Clearing the crossed lane
132
6%
4%
2%
0%
10 mph
15 mph
20 mph
25 mph
0
10
20
30
40
0
200
400
600
800
1000

Acceleration From an Initial Speed

Acceleration from an initial speed, or merging acceleration was evaluated similarly to the acceleration from a stand-still. In this case, however, the truck started at some initial speed. Not all the sites were simulated. Since pertinent data needed for the simulation were missing in the drawings, and by studying what data were available, those sites appeared to be represented by those that were simulated. Sites that were studied and presented here are:

Jackson Road to I-94 eastbound (departing Lakeview Drive) on drawing sets 6 and 8

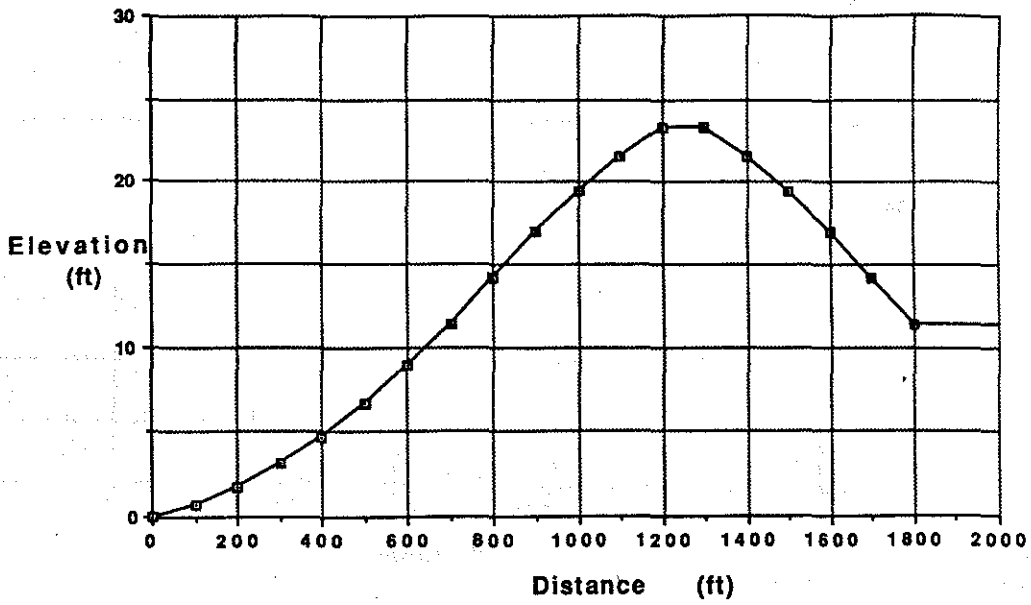
Departing ramp I from Whittaker Road northbound to I-94 (westbound), in site 9

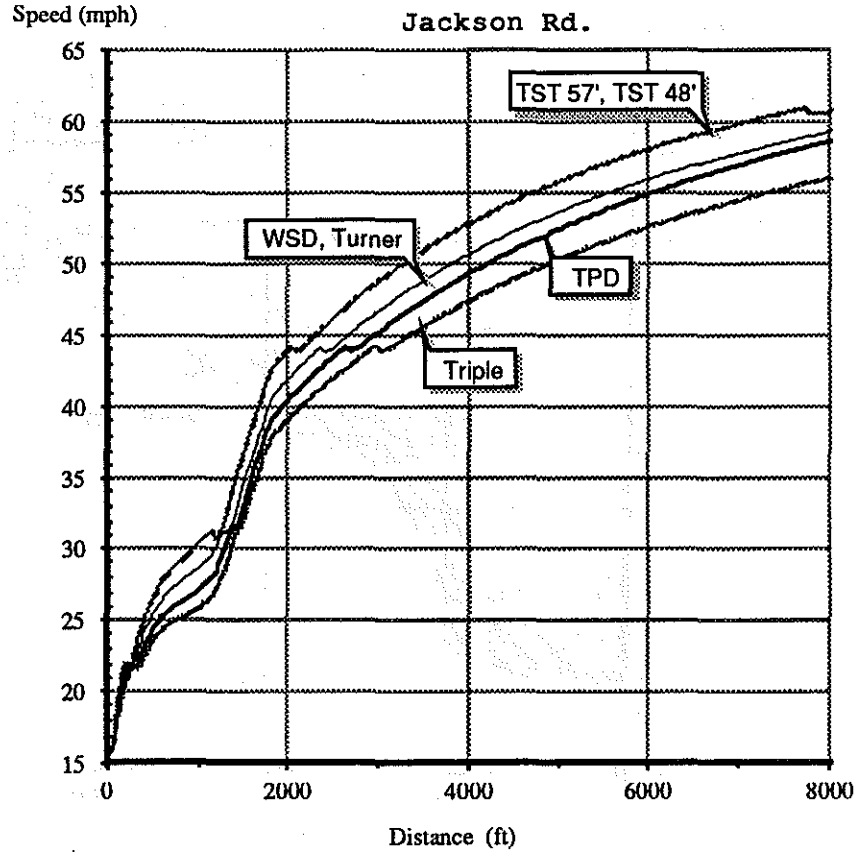
In addition to using the various truck combinations in computing time, distance, and speed when simulating the above sites, a set of generic trucks on generic sites was also studied. Since the length of the truck is not a contributing parameter when acceleration capability is evaluated, a set of three lb/hp truck ratios, assumed to be representative of the LCV population, was computed as accelerating along some constant upgrade slopes from some initial speeds.

Content of this section

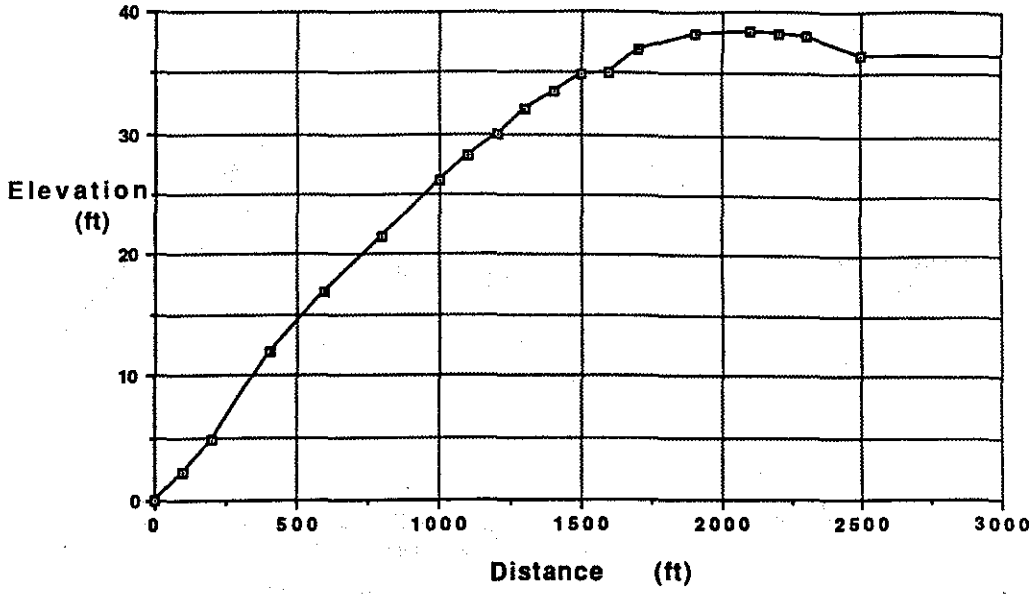
First, the elevation profile of the actual sites is provided, followed by speed-distance plots for the various combinations. Next, the generic conditions results are presented. The output of the simulations is introduced as tabulated distances to reach various speeds. The results are also displayed as plots.

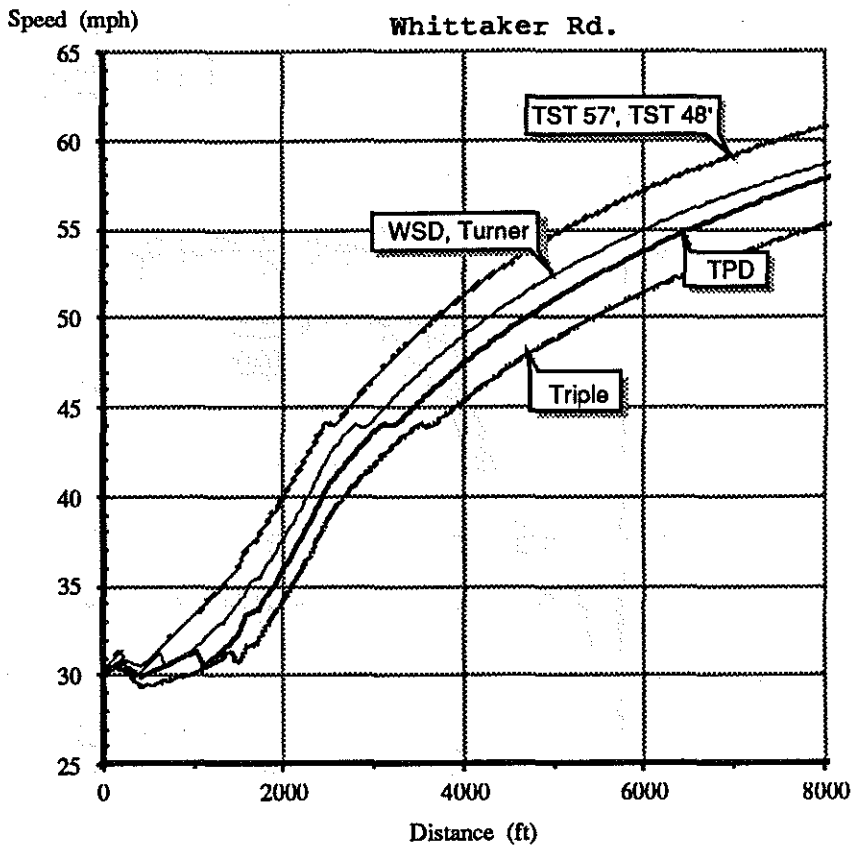
Jackson Rd. to I-94 EB- elevation profile





Whittaker NB to I-94 WB - elevation profile





230 lb./hp.

≈ 80,000 lb / 345 hp.

0% Grade

From: / Speed to:	15	22	30	37	45
23	270	27			
31	603	361	55		
39	1313	1060	775	189	
47	2570	2318	2032	1448	334
53	3950	3697	3411	2827	1713

2% Grade (Can't go faster than ≈ 44.5 mph)

From: / Speed to:	15	22	30	37	45
23	365	43			
31	989	666	117		
39	3081	2744	2202	738	
47	—	—	—	—	—
53	—	—	—	—	—

4% Grade (Can't go faster than ≈ 29 mph)

From: / Speed to:	15	22	30	37	45
23	655	98			
31	—	—	—		
39	—	—	—	—	
47	—	—	—	—	—
53	—	—	—	—	—

265 lb./hp.

≈ 80,000 lb / 300 hp.

0% Grade

From: / Speed to:	15	22	30	37	45
23	289	32			
31	677	422	65		
39	1497	1255	887	225	
47	2969	2727	2360	1701	405
53	4670	4428	4060	3402	2105

2% Grade (Can't go faster than ≈ 41 mph)

From: / Speed to:	15	22	30	37	45
23	429	55			
31	1296	922	172		
39	5630	5257	4496	2014	
47	—	—	—	—	—
53	—	—	—	—	—

4% Grade (Can't go faster than ≈ 26 mph)

From: / Speed to:	15	22	30	37	45
23	1050	203			
31	—	—	—		
39	—	—	—	—	
47	—	—	—	—	—
53	—	—	—	—	—

300 lb./hp.

≈ 80,000 lb / 265 hp.

0% Grade

From: / Speed to:	15	22	30	37	45
23	308	36			
31	751	479	73		
39	1665	1411	1007	254	
47	3299	3045	2641	1882	448
53	5137	4879	4475	3716	2281

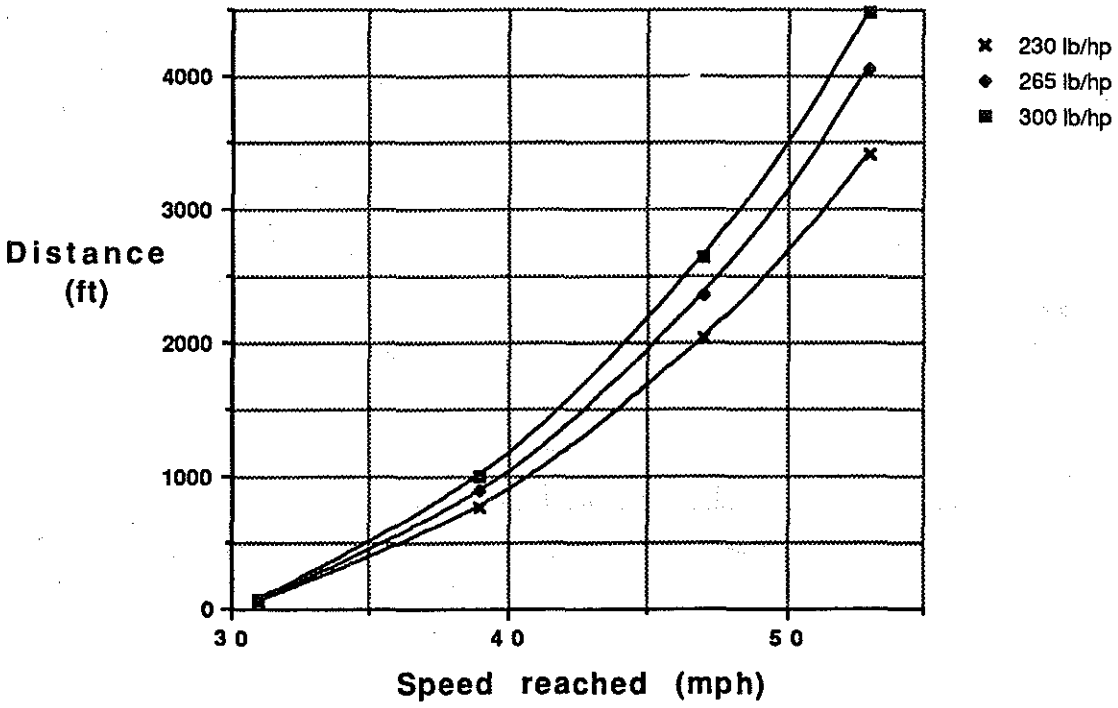
2% Grade (Can't go faster than ≈ 38 mph)

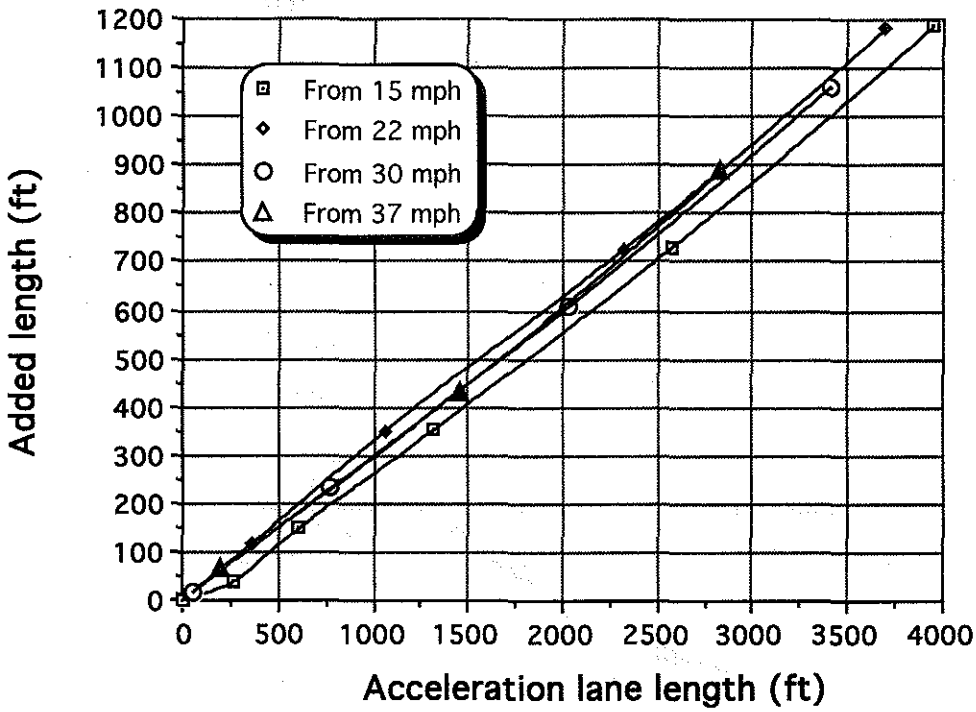
From: / Speed to:	15	22	30	37	45
23	514	70			
31	1712	1267	252		
39	—	—	—	—	
47	—	—	—	—	—
53	—	—	—	—	—

4% Grade (Can't go faster than ≈ 23 mph)

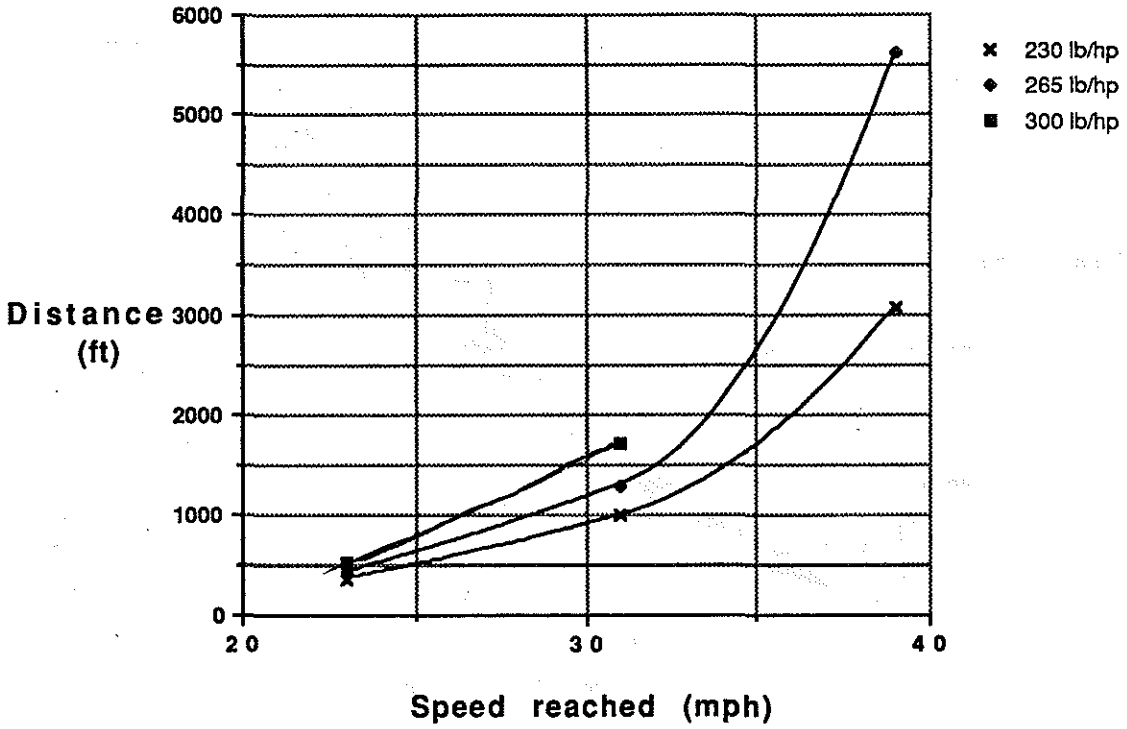
From: / Speed to:	15	22	30	37	45
23	2688	1078			
31	—	—	—		
39	—	—	—	—	
47	—	—	—	—	—
53	—	—	—	—	—

From 30 mph, level road

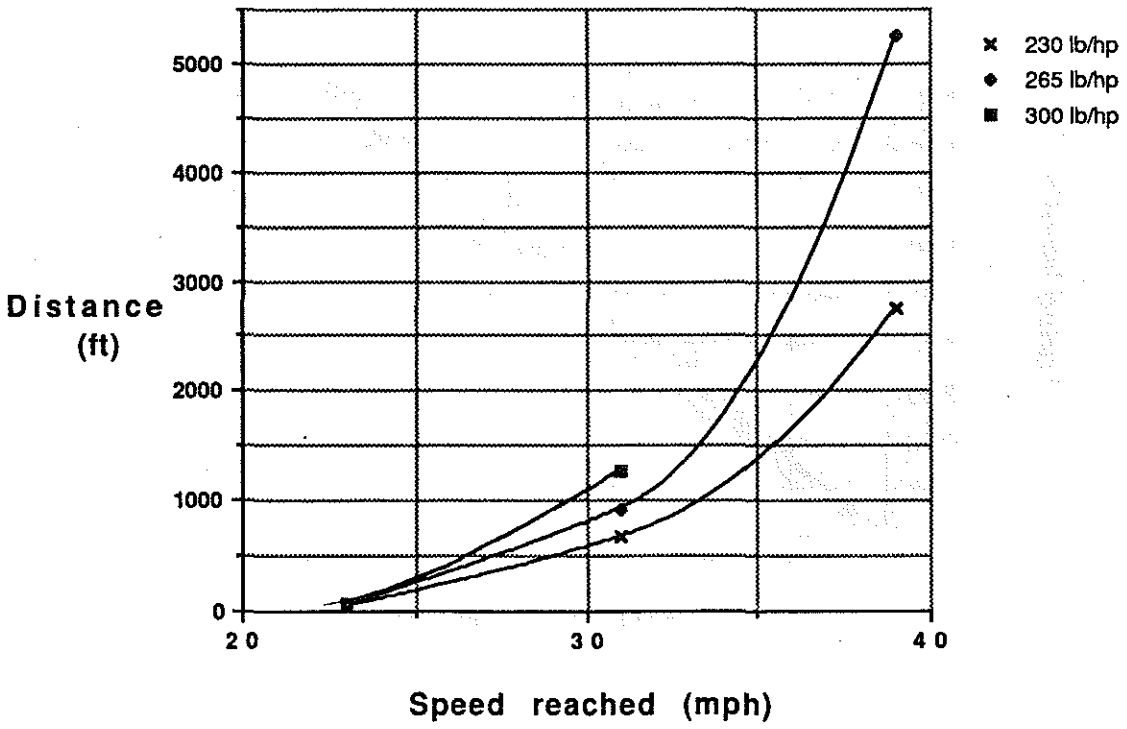




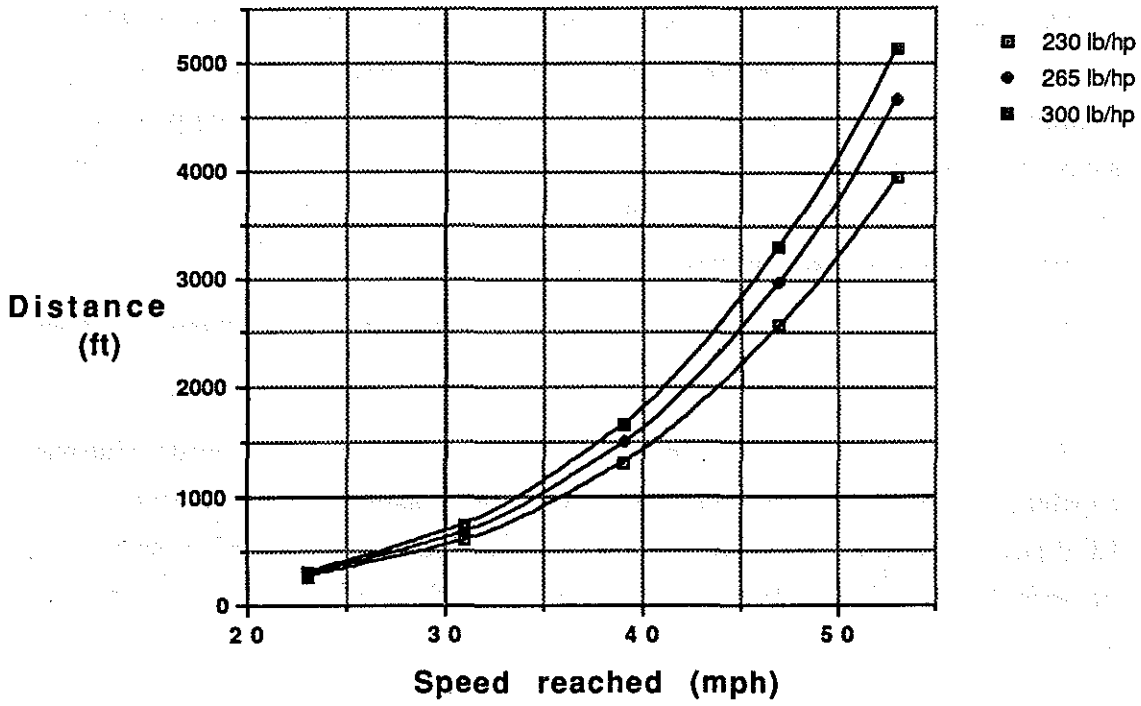
From 15 mph, 2% grade



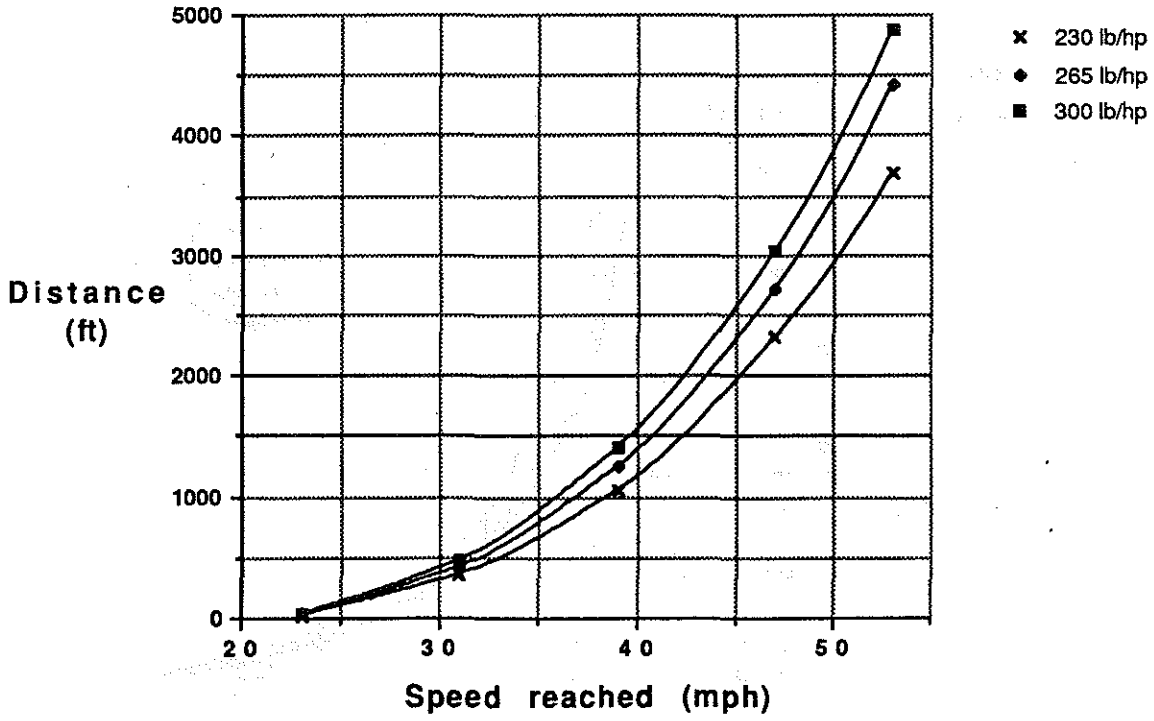
From 22 mph, 2% grade



From 15 mph, level road



From 22 mph, level road



speed maintenance on upgrades

The state of Michigan, in general, and the representative sites provided by MDOT, in particular, are not very demanding from a gradeability standpoint. None of the site areas portrayed in the drawing sets incorporated long uphill slopes. For the purpose of this study, uphill slope values from the drawings (even short) were assumed as being kept continuous for a long distance. The selected sites were:

Working zone on I-94 / Willow-Run exit, site 2

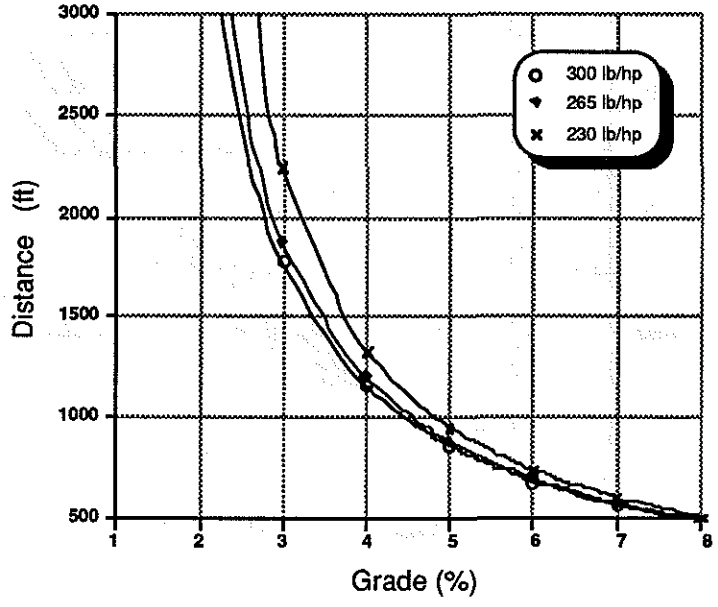
Jackson Road to I-94 eastbound (departing Lakeview Drive) on drawing sets 6 and 8

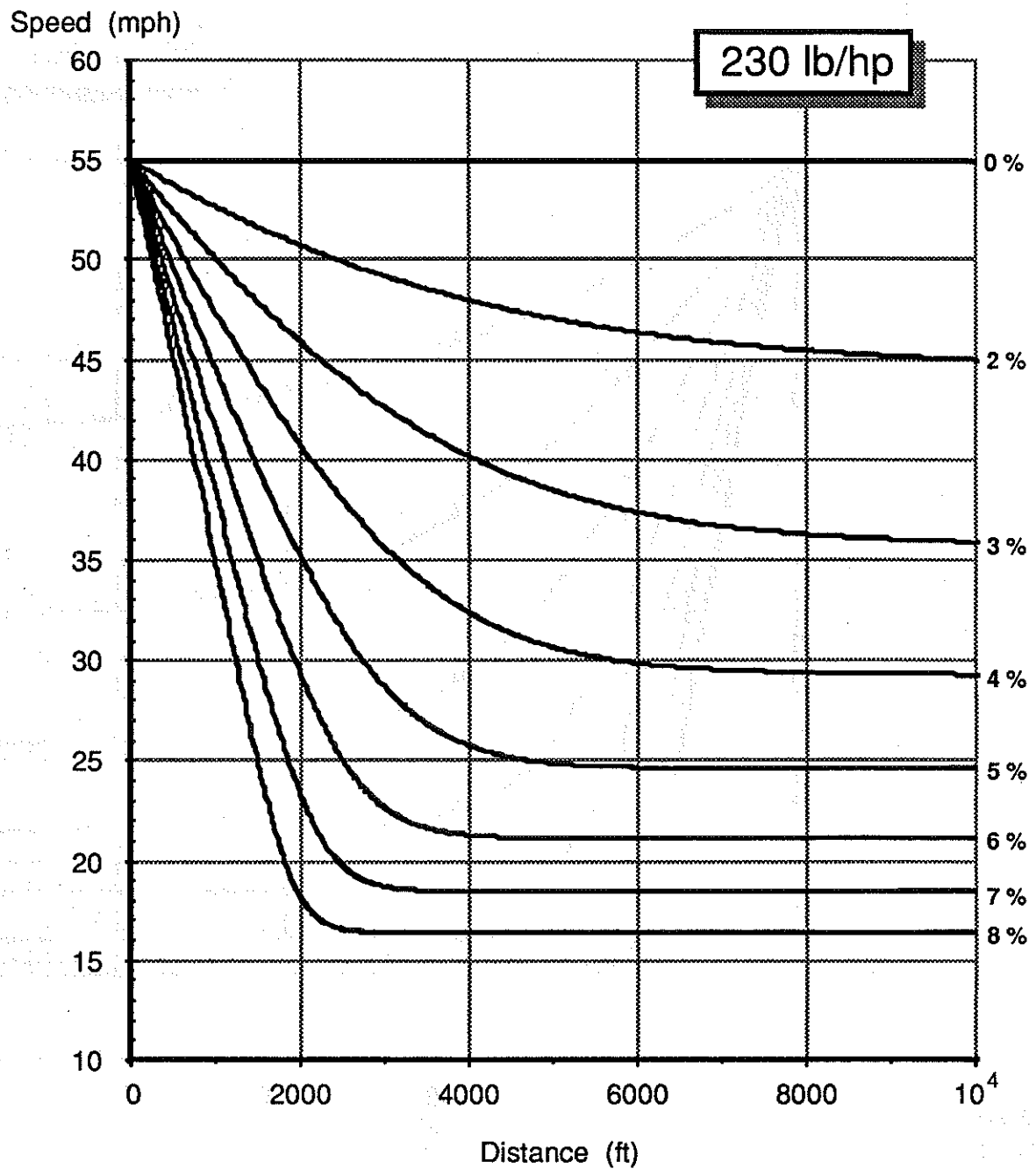
Jackson Road to I-94 westbound (left turn) on drawing sets 6 and 8

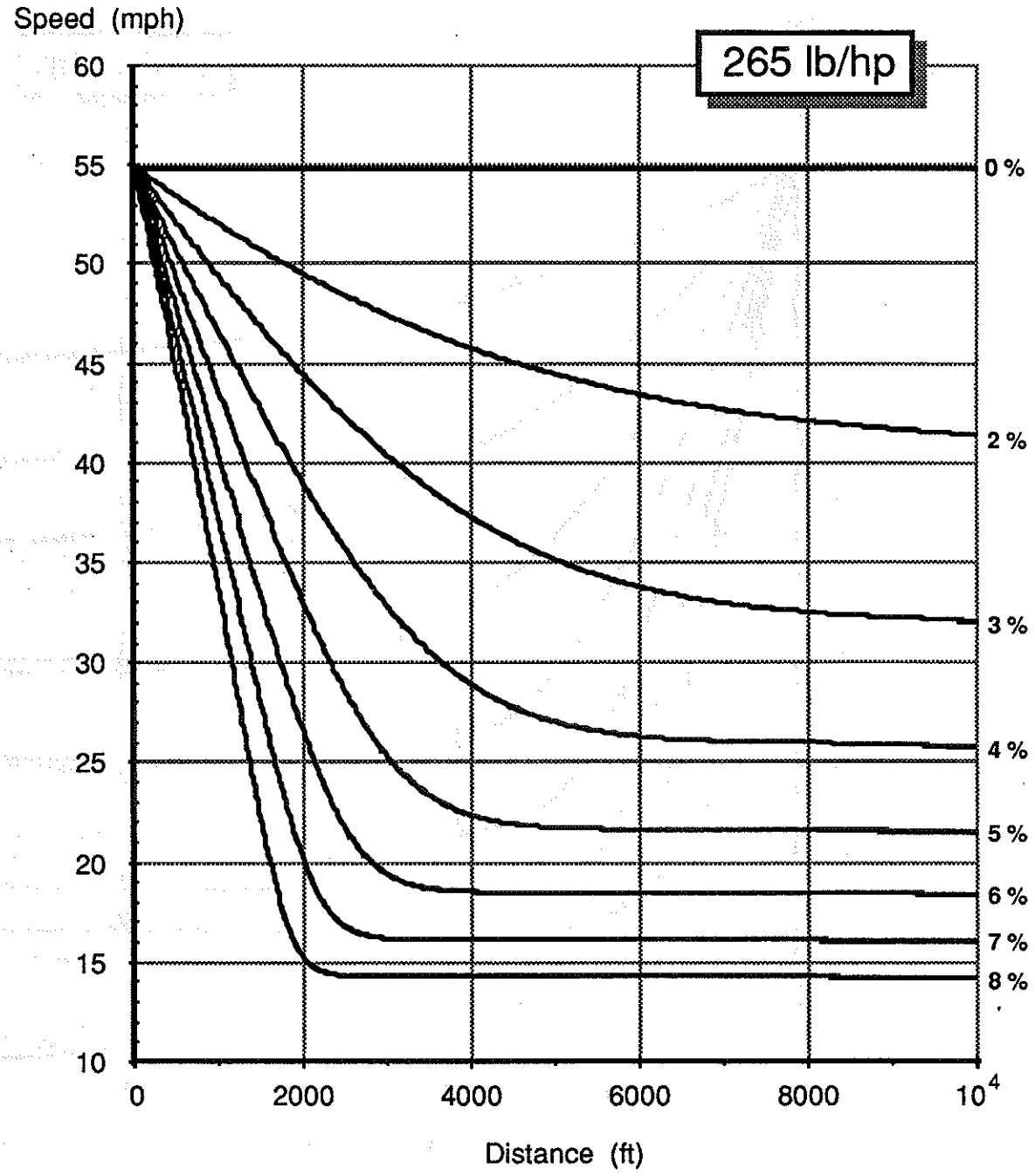
Since the length of the truck is not a contributing parameter when speed maintenance capability is evaluated, a set of three lb/hp truck ratios, assumed to be representative of the LCV population, was used in the calculations. Based on the selected sites, speed maintenance capability of these generic truck combinations on upgrades of 2% to 8% was computed.

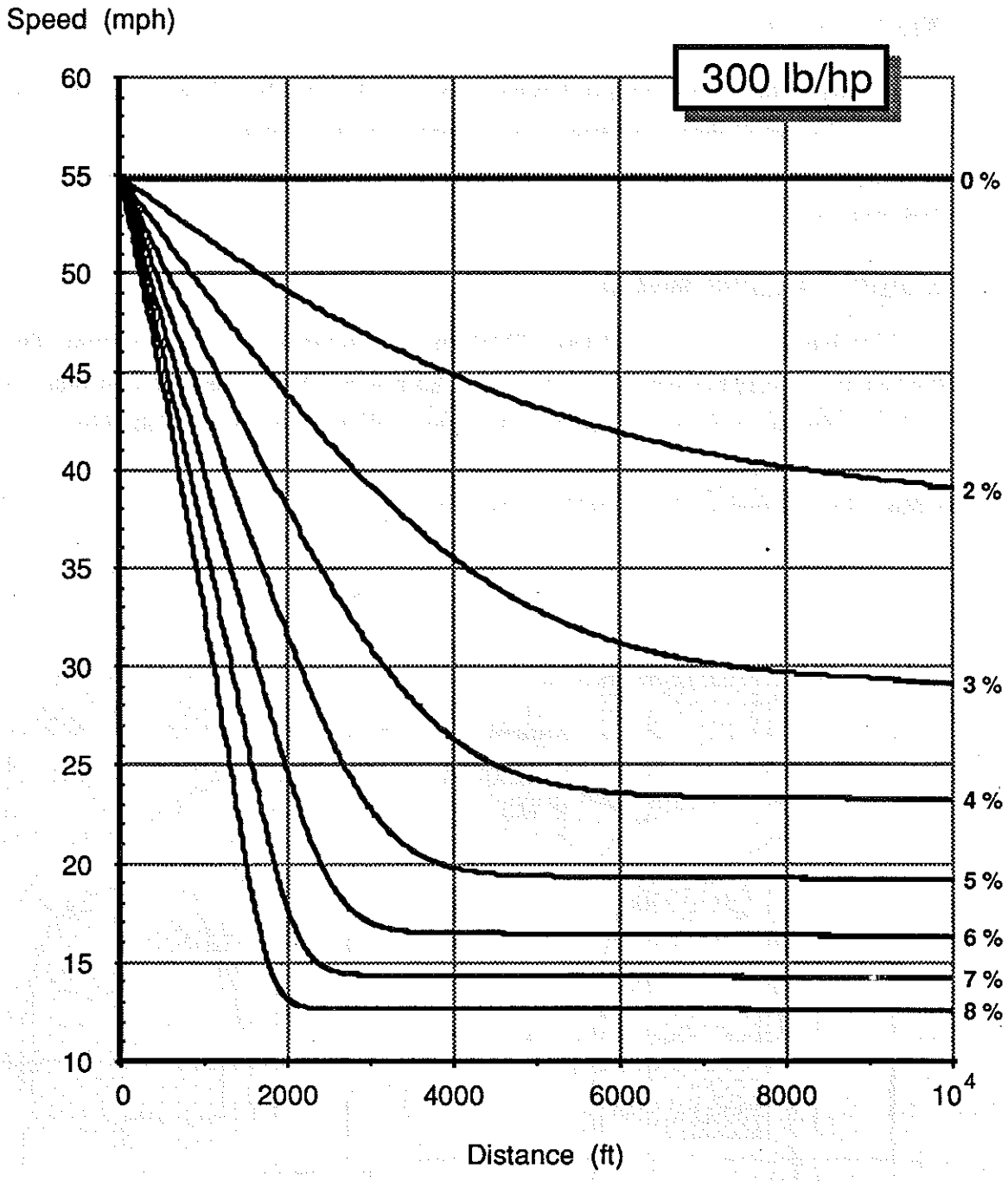
Content of this section

First, the distance it takes for the various lb/hp combinations to lose 10 mph, when transitioning from a flat road travel at 55 mph to different upgrade slopes, is presented as a plot. Next, speed-distance histories for the various lb/hp combinations from 55 mph on different upgrade slopes are plotted. These plots are similar to those found in the appropriate section of AASHTO's *Green Book*..




Speed (mph)
230 lb/hp
60
55
50
45
40
35
30
25
20
15
10
0 %
2 %
3 %
4 %
5 %
6 %
7 %
8 %
0
2000
4000
6000
8000
10^4
Distance (ft)


265 lb/hp
Speed (mph)
60
55
50
45
40
35
30
25
20
15
10
0
2000
4000
6000
8000
10^4
Distance (ft)
0 %
2 %
3 %
4 %
5 %
6 %
7 %
8 %

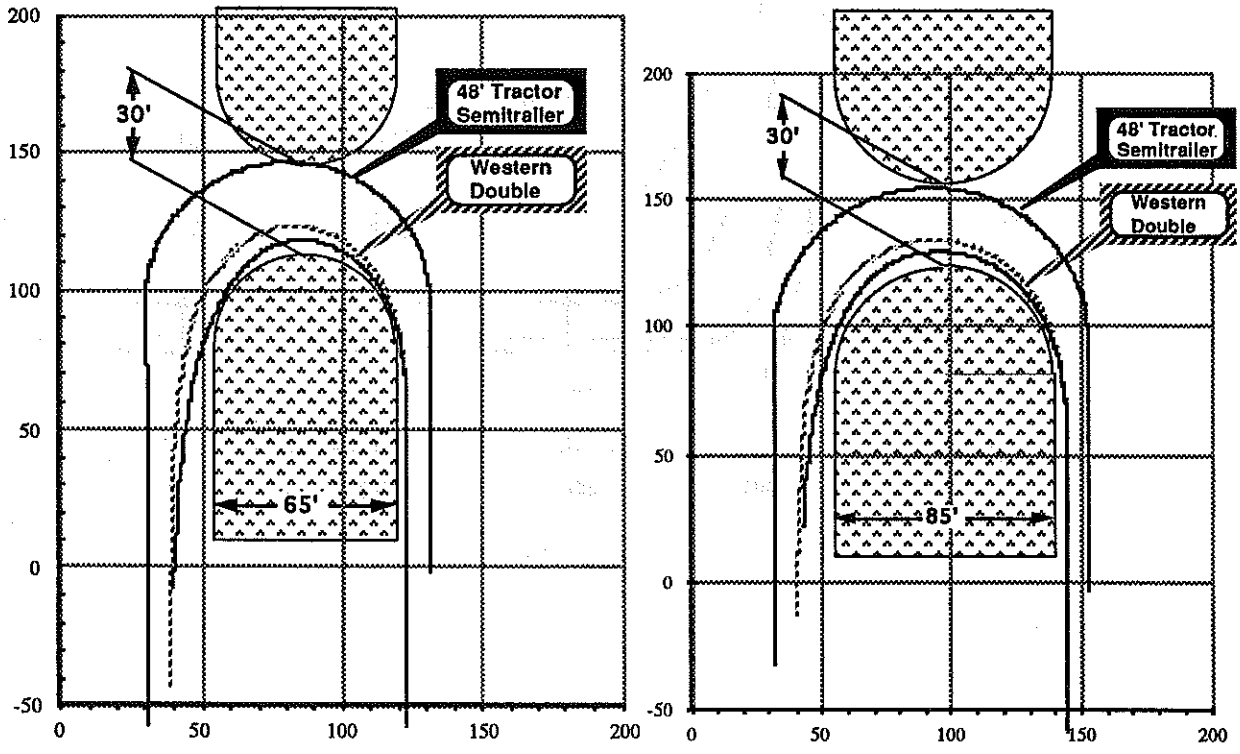

Speed (mph)
300 lb/hp
60
55
50
45
40
35
30
25
20
15
10
0
2000
4000
6000
8000
10^4
Distance (ft)
0 %
2 %
3 %
4 %
5 %
6 %
7 %
8 %

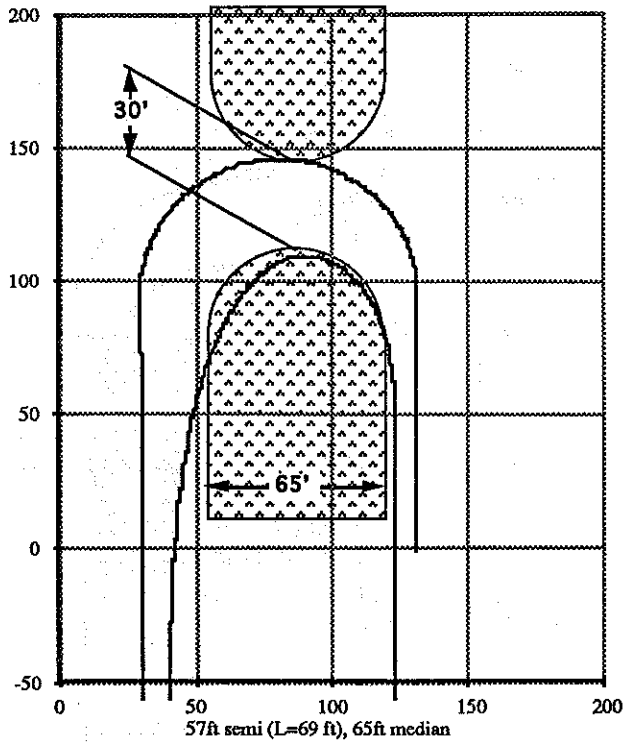
Median U-turn

Median U-turn capabilities or limitations were calculated based on the standard design guides. Geometric details of crossovers are portrayed in Michigan's standard design drawing VII-670B. No other drawing set provided by MDOT included similar information.

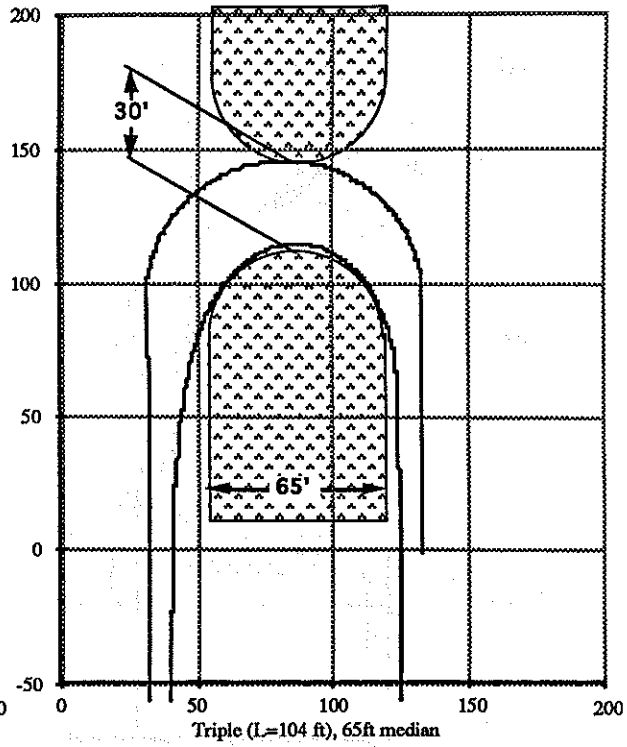
Content of this section

Simulation results of the U-turn offtracking runs are included in this section. Two median cases were evaluated: 65-ft wide and 85-ft wide. Both cases had a median opening of 30 ft. Turning radii as used in the calculations and as shown in the following plots were 50 ft around the narrow median, and 60 ft around the 85 ft median. Amounts of offtracking are summarized in table 14 in the report.

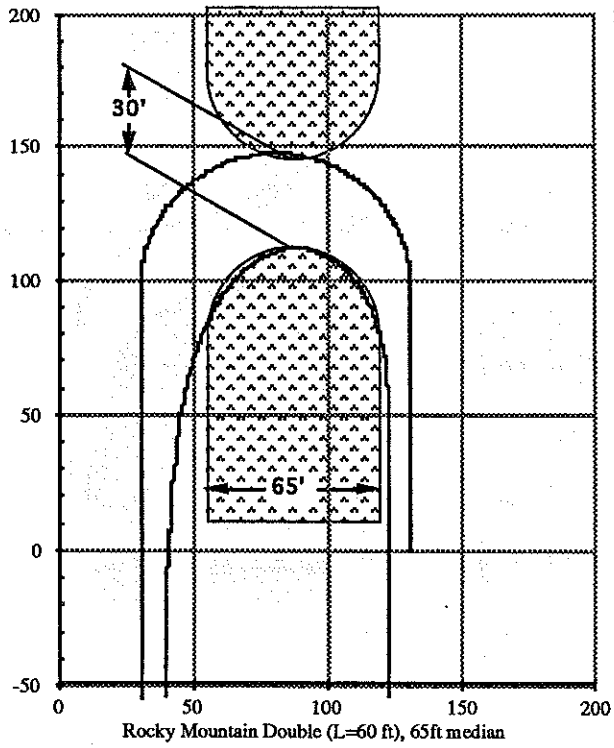




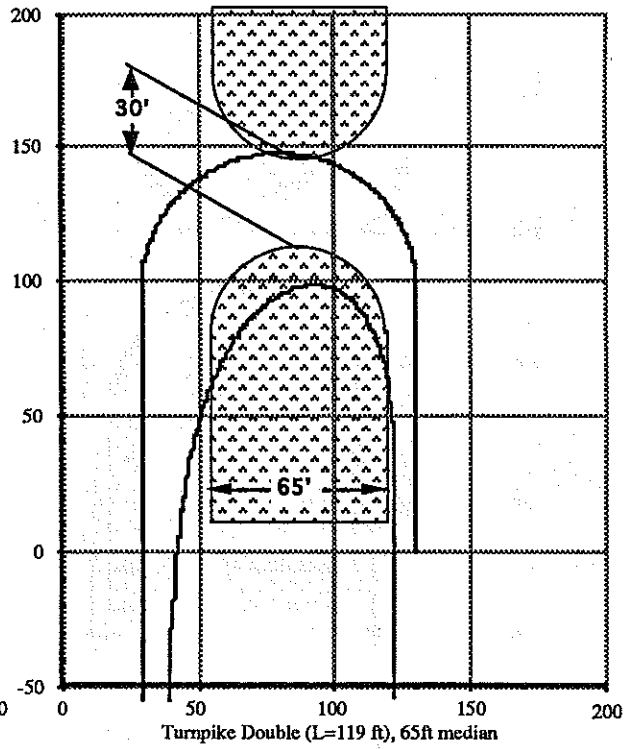
57ft semi (L=69 ft), 65ft median



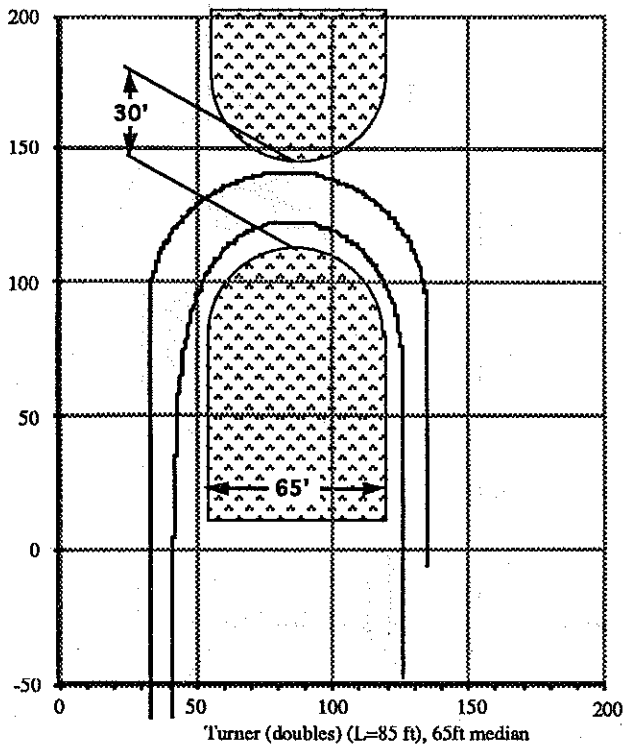
Triple (L=104 ft), 65ft median



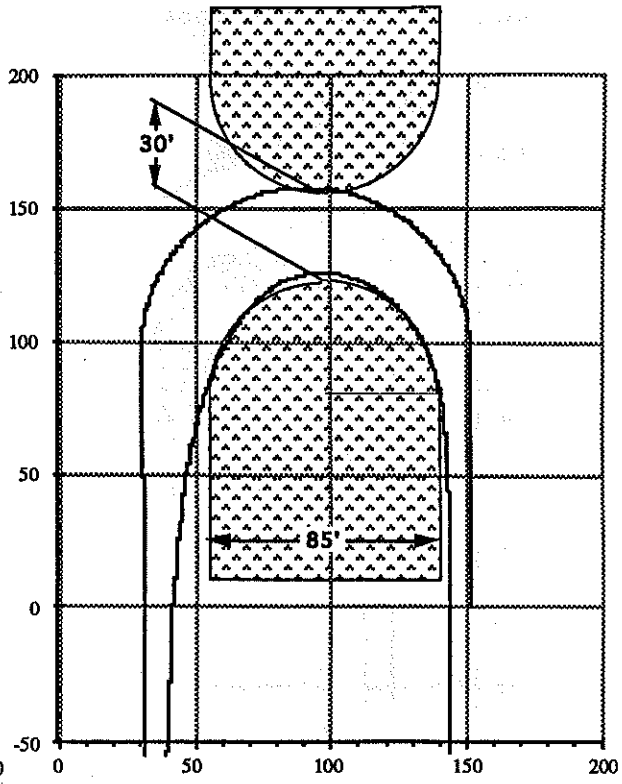
Rocky Mountain Double (L=60 ft), 65ft median



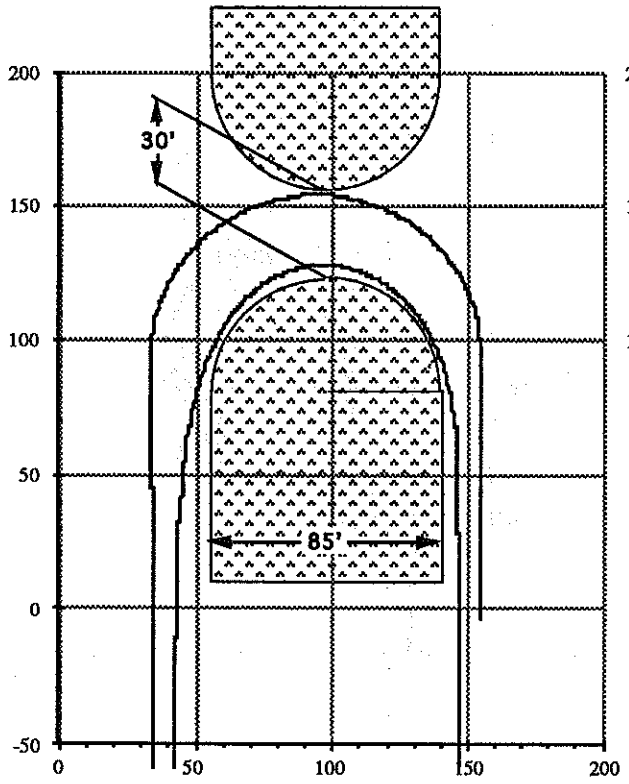
Turnpike Double (L=119 ft), 65ft median



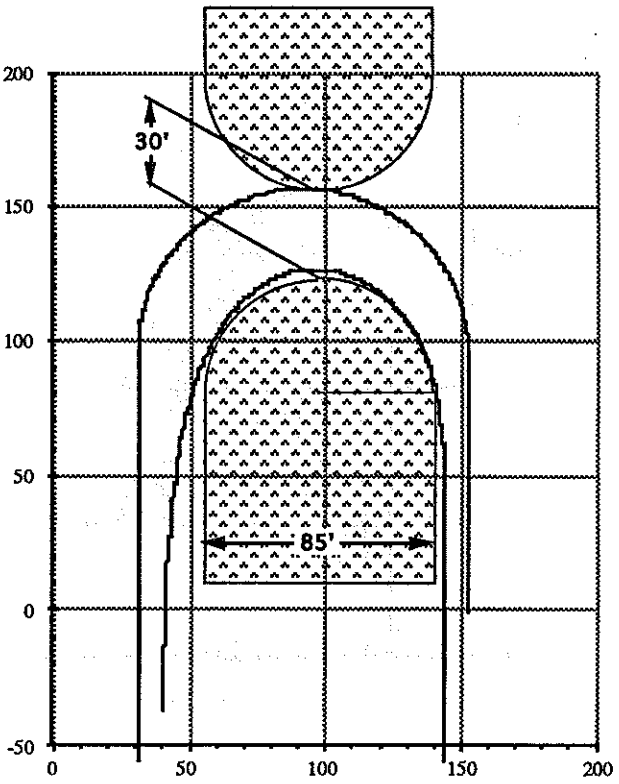
Turner (doubles) (L=85 ft), 65ft median



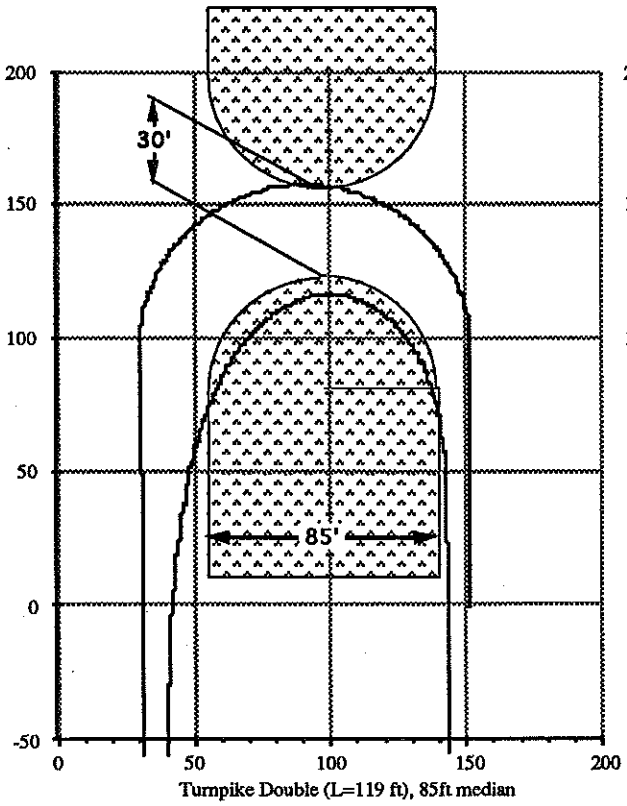
57ft semi (L=69 ft), 85ft median



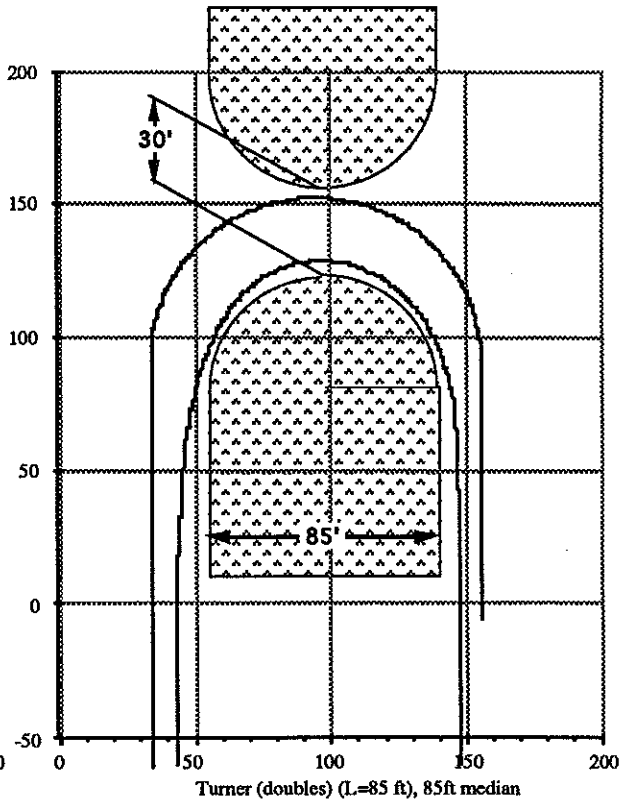
Triple (L=104 ft), 85ft median



Rocky Mountain Double (L=60 ft), 85ft median



Turnpike Double (L=119 ft), 85ft median



Turner (doubles) (L=85 ft), 85ft median

APPENDIX D

PASSING SIGHT DISTANCE

Passing sight distance (PSD) requirements used in the design of two lane highways are currently determined according to the AASHTO *Green Book* [1]. Highway markings are warranted according to the *Manual of Uniform Traffic Control Devices* (MUTCD) by FHWA [2]. During the last two decades, the AASHTO practice has been subjected to criticism by several researchers as a method that does not represent real passing situations, and, moreover, a method that is based on outdated data. Incompatibilities between the *Green Book* and the MUTCD practices have also been identified.

J.C. Glennon, one of the more ardent researchers asserting incompatibility between the *Green Book* passing sight distance criteria and the actual passing scenarios on today's highways, provides an overview of criticized issues associated with sight distance design topics in the *Green Book* [1]. A summary of research conducted on passing sight distance since 1971 is presented in [3]. In that work, a new and improved model to determine passing sight distance is introduced.

The primary difference between AASHTO's approach to determining passing sight distance and the approach used by Glennon is the assumed termination of the maneuver. AASHTO bases its practice on a "distance to complete" consideration. The driver is assumed to be committed to completing the pass, so the passing sight distance is supposed to be accordingly adequate. Glennon's approach, on the other hand, is based on a "distance to decide" consideration. When the pass is initiated, the driver does not have enough sight distance to complete it, but as the pass progresses he/she will have sufficient sight distance to decide whether to abort or complete the maneuver — whichever is shorter. By nature, passing sight distances determined using this method will be shorter than those set by AASHTO.

In this section, both AASHTO's and Glennon's methods are discussed briefly. Some of their pros and cons are indicated, and the effect each approach has on the passing sight distance as it pertains to trucks is discussed.

AASHTO Practice

The passing sight distance, as determined by AASHTO, is aimed at enabling the driver to see far enough ahead to safely initiate and complete a pass. In doing so, AASHTO

makes use of data and values that are based on field observations conducted between 1938 and 1941. Another study from 1957 was used to validate the data.

The total passing sight distance is defined as D. It is the total clear distance in the left lane required for a vehicle to successfully complete a passing maneuver. According to the passing scenario used in AASHTO's policy, this distance is the sum of the four following segments (see figure D-1):

d_1 — Initiation of the passing maneuver. Driver's perception and reaction to road conditions, decision making, and acceleration onto the left lane.

d_2 — Occupation of left lane. From the point when the passing vehicle entered the opposing lane, until the maneuver was completed and the passing vehicle is fully returned to the right lane.

d_3 — Clearance length. Distance between the passing vehicle after it returned to the right lane, and the opposite vehicle in the left lane.

d_4 — Opposing vehicle. The distance covered by the opposing vehicle in the left lane during 2/3 of the time the passing vehicle occupied the left lane.

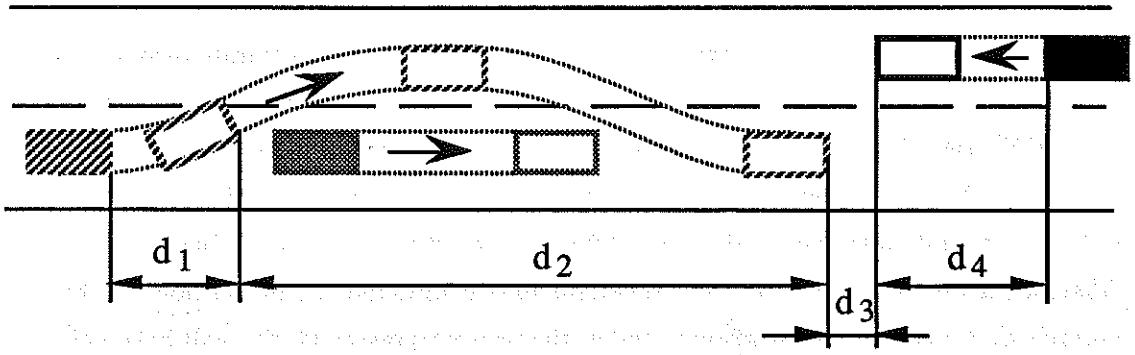


Figure D-1. AASHTO's passing scenario

AASHTO employs linear motion equations and some empirical values to compute the four segments of the passing sight distance under various roadway conditions. The design values used in these computations were derived from the field study data mentioned above and from the following assumptions:

1. The overtaken vehicle travels at a uniform speed.
2. The passing vehicle has reduced speed and trails the overtaken vehicle as it enters a passing section.

3. When the passing section is reached, the driver requires a short period of time to perceive the clear passing section and to react to start the maneuver.

4. Passing is accomplished under what might be termed a delayed start and a hurried return in the face of opposing traffic. The passing vehicle accelerates during the maneuver and its average speed during the occupancy of the left lane is 10 mph higher than that of the overtaken vehicle.

5. When the passing vehicle returns to its lane, there is a suitable clearance length between it and an oncoming vehicle in the other lane.

When evaluated for applicability to this study, AASHTO's practice under the above assumptions and with the design values derived from the data acquired in the field study was found to have some deficiencies:

- This practice cannot be related to trucks passing other vehicles in particular. Acceleration levels assumed (0.065g) are twice as high as those that trucks are capable of (0.035g). Furthermore, it is explicitly said that the assumed acceleration levels are well below what can be considered as the maximum capability of the passing vehicles. Values of 0.035g represent maximum acceleration levels of heavy trucks.

- Length of passing or passed vehicles is not a parameter being considered in the computations. The calculations are based on a "zero-length" (point) vehicle.

In addition, Glennon [3, 4] and other researchers criticized the AASHTO practice of determining passing sight distance and MUTCD highway markings as follows:

- The studies that were used to acquire the data on which the practice is based are outdated (1938, 1941).

- There are significant discrepancies between the AASHTO passing sight distances and those highway markings warranted by MUTCD (it should be noted, though, that in the *Green Book* , AASHTO itself points to the fact that the computed passing sight distances "should not be confused with other distances used as the warrants for placing no-passing-zone pavement stripes on completed highways." [1, p. 134])

- Questionable speeds are used in establishing AASHTO's PSDs. At low speeds, the passing vehicle travels significantly faster than design speed, and at high speeds it travels significantly slower.

- The definition of the PSD as the sum of the four distances is very conservative. It assumes the driver is determined to complete the pass, and it ignores the possibility of aborting the maneuver.
- MUTCD's criteria are based on an average between passing sight distances for a "delayed" pass and for a "flying" pass, not on any particular passing maneuver. A delayed pass is when the passing vehicle tracks behind the impeding vehicle for a while, so that when the pass is executed it involves accelerating and lane changing. In the second type of pass, the passing vehicle approaches the other vehicle from behind and, while maintaining the higher speed, it executes the pass.
- Neither AASHTO nor MUTCD addresses vehicles other than passenger cars. Furthermore, they are both based on old data that can not be considered as representative of today's traffic. The influence of trucks can not be assessed from those formulations, as vehicle length is not a parameter.

Nevertheless, and in spite of some of the above claims, an assessment was made to approximate the effect that longer combination vehicles (LCVs) might have on passing sight distance as computed by AASHTO's practice. The results are introduced later in this section, under the appropriate subsection.

Glennon's revised model for PSD

The revised model suggested by Glennon to determine passing sight distance on two-lane highways is based on the "critical position" concept. According to this concept, there is a point during the passing maneuver at which the driver of the overtaking vehicle will need the same passing sight distance to either safely complete the pass or safely abort it. That point is also referred to in the literature as the "point of no return" [5]. The sight distance value required to either successfully complete or successfully abort the passing maneuver is the passing sight distance suggested by Glennon for both design and highway-marking warrants.

The passing maneuver, according to Glennon, is comprised of four phases. Each phase has a different passing sight distance requirement. The four phases are described in figure D-2. At first, when the passing maneuver is being initiated, the required sight distance is the shortest. It is based on the driver's need to abort the pass, since he/she can almost immediately return to the right lane in the face of an oncoming vehicle. As the pass

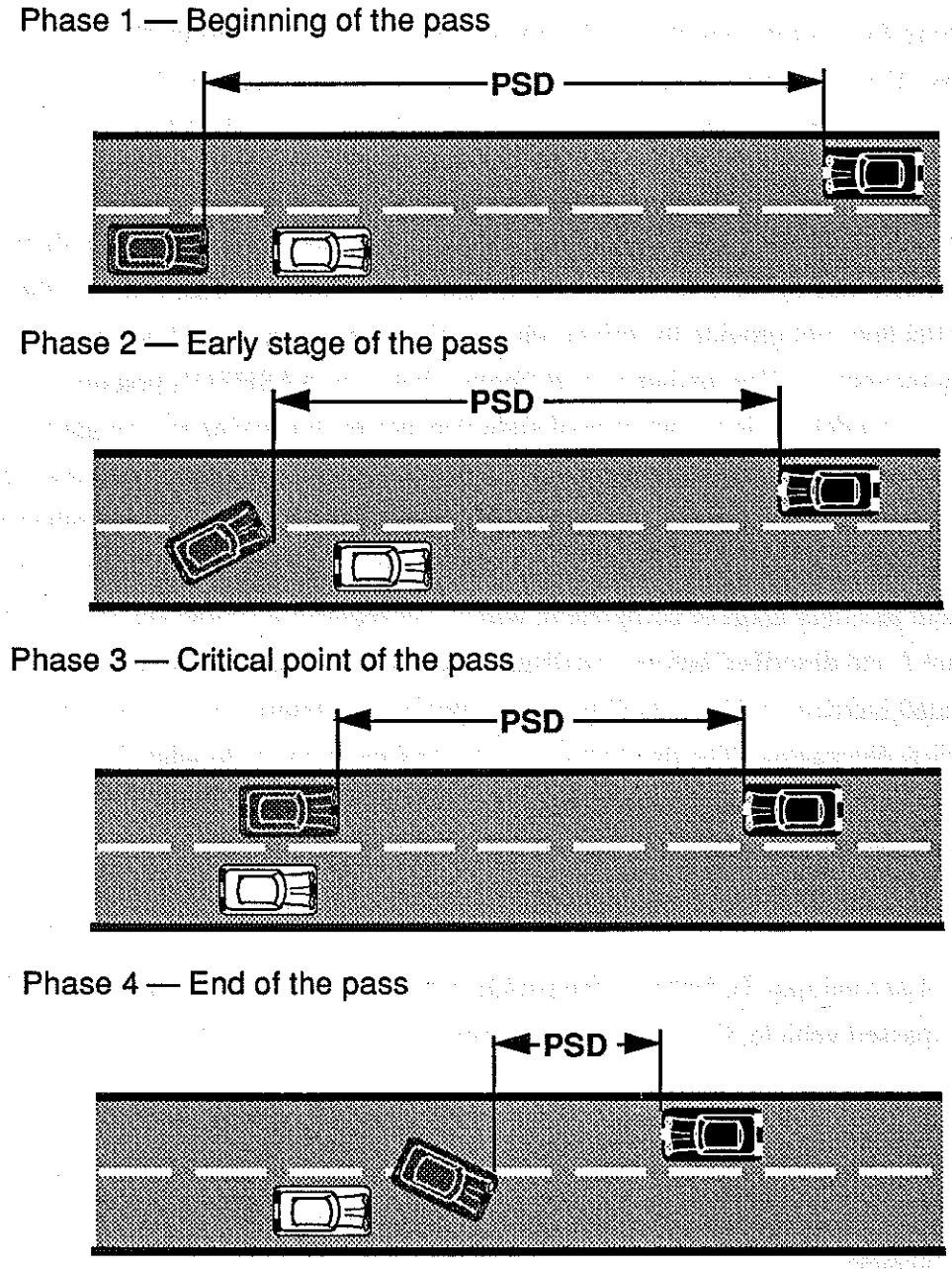


Figure D-2. Glennon's passing scenario

progresses and the passing vehicle encroaches deeper into the left lane, the PSD increases, since more time will be required to abort and return to the right lane. Passing sight distance needs are still based on aborting the pass during this second phase. The critical point of the pass constitutes the third phase of the maneuver. At this point, the passing vehicle is trapped in the left lane and is in its most vulnerable position. The driver needs the same

clear distance ahead to either safely complete the pass or safely abort it. Beyond this point, into phase four of the pass, the PSD starts to decrease and is based on the need to complete the pass. Given constant conditions, after the critical position or the "point of no return," the driver of the overtaking vehicle can only complete the pass. He/she can no longer safely abort the maneuver.

The model suggested by Glennon sets significantly shorter passing sight distances than those determined by the *Green Book* under similar conditions. This is due to the fact that the model does not provide the driver with a sight distance far enough ahead for the entire passing maneuver. The fundamental difference between AASHTO's practice and Glennon's model lies in the amount of sight distance each is trying to provide the driver of the passing car. AASHTO's message to the driver can be phrased as "you can see far enough ahead to initiate and complete a pass." Glennon's message, on the other hand, can be phrased as "you can initiate a pass, but at any given time your sight distance will only be sufficient to safely abort or complete it, whichever requires a shorter distance." As shown in figure 2 and described before, the distance required to return to the right lane once a pass is initiated increases to the critical position ("point of no return") where it is maximum, and then starts decreasing. The driver does not get any clear cue as to when he passes that point, and when it is safer for him/her to complete the pass or to abort it. Clearances during Glennon's passing maneuver are assumed to be as follows:

- 1 second for perception-reaction time prior to initiating a pass
- 1 second gap, G, between the passing vehicle returning to its right lane behind the passed vehicle, if the pass was aborted
- 1 second gap, G, between the passing vehicle returning to its right lane ahead of the passed vehicle, if the pass was completed
- 1 second minimum clearance gap between the passing vehicle and an opposing vehicle

According to Hardwood and Glennon [4, p. 63], "*The Glennon model, together with accepted enforcement practices, provides a very conservative safety approach for marking passing and no-passing zones on two-lane highways.*" How conservative or how safe is questionable, since this is a design approach that puts the overtaking driver in an anxious position — expecting the unknown while waiting to decide whether to complete or abort the pass. It is not an unsafe design criteria, yet it might be disconcerting to some drivers.

Two analytical issues associated with the model developed by Glennon [3], are questionable. The first issue is the use of the numerical value m, the relative velocity between the passing and the passed vehicles, as representing the headway gap of G. The second issue is the validity of applying the concept of this model to low speed passes.

In his expression for the critical position (equation (7) in [3]), Glennon uses G as the desired headway gap between the passing and impeding vehicles at the end of passing or aborting the pass. Then, by assuming a minimum acceptable headway of one second for G, Glennon uses $G = 1 \cdot m$ to substitute m for G in his equation. With the use of m for headway and the 15th percentile values tabulated in [3], there will be less than a 12 ft gap at 70 mph (m = 8 mph for that speed). Most practices will consider such a headway gap as less than an accepted minimum.

Using the critical position approach of pass / abort, Glennon determined the passing sight distances for cars and trucks (tables 5 and 6 in [4]). The same equations were used to compute sight distance values for various speeds and lengths, which are provided in a tabulated manner in the next section. A closer examination of the values computed at low speed, together with the deceleration rate used (0.25g), revealed that the abort maneuver resulted in a negative velocity. In other words, the driver of the aborting car would have to engage the reverse gear in order to successfully abort the pass. Needless to say, this situation is unacceptable. The next section contains tables with detailed results based on Glennon's approach. The notation "NA" was used in the appropriate places in these tables where the calculations result in a negative velocity.

While technically both AASHTO's and Glennon's approaches can be considered as safe, it is a policy-making issue (i.e., message delivered to the driver) as to what approach should be used when highways and streets are designed and marked.

The effect of LCVs on the passing sight distance

Modification of AASHTO Practice

The length of the vehicles involved in the passing maneuver (both passing and being passed) is not explicitly expressed in the equations used to determine passing sight distance in the *Green Book* . Hence, a direct analysis of the influence of LCVs on the sight distance values determined by AASHTO can not be done. Nevertheless, by following the assumptions and the design values used in the *Green Book* , and by applying those

assumptions and values that pertain to trucks instead, a fairly good assessment of the effects LCVs might have on sight distance can be made. In the following discussion, the results of such analyses are described.

As outlined earlier, the passing maneuver is broken down by AASHTO into four distinct distance segments. When vehicle length is considered, the lengths of the first and third segments of the passing maneuver (d_1, d_3) are not changed. The first segment, d_1, is the distance associated with acceleration and speed differentials between the vehicles, hence it is independent of vehicle's length. Indeed, when all aspects of heavy trucks are considered in determining their passing sight distance, d_1 is also changed since the acceleration capabilities of trucks are much lower than those of cars. Nevertheless, in this study the acceleration performance of trucks in the context of passing sight distance is not considered (i.e., when a car passes a long truck no acceleration correction should be made). The third segment d_3 is a clearance value set according to speed groups. Only d_2 and, subsequently, d_4 are affected by incorporating the length of the vehicles into the sight distance computation. Figure D-3 shows the details of section d_2.

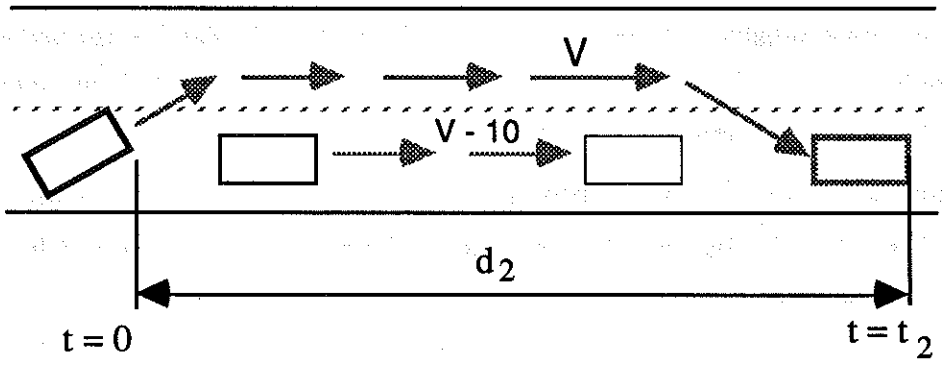


Figure D-3. The second segment of AASHTO's passing maneuver

The passing speed (V) and the speed of the passed vehicle (V-10) are assumed to be constant throughout the maneuver.

$$\mathbf{d_2 = 1.47 \cdot V \cdot t_2} \qquad (1)$$

AASHTO's practice does not account for the length of the vehicles involved in the pass. A simplified depiction of segment d_2 can therefore use points (zero-length) to represent the vehicles (see figure D-4). In this simplified description, dimension *a* represents the clearance of the passing vehicle behind the vehicle being passed when the

passing vehicle enters the left lane. Dimension δ represents the clearance of the passing vehicle ahead of the passed vehicle when the passing vehicle returns to the right lane after completing the pass.

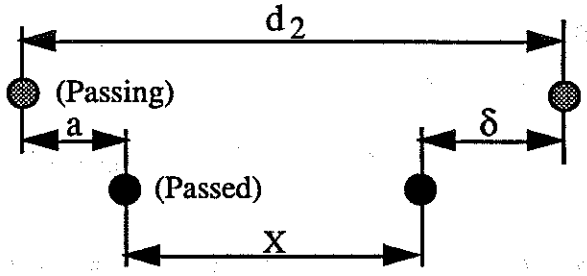


Figure D-4. The second segment of the passing maneuver, "zero-length" vehicles

Using the 10 mph speed difference assumption, the distance X covered by the passed vehicle during the pass is:

$$X = 1.47 \cdot (V - 10) \cdot t_2 \qquad (2)$$

When a truck is involved in the passing maneuver (for demonstration purposes assume a truck being passed by a passenger car), its length should be brought into consideration instead of just a "zero-length" vehicle as in figure D-4. Under these conditions, the segment d_2 of the passing maneuver now takes more time than before and is $t_2 + \Delta t_2$. The additional time is due to (a) the fact that the passed vehicle is longer and therefore takes more time to pass, and (b) during that additional time, the passed vehicle travels farther. The time spent in the left lane by the passing vehicle is also longer by Δt_2. That situation is illustrated in figure D-5. The distances depicted with the prefix "Δ" are added distances due to the length of the truck being considered.

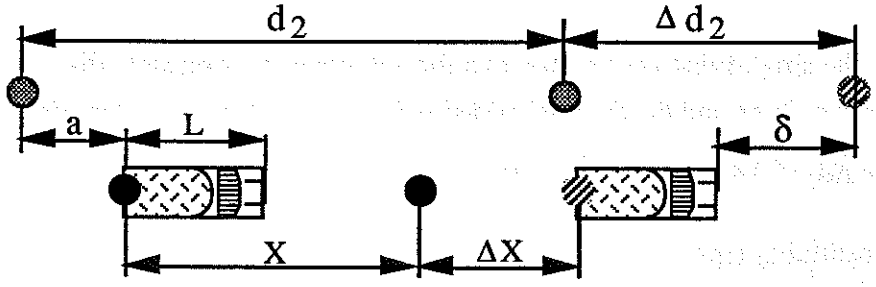


Figure D-5. The second segment of the passing maneuver, passed vehicle has length

The additional distances ΔX and Δd_2 can be expressed as:

$$\Delta X = 1.47 \cdot (V - 10) \cdot \Delta t_2 \qquad (3)$$

$$\Delta d_2 = 1.47 \cdot V \cdot \Delta t_2 \qquad (4)$$

Both a and δ are the same in the two scenarios depicted by figures 4 and 5. Equation (5) describes δ in terms of the situation according to figure 4 (using also equation (2)). Equation (6) describes δ as per figure 5:

$$\delta = d_2 - a - 1.47 \cdot (V - 10) \cdot t_2 \tag{5}$$

$$\delta = d_2 + \Delta d_2 - a - (X + \Delta X) - L \tag{6}$$

Substituting (3) and (4) into (6), δ is used to equate the right side of equation (5) with (6):

$$d_2 - a - 1.47 \cdot (V - 10) \cdot t_2 = d_2 + 1.47 \cdot V \cdot \Delta t_2 - a - X - 1.47 \cdot (V - 10) \cdot \Delta t_2 - L \tag{7}$$

Carrying out the algebraic operations and back-substituting into (4), the expression for Δd_2 is:

$$\Delta d_2 = \frac{V \cdot L}{10} \tag{8}$$

The length of the second segment in the passing maneuver is therefore:

$$d_{2new} = 1.47 \cdot V \cdot t_2 + \frac{V \cdot L}{10} \tag{9}$$

According to the AASHTO practice, the fourth segment of the total distance during the passing maneuver is assumed to be:

$$d_4 = \tfrac{2}{3} \cdot d_2 \tag{10}$$

The addition to d_4 is:

$$\Delta d_4 = \tfrac{2}{3} \cdot \Delta d_2 \tag{11}$$

Based on the simplifying assumption that the additional passing sight distance is due only to the increase in d_2 and d_4, the total added passing sight distance is therefore:

$$\Delta D = \Delta d_2 + \Delta d_4 = \Delta d_2 + \tfrac{2}{3} \cdot \Delta d_2 = \tfrac{5}{3} \cdot \Delta d_2 \tag{12}$$

or, by substituting equation (8):

$$\Delta D = \tfrac{5}{3} \cdot \frac{V \cdot L}{10} = \frac{V \cdot L}{6} \tag{13}$$

With regard to heavy duty trucks, the length of the vehicle is anywhere from 60' (a 48' tractor-semitrailer) to about 119' (a turnpike double). The added passing sight distances as computed from equation (13) are given in table D-1. The various highway design speeds

and the assumed speed of the passing vehicles are derived from Table III-5 (p. 133) of the AASHTO policy.

Table D-1. Added passing sight distance due to length of trucks being passed

Design Speed	Assumed Speed of Passing Vehicle	Added Passing Sight Distance (ΔD), truck length being passed:			
		60 ft	80 ft	100 ft	120 ft
20	30	300	400	500	600
30	36	360	480	600	720
40	44	440	587	733	880
50	51	510	680	850	1020
60	57	570	760	950	1140
65	60	600	800	1000	1200
70	64	640	853	1067	1280

Compensation of passing sight distance for LCVs

The following scheme represents an attempt to apply our incremental approach (discussed in the previous section) to a hypothetical situation in which there is a requirement for the lengths of trucks on a particular road to increase from 60-feet to 80-feet long. Suppose that, as far as we know, the road has been operating satisfactorily with 60-foot trucks. The problem might be to decide what changes in road markings for no-passing zones are needed. If the markings are changed, what effect will the additional no-passing zone lengths have on traffic flow?

Let us consider first an estimate of the additional passing sight distance needed for an extra length of 20 ft. The following analysis is based on passing the additional 20 ft of truck at a relative velocity of 14.67 ft/sec (10 mph); viz.,

$$\Delta t = \frac{\Delta L}{m} = \frac{20}{14.67} = 1.3633 \text{ sec} \qquad (14)$$

If the design speed of the road is 60 mph (88 ft/sec), the additional distance traveled by a passing car is as follows:

$$\Delta d_2 = 88 \cdot 1.3633 = 120 \text{ ft} \qquad (15)$$

(Reference [6] contains discussion of this kind of an approach.)

In this case we might presume that opposing vehicles might be traveling at the design speed (88 ft/sec) and, rather than using the 2/3 factor for the incremental change in d_4, provide the full increment of 120 ft of extra travel for the opposing vehicle. This would suggest to us that we might start striping the no-passing zones 120 ft sooner than before. This would provide an additional warning to car drivers in order to compensate for the increased lengths of the new trucks.

In the above example, one might interpret the result as a 240 ft increase in passing sight distance. However, unless the road were to be redesigned and rebuilt, the available passing sight would not change. The drivers on the existing road would still be expected to judge whether or not they have enough distance to complete a pass before entering a no-passing zone. (Presumably, this is the strategy that drivers now use when passing trucks.)

Although we are not currently prepared to estimate the influence of the lengths and frequencies of passing zones on traffic flow, we do know that techniques exist for estimating the change in traffic flow. Given an estimate of the change in traffic flow, a policy decision could be made as to an appropriate course of action with regard to increased striping, reduced traffic flow, and the percentage of longer vehicles using the road.

The above has been presented as an example of trying to apply our ideas to develop a proposed course of action. Clearly, we are interested in MDOT's reactions and suggestions to this hypothetical discussion. In conclusion, the following table D-2 presents similar results for various design speeds and vehicle lengths using 60 ft as the baseline vehicle.

Table D-2. Entries are the additional distances in the left lane over those required for 60 ft trucks. (Per our hypothesis, these entries are the additional striping lengths for the conditions indicated. The additional passing distance would be twice the value of the entries.)

Design Speed	**Vehicle length**		
	80 ft (1.3633 sec)	**100 ft** (2.1272 sec)	**120 ft** (4.0908 sec)
40 (58.7 ft/sec)	80	160	240
50 (73.3 ft/sec)	100	200	300
60 (88.0 ft/sec)	120	240	360
70 (102.7 ft/sec)	140	280	420

Glennon's suggested practice

With regard to the concept of passing sight distance computation, an examination of the procedure suggested by Glennon [3] as compared to that of AASHTO reveals the following:

- Both AASHTO and Glennon determine the total required sight distance as a sum of segmented distances.
- Glennon's procedure uses vehicle length explicitly, so that the effect of LCVs can be accurately assessed with comparison to an "all passenger cars" situation.
- Glennon uses the same definition for the first segment (d_1) as AASHTO.
- The fourth segment of the sight distance (d_4) does not exist in Glennon's procedure as a computational entity. There is assumed to be some fixed clearance (1 sec.) between the passing vehicle and the one in the opposite lane when the maneuver is either completed or aborted.
- Both AASHTO and Glennon assume that the design speed, the speed of the passing vehicle and the speed of the vehicle in the opposite lane are all the same.

As described before, Glennon's approach is based on the concept of a critical point, or a "point of no return." The point of no return is where the location of the passing vehicle with respect to the passed vehicle is such that the same passing sight distance is required to either safely complete or safely abort the maneuver. This relative position between the vehicles is defined as the critical separation. It is the distance measured from the front of the passing vehicle to the front of the passed vehicle at the critical point. The location of the critical point, or the critical separation distance is computed according to equation (1). The passing sight distance, D, according to Glennon's method, is given by equation (2) once the critical position is computed.

$$\Delta_c = L_p + 1.47m\left(\frac{2.93m + L_I + L_p}{1.47(2V - m)} - \sqrt{\frac{4V\left(2.93m + L_I + L_p\right)}{d(2V - m)}}\right) \qquad (1)$$

where:

Δ_C is the critical separation distance, ft
V is the speed of the passing (or opposing vehicle), mph
m is the speed difference between the passing vehicle and the passed vehicle, mph
d is the deceleration rate used in aborting the passing maneuver, ft/sec^2

L_p is the length of the passing vehicle, ft
L_I is the length of the passed vehicle, ft

$$D = 2 \cdot V \cdot \left(2.93 + \frac{L_p - \Delta_c}{m} \right) \quad (2)$$

Using equations (1) and (2), Glennon's model was employed to study passing sight distances for various passing scenarios. Design values used were the same as those used by Glennon, based on the studies specified in [3] and [4]:

- Passenger car length is 19 ft.
- Deceleration rate for cars is 8 ft/sec^2.
- Deceleration rate for trucks is 5 ft/sec^2.
- While in the left lane, and when the passing vehicle is a passenger car, the speed difference between the passing and the passed vehicle is per the following table D-3:

Table D-3. Speed differences between passing and passed vehicles

Passing speed (road design speed)	Speed difference
20	13
30	12
40	11
50	10
60	9
70	8

- When the pass is made by a truck, the speed difference between the passing and the passed vehicle is only half the value quoted in table D-2.

Passing sight distances computed by the model suggested by Glennon under these assumptions for various passing scenarios are presented in table D-4 (results are rounded up to the next 25 ft). Since both AASHTO and Glennon treat the case in which a passenger car is being passed by another passenger car as a baseline scenario, the results in table 4 were appropriately compared to that case. The additional passing sight distance due to the involvement of trucks is given in table D-5.

Table D-4. Passing sight distance using Glennon's model

Passing Sight Distance

A car Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	13	NA	NA	NA	NA	NA
30	12	525	NA	NA	NA	NA
40	11	700	775	825	850	875
50	10	875	1000	1050	1075	1125
60	9	1025	1200	1250	1325	1375
70	8	1200	1375	1475	1525	1600

A 60' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	575	650	650	NA	NA
40	5.5	825	925	950	1000	1025
50	5	1075	1200	1250	1300	1350
60	4.5	1300	1475	1550	1625	1675
70	4	1550	1750	1825	1925	2000

A 80' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	625	650	NA	NA	NA
40	5.5	875	950	1000	1025	1050
50	5	1150	1250	1300	1350	1400
60	4.5	1400	1550	1625	1675	1725
70	4	1650	1825	1925	2000	2050

A 100' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	650	NA	NA	NA	NA
40	5.5	925	1000	1025	1050	1075
50	5	1200	1300	1350	1400	1425
60	4.5	1475	1625	1675	1725	1775
70	4	1750	1925	2000	2050	2125

A 120' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	650	NA	NA	NA	NA
40	5.5	950	1025	1050	1075	1100
50	5	1250	1350	1400	1425	1475
60	4.5	1550	1675	1725	1775	1825
70	4	1825	2000	2050	2125	2200

Table D-5. Additional passing sight distance when trucks are involved

Increased Passing Sight Distance

(Compared to a car passing a car)

A 60' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	50	NA	NA	NA	NA
40	5.5	125	225	250	300	325
50	5	200	325	375	425	475
60	4.5	275	450	525	600	650
70	4	350	550	625	725	800

A 80' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	100	NA	NA	NA	NA
40	5.5	175	250	300	325	350
50	5	275	375	425	475	525
60	4.5	375	525	600	650	700
70	4	450	625	725	800	850

A 100' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	125	NA	NA	NA	NA
40	5.5	225	300	325	350	375
50	5	325	425	475	525	550
60	4.5	450	600	650	700	750
70	4	550	725	800	850	925

A 120' Truck Passing:

Speed	Speed dif.	Car	60'	80'	100'	120'
20	6.5	NA	NA	NA	NA	NA
30	6	125	NA	NA	NA	NA
40	5.5	250	325	350	375	400
50	5	375	475	525	550	600
60	4.5	525	650	700	750	800
70	4	625	800	850	925	1000

A Car Passing:

Speed	Speed dif.	60'	80'	100'	120'
20	13	NA	NA	NA	NA
30	12	NA	NA	NA	NA
40	11	75	125	150	175
50	10	125	175	200	250
60	9	175	225	300	350
70	8	175	275	325	400