CHAPTER 15
TWO-LANE HIGHWAYS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

Two-lane highways have one lane for the use of traffic in each direction. The single lane in each direction may be supplemented with passing lanes, truck climbing lanes, turnouts, or pullouts. Two-lane highways with a continuous middle lane used for alternating passing lanes, referred to as a “2+1” configuration, are addressed in Appendix A of this chapter.

Intersections are generally uncontrolled for the main highway. Signals, all-way stops, or roundabouts that control or reduce the speed of through traffic on the mainline, if present, should generally be 2 miles or more apart. Highways with denser controlled intersection spacing should be evaluated using the urban streets methods in Volume 3.

The principal characteristic that distinguishes the analysis of motor vehicle traffic on two-lane highways from other uninterrupted-flow facilities is that passing maneuvers can take place in the opposing lane of traffic. Passing maneuvers are limited by the availability of gaps in the opposing traffic stream and by the availability of sufficient sight distance for a driver to discern the approach of an opposing vehicle safely. As demand flows and geometric restrictions increase, opportunities to pass decrease. This creates platoons within the traffic stream, with trailing vehicles subject to additional delay because of the inability to pass the lead vehicles. Consequently, operating quality on two-lane highways can become “unacceptable” at relatively low volume-to-capacity ratios and/or high average travel speeds. For this reason, few two-lane highways ever operate at flow rates approaching capacity; in most cases, poor operating quality leads to improvements or reconstruction long before demand reaches capacity.

CHAPTER ORGANIZATION

Chapter 15 presents methodologies for the analysis, design, and planning of two-lane highway facilities operating under uninterrupted flow, for both automobiles and bicycles. Uninterrupted flow exists when there are no traffic control devices that interrupt traffic and where no platoons are formed by upstream signals or roundabouts. In general, any stretch of highway that has major intersections (e.g., traffic signals, roundabouts) spaced approximately 2.0 mi or less should be classified as an urban street and analyzed with the methodologies of Chapter 16, Urban Street Facilities, and Chapter 18, Urban Street Segments, which are located in Volume 3. Furthermore, unlike two-lane highways, passing in the opposing lane typically is not allowed on urban streets.

Section 2 of this chapter presents the basic concepts for analyzing two-lane highways. It covers the characteristics of two-lane highways, including the geographic and land use context, and base conditions. It covers the analysis concepts, including: segmentation of the facility for analysis purpose, the definition of access points, and an overview of the treatment of heavy vehicles and terrain. This section also covers applicable performance measures, analysis approach, capacity, and level of service (LOS). The discussion of performance measures includes graphs showing the sensitivity of performance to demand.

Section 3 presents the method for evaluating motorized vehicle operations on two-lane highways. The method produces estimates of free-flow speed, average speed, percent followers, follower density, and motor-vehicle LOS.

Section 4 presents a method for evaluating bicycle operations on two-lane and multilane highways. The method is applicable to bicycle operations in a shared lane, bicycle lane, or shoulder bikeway. This method generates two performance measures: (*a*) a bicycle LOS score reflecting bicyclist perceptions of operating conditions and (*b*) a bicycle LOS letter based on the bicycle LOS score. Both the bicycle LOS score and letter are comparable with similar scores and letters produced for urban streets in HCM Chapters 16 and 18. Bicycle operations on exclusive- or shared-use paths separate from the highway can be evaluated by using the methods in Chapter 24, Off-Street Pedestrian and Bicycle Facilities.

Section 5, Applications, provides advice on the practical application of the motorized vehicle and bicycle analysis methodologies contained in this chapter.

Appendix A provides additional guidance on evaluating the downstream effects of passing lanes.

RELATED HCM CONTENT

Other HCM content related to this chapter includes the following:

- Chapter 3, Modal Characteristics, where the Variations in Demand subsection of the Motorized Vehicle Mode section describes typical travel demand patterns for two-lane highways;
- Chapter 4, Traffic Operations and Capacity Concepts, which provides background for the refinements specific to two-lane highways presented in this chapter's Section 2;
- Chapter 26, Freeway and Highway Segments: Supplemental, where Section 2 presents state-specific heavy-vehicle percentages that can be used as default values, Section 8 provides example problems, and Appendix B presents a method for evaluating the capacity of work zones on two-lane highways; and
- Section J, Two-Lane Highways, in the *Planning and Preliminary Engineering Applications Guide to the HCM,* found in Volume 4.

2. CONCEPTS

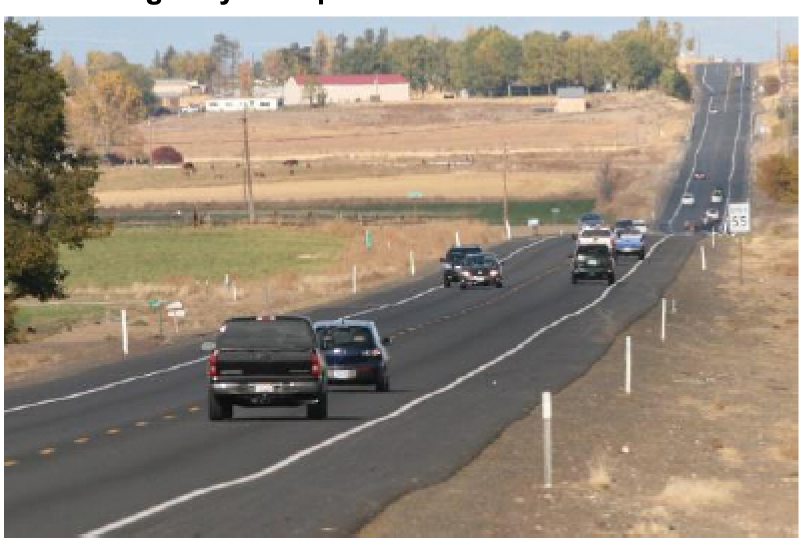
CHARACTERISTICS OF TWO-LANE HIGHWAYS

Geographic and Land Use Context

Two-lane highways are a key element in the highway systems of most states and counties. They are located in many different geographic areas and serve a wide variety of traffic functions. Two-lane highways provide critical (and often the only) access to rural areas for both people and goods movement, and the efficient operation of these highways is often vital to the economic well-being of the areas they serve. Two-lane highways also serve a number of bicycle trips, particularly recreational trips.

As the above descriptions suggest, two-lane highways serve a variety of functions and land uses and provide a wide range of operational characteristics along the spectrum of mobility and accessibility. Any consideration of operating quality criteria must account for these disparate functions. Exhibit 15-1 shows examples of various types of two-lane highways.

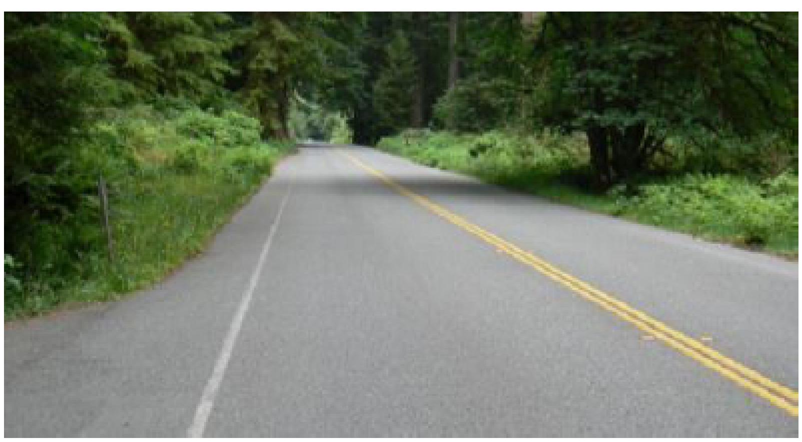
Exhibit 15-1: Two-Lane Highway Examples



(a1) Intercity/regional connectors

(a2) Intercity/regional connectors

(b) Intracity connector



(c) Section passing through scenic area

(d) Section passing through challenging terrain

(e) Section with climbing lane

Base Conditions

The base conditions for two-lane highways are the absence of restrictive geometric, traffic, or environmental factors. Base conditions are not the same as typical or default conditions, both of which may reflect common restrictions. Base conditions are closer to what may be considered as ideal conditions (i.e., the best conditions that can be expected given normal design and operational practice). This chapter's methodology accounts for the effects of geometric, traffic, and environmental factors that are more restrictive than the base conditions. The base conditions for two-lane highways are as follows:

- Lane widths greater than or equal to 12 ft,
- Clear paved shoulders wider than or equal to 6 ft,
- Traffic stream composed entirely of passenger cars,
- Level terrain, straight alignment (i.e., no horizontal curves with radii under 2,550 ft),
- No impediments to through traffic (e.g., no traffic signals, comparatively few vehicles turning on or off the highway), and
- Good environmental conditions (e.g., clear weather, good visibility, paved road surface in good condition).

Traffic can operate at maximum speeds only if lanes and shoulders are wide enough not to constrain speeds. Lanes narrower than 12 ft and shoulders narrower than 6 ft have been shown to reduce speeds and may increase the percentage of vehicles in a follower status.

ANALYSIS CONCEPTS

This section describes the various segment types along a two-lane highway facility, the identification of access points, the treatment of terrain and heavy vehicles, the capacity of two-lane highways, the criteria for determining motor vehicle and bicycle LOS, and other applicable performance measures.

Segmentation

A two-lane highway is divided into segments for analysis purposes. The ability to pass, lane geometry, grades, lane and shoulder widths, posted speed limits, traffic demands, adjacent land uses, driveways, and other characteristics of the facility should be homogeneous within each analysis segment. Note that segmentation will be different for each direction of the highway because passing zones and other characteristics will start and end in different locations depending on the direction of travel. The results of each segment analysis are then combined into results for the full highway.

This chapter’s analysis methodology can be used to analyze individual homogeneous segments of a two-lane highway, as well as extended lengths of a two-lane highway that are composed of multiple contiguous segments. The methodology applies to the following segment types described below: Passing Constrained, Passing Zone, and Passing Lane.

Passing Constrained

A Passing Constrained segment is one in which passing in the oncoming lane is either prohibited or is effectively negligible due to geometric or sight distance limitations. Contiguous stretches of roadway with varying geometric conditions can be combined into a single Passing Constrained analysis segment when the vehicle performance of passenger cars and heavy vehicles is relatively consistent from one sub-segment to another, and the difference in vehicle performance capability due to the roadway geometry between passenger cars and heavy vehicles is minimal. Thus, truck performance is the critical factor for determining when it is appropriate to combine contiguous sub-segments. In addition, roadway sections where passing in the oncoming lane is allowed, but essentially does not take place (regardless of opposing traffic demand), can also be included in a Passing Constrained analysis segment.

A Passing Constrained segment may contain some heterogeneity in the geometric alignment; however, no section of roadway within this segment should have significantly different operating conditions than other sections within the segment. If significant operating differences exist, that portion of the roadway should be split into a separate segment. The traffic operations in a Passing Constrained segment are a function of:

- Analysis direction flow rate,
- Percent heavy vehicles,
- Horizontal and vertical alignment, and
- Segment length.

Passing Zone

Passing opportunities have a significant influence on two-lane highway performance. One way to provide passing opportunities is through the provision of passing zones: locations where passing in the oncoming lane is not restricted. However, to be effective in accommodating passing maneuvers, these zones must provide a minimum length of useable passing distance. The effectiveness of a passing zone in improving traffic operations is a function of:

- Analysis direction flow rate,
- Opposing direction flow rate,
- Percent heavy vehicles,
- Vertical and horizontal alignment, and
- Passing zone length.

Passing and Climbing Lanes

A passing lane, a relatively short length of roadway where an additional lane is provided in the same travel direction, is another mechanism for providing passing opportunities. A passing lane can be effective in dispersing platoons by providing an opportunity for faster vehicles to pass slower vehicles. Passing lanes on significant upgrades (i.e., where the speed of large trucks is reduced well below their desired speed) are generally referred to as *climbing lanes*. Very short lengths of added lane, on the order of a few hundred feet, are considered turnouts and not passing lanes. This chapter's analysis methodology does not explicitly address two-lane roadways with turnouts. The effectiveness of a passing or climbing lane in improving traffic operations is a function of:

- Analysis direction flow rate,
- Percent heavy vehicles,
- Vertical and horizontal alignment, and
- Passing lane length.

Performance improvements in roadway operations can persist well downstream of the end of a passing lane segment, particularly with respect to percent followers. Average speed also improves; however, this improvement is relatively minor and persists for a much shorter distance downstream, relative to follower-related improvements.

The distance downstream of the end of the passing lane to which the operational improvements resulting from the passing lane applies is referred to as the effective length of the passing lane. Specifically, *effective length* is the distance from the start of the passing lane to a point downstream where the roadway's performance returns to its original value; that is, the performance measured immediately upstream of the start of the passing lane. How the concept of the effective length factors into the analysis will be presented in the step-by-step methodology discussed in Section 3.

Access Points

Access points are major driveways and side roads where significant traffic enters and/or leaves the two-lane highway within an analysis segment. Access points lower the free-flow speed for the segment. By lowering the free-flow speed, access points will also indirectly affect the average speed and the follower density.

The total number of access points on an analysis segment is the sum of the number of active major driveways and road or street approaches (on both sides of the highway) where traffic enters and/or leaves the two-lane highway within the segment. Residential driveways and other low-volume driveways and side roads (generally with ADT below 20 vehicles per day) should not be counted as access points. If the two-lane highway has a physical median barrier, or barrier striping, that prevents access to driveways on the opposite side of the barrier, then the access points on the opposite side of the median should not be included in the total for the segment.

Note that the methodology for estimating segment speeds does not provide for the computation of the effects of intersection delays *within* a two-lane highway analysis segment. Therefore, segments cannot include all-way STOP, roundabout, or signal-controlled intersections between their endpoints. The segment must be split into smaller segments so that these intersections fall at the segments' start- or endpoints. Intersections at the beginning or end point of a segment do not count as access points.

See the discussion under Step 1, in Section 3, Motorized Vehicle Methodology, for desirable lower limits on segment lengths.

Treatment of Terrain and Heavy Vehicles

Unlike other facility analysis methodologies in the HCM, the two-lane highway analysis procedure works directly with traffic stream units of veh/h, rather than pc/h. This approach provides the ability to more accurately represent the performance measure relationships as a function of the more varying horizontal and vertical alignment often encountered on two-lane highways. Additionally, it simplifies the analysis methodology by removing the process of converting units from veh/h to pc/h. The two-lane highway analysis methodology therefore includes the percentage of heavy vehicles as an input to the performance measure estimation models.

In general, a heavy vehicle is defined as any vehicle (or vehicle–trailer unit) with more than four wheels on the ground during normal operation. Heavy vehicles generally consist of large trucks, buses, and recreational vehicles (RVs). The performance measure estimation models presented in this chapter assume three general classifications of heavy vehicles: small, medium, and large. Small heavy vehicles are those in FHWA classifications 4–7, medium heavy vehicles are those in FHWA classification 8, and large heavy vehicles are those in FHWA classifications 9 and 10 (*1*). FHWA classifications 11–13 are comparatively rare in the field and were consequently not specifically identified in the performance measure estimation model. The models assume that the relative split between the three truck classifications is 50% small, 25% medium, and 25% large (*2*).

Vertical alignment is accommodated through a classification scheme providing five different levels. Each classification is a function of the segment length and up- or downgrade percentage. The classification levels are based on reductions in heavy-vehicle free-flow speed. On an upgrade, the speed reduction is a function of the effect of grade resistance limiting a vehicle’s acceleration capability. On a downgrade, the speed reduction is a result of trucks downshifting to avoid the potential of a “runaway” acceleration condition. Vertical Alignment Class 1 corresponds to a minimal reduction in free-flow speed, while Vertical Alignment Class 5 corresponds to a crawl-speed condition. The vertical classification guidelines are given in Section 3.

Horizontal alignment is also accommodated through a classification scheme that considers reductions in heavy-vehicle free-flow speed. The horizontal classifications are a function of curve radius and superelevation. The horizontal classification guidelines are given in Section 3.

Applicable Performance Measures and Their Sensitivities

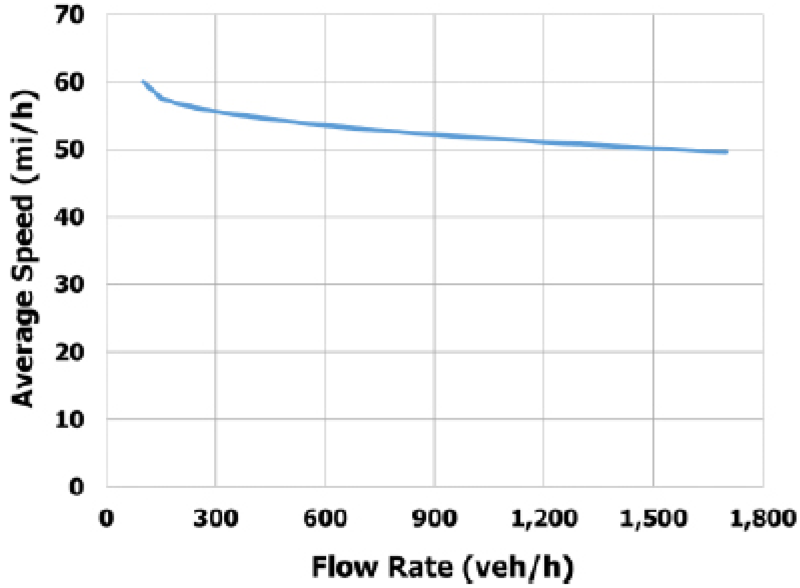
Three performance measures underpin this chapter's analysis methodology: average speed, percent followers, and follower density.

These three performance measures were selected to represent the quality of service provided by two-lane highways because they most closely conform to typical agency performance objectives for two-lane highways of reduced travel times and reduced pressure to pass (i.e., reduced percent and density of followers). They also have the advantage of being sensitive to the design and demand features typically considered when planning and designing two-lane highways.

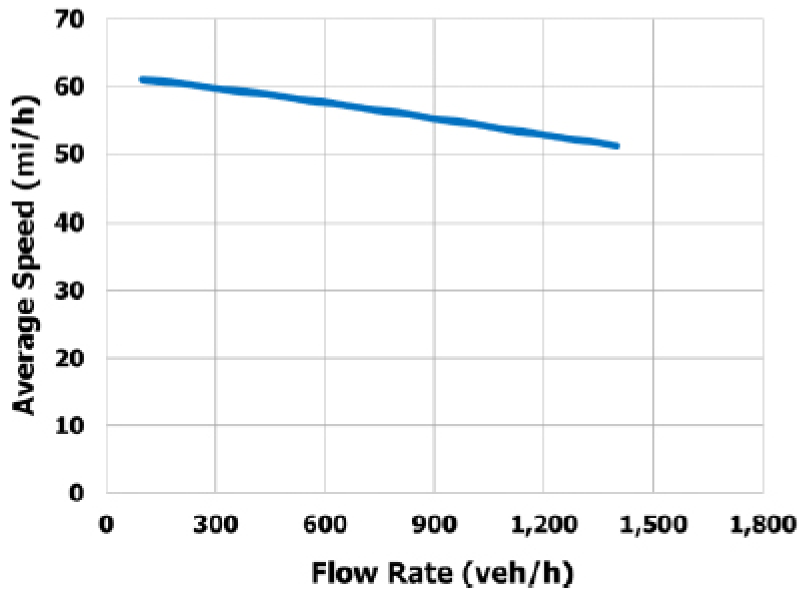
Average Speed

Average speed is a key performance measure for two-lane highways, and factors into the determination of level of service (LOS). The general relationship between average speed and flow rate is nonlinear, as illustrated in Exhibit 15-2.

Exhibit 15-2: Average Speed Versus Directional Flow Rate



(a) Passing Zone Segment



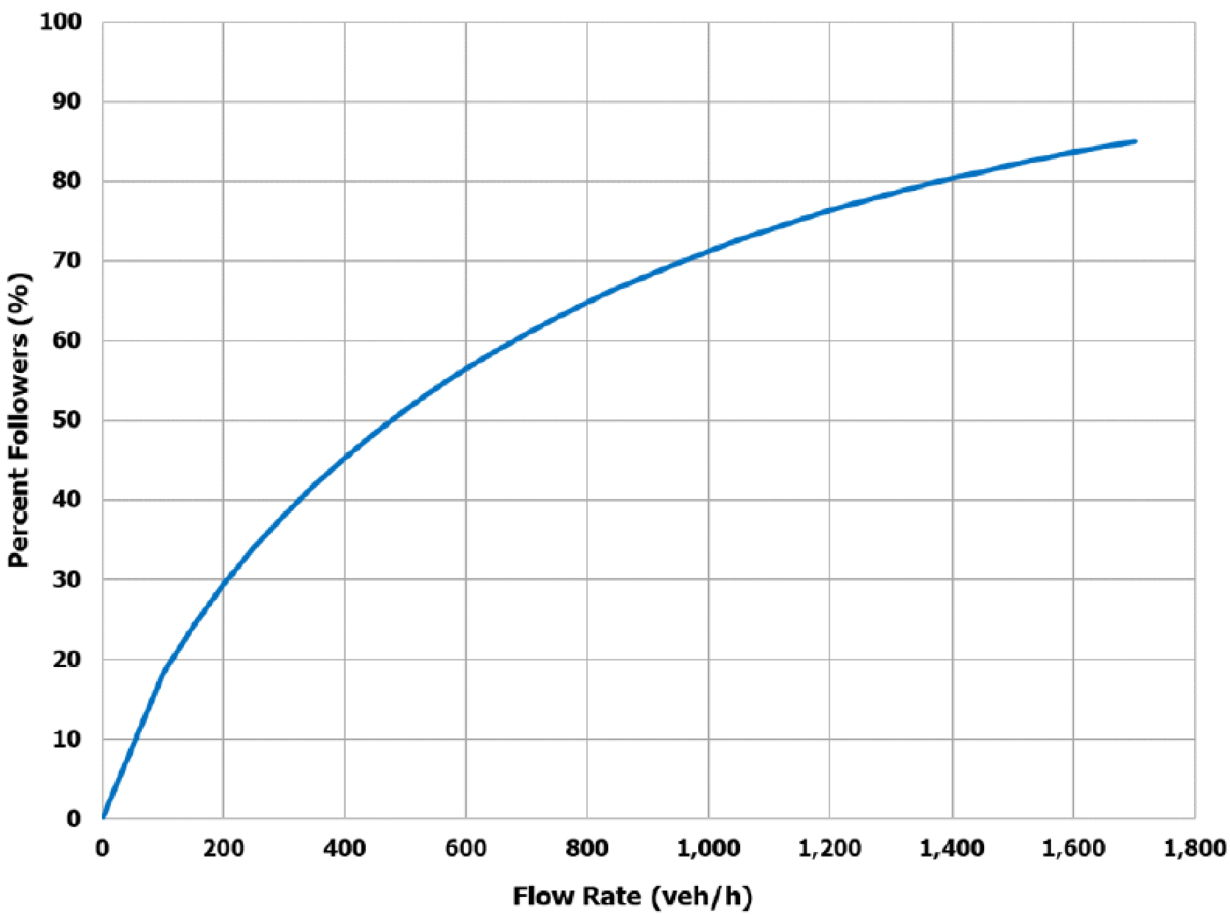
(b) Passing Lane Segment

Percent Followers

The measure *percent followers* represents the freedom to maneuver and the comfort and convenience of travel. It can also serve as a proxy for the need to provide passing opportunities. Percent followers is the percentage of vehicles passing a given point on the roadway that are considered to be in a follower state. Being in a follower state is used as a surrogate to indicate a driver's perception that they are being delayed by a slower driver. Higher values are generally indicative of restrictions in passing (e.g., very infrequent passing zones or passing lanes, high volumes in the opposing direction).

A critical headway threshold value of 2.5 s is used to determine whether a vehicle is in a follower state. Thus, any vehicle following another vehicle at a headway of 2.5 s or less is considered to be in a follower state and percent followers is simply the percentage of all vehicles with a headway of 2.5 s or less at a given roadway location. This approach was found to provide reasonable agreement with the identification of follower status through more complex methods (*2*). The general relationship between percent followers and flow rate is non-linear, as illustrated in Exhibit 15-3.

Exhibit 15-3: Percent Followers Versus Directional Flow Rate



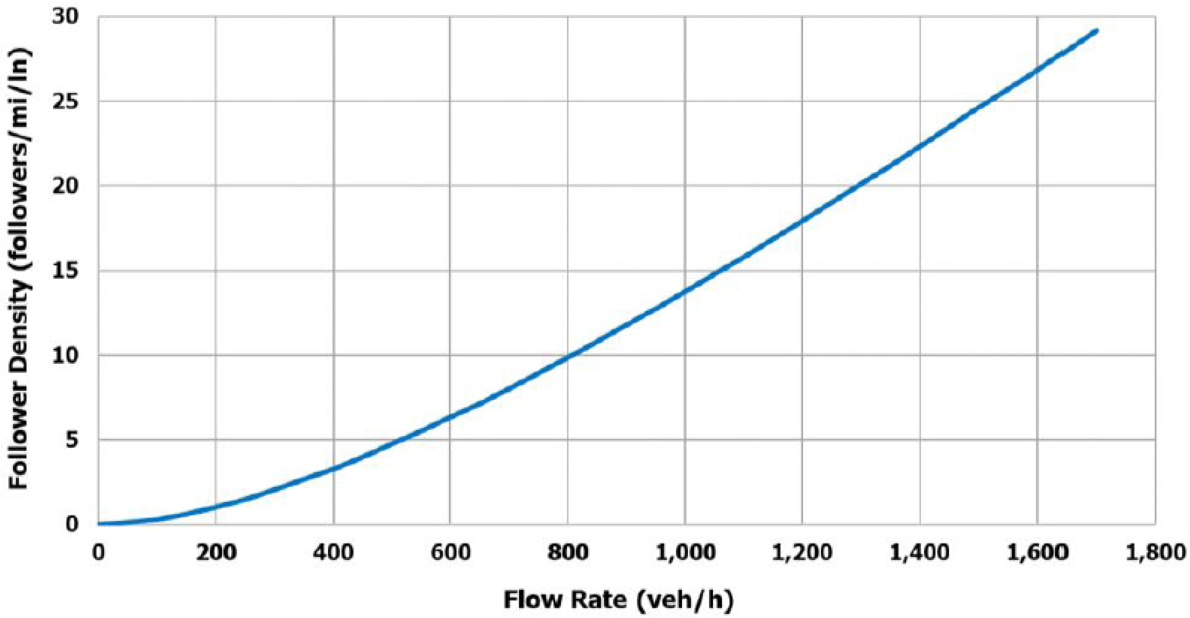
Note that even at a capacity flow rate, 100% followers will not be reached. This is because there will always be some gaps between platoons within the traffic stream as a result of different platoon lead vehicle desired speeds.

Although the two directions of traffic flow can interact on a two-lane highway (because of passing maneuvers in the opposing lane), this chapter's methodology analyzes each direction separately. Exhibit 15-3 illustrates a critical characteristic that affects two-lane highways. Low directional volumes can still result in high values of percent followers. In multilane uninterrupted flow, acceptable speeds usually can be maintained at relatively high proportions of capacity. On two-lane highways, however, service quality begins to deteriorate at relatively low demand flows.

Follower Density

Follower density is defined as the number of vehicles in a follower state per mile per lane. Mathematically, it is the percent followers multiplied by density. This measure is used as the service measure for two-lane highways because of its sensitivity to both traffic demand and geometric alignment variability. On two-lane highways, it is possible for two roadways to have similar values of density but very different levels of percent followers. Likewise, it is possible for two roadways to have similar percent followers but very different values of density. Therefore, service quality is better represented by considering the combination of follower percentage and density. The general relationship between follower density and flow rate is illustrated in Exhibit 15-4.

Exhibit 15-4: Follower Density Versus Directional Flow Rate



Analysis Approach

Individual segments can be analyzed with this methodology. Additionally, multiple contiguous two-lane highway segments (in the same direction) may be combined to analyze a longer section (with varying characteristics) as a facility.

The operational performance of a segment, either individually or within a facility, is reported for the end of the segment, rather than corresponding to an aggregated value across the full length of the segment. Thus, the reported values are point estimates of performance, and are not necessarily representative of average conditions along an extended length of segment. This approach was selected to make it easier for practitioners to use field-measured point values to directly calculate LOS with the method, and to use point values to validate method outputs. Nevertheless, when considering multiple contiguous segments as a facility, the point measure is used as the estimate of the performance of a given segment. From a traveler's perspective, the conditions at the end of a segment (particularly passing zones) probably factor more heavily into their assessment of the quality of service. For passing lane segments, additional point performance measures are calculated, which is described in Section 3.

While this chapter provides estimation equations for all of the key performance measures, it is also possible to assess LOS through direct field measurement of speed, flow rate, and percent followers at a specific point. See Section 5 for further guidance on this topic.

Capacity

Flow rates equivalent to capacity are rarely observed on two-lane highways, except possibly in short segments. Because service quality deteriorates at relatively low demand flow rates, most two-lane highways are upgraded before demand approaches capacity. Thus, the consideration of a capacity value for a two-lane highway operations analysis is rarely a concern. Nevertheless, being able to estimate capacity can be important for some planning situations, such as evacuation planning, special event planning, recreational routes, and evaluating the downstream impacts of incident bottlenecks once cleared.

The capacity of a section of two-lane highway without a passing lane, under base conditions, is 1,700 veh/h/ln. This value assumes a low percentage of large trucks in the traffic stream, on the order of 5% or less. A distinction between the capacities of a Passing Zone and a Passing Constrained segment is not made, as the empirical evidence is currently too limited in this regard.

Maximum Analysis Flow Rates on Passing Lane Segments

Passing lane segments can significantly improve traffic flow, especially on steep and long grades. However, the merging behavior of vehicles at the end of the passing lane can become problematic at high flow rates. Higher flow rates reduce the average gap between vehicles, which forces drivers to merge into smaller gaps. This behavior creates shockwaves, as following vehicles must decelerate for the merging vehicles. At some point, breakdown is reached, and the performance of the passing lane degrades below that of a non–passing lane segment. Guidelines for maximum flow rates for passing lane segments are given in Exhibit 15-5. These values are a function of the heavy vehicle percentage and the vertical classification. See Section 3 and Exhibit 15-11 for the vertical alignment definitions.

Exhibit 15-5: Maximum Flow Rates for Passing Lane Segments

Heavy Vehicle Percentage (%)	Maximum Flow Rate (veh/h) by Vertical Class				
	1	2	3	4	5
< 5	1,500	1,500	1,500	1,500	1,500
≥ 5 < 10	1,500	1,500	1,500	1,500	1,400
≥ 10 < 15	1,400	1,400	1,400	1,300	1,300
≥ 15 < 20	1,300	1,300	1,300	1,300	1,200
≥ 20 < 25	1,300	1,300	1,300	1,200	1,100
≥ 25	1,100	1,100	1,100	1,100	1,100

Note: Capacity is governed by merge point at end of passing lane segment.

The merging friction at the end of the passing lane results in capacities for segments with passing lanes that are noticeably lower than for segments without passing lanes. Tests found that slower vehicles (which included most of the trucks) moved to the added lane and had to merge back into the "regular" lane.

If expected demand flow rates for a two-lane highway will exceed the capacity values given here, the level of service is considered to be F and the chapter's analysis methodology is not applicable.

Levels of Service

Motorized Vehicle Mode

If the demand-to-capacity ratio is less than or equal to 1.0, follower density is used as the service measure for all two-lane highways. However, two sets of LOS thresholds are used to account for differences in driver perception between driving on higher-speed versus lower-speed highways.

On higher-speed two-lane highways (≥50 mi/h), absolute speed and delay due to passing restrictions are generally both important to motorists. Higher-speed two-lane highways are most commonly encountered as inter-city connecting routes. Lower-speed two-lane highways (< 50 mi/h) are typically encountered as intra-city routes and in scenic and rural-developed areas. These highways generally have posted speed limits of 35–45 mi/h and have limited passing opportunities. Thus, for two-lane highways in these areas, high speeds are usually not expected and higher percentages of followers are generally tolerated. Consequently, the follower density thresholds for a given LOS are higher for lower-speed highways than higher-speed highways. The LOS criteria for two-lane highways are given in Exhibit 15-6.

Exhibit 15-6: Motorized Vehicle LOS Criteria for Two-Lane Highways

LOS	Follower Density (followers/mi/ln) Higher-Speed Highways Posted Speed Limit ≥ 50 mi/h	Follower Density (followers/mi/ln) Lower-Speed Highways Posted Speed Limit < 50 mi/h
A	≤ 2.0	≤ 2.5
B	> 2.0 – 4.0	> 2.5 – 5.0
C	> 4.0 – 8.0	> 5.0 – 10.0
D	> 8.0 – 12.0	> 10.0 – 15.0
E	> 12.0	> 15.0
F	Demand exceeds capacity	

At LOS A, motorists experience operating speeds near the posted speed limit and little difficulty in passing. Platooning is minimal and follower density is very low. At LOS E, speeds may still be reasonable, but platooning is significant and follower density is high. Passing, if allowed, is essentially impossible. Conditions for LOS B, C, and D represent gradations between the conditions for LOS A and E. LOS F exists whenever demand flow exceeds the capacity of the segment. When demand exceeds capacity, it is expected that there will be a reduction in the capacity at the bottleneck (i.e., the queue discharge rate will be lower than capacity under uncongested conditions).

Bicycle Mode

Bicycle levels of service for two-lane and multilane highway segments are based on a bicycle LOS (BLOS) score, which is in turn based on a traveler perception model. This score is based, in order of importance, on five variables:

- Average effective width of the outside through lane,
- Motorized vehicle volumes,
- Motorized vehicle speeds,
- Heavy vehicle (truck) volumes, and
- Pavement condition.

The LOS ranges for bicycles on two-lane and multilane highways are given in Exhibit 15-7.

Exhibit 15-7: Bicycle LOS Criteria for Two-Lane and Multilane Highways

LOS	BLOS Score
A	≤1.5
B	>1.5–2.5
C	>2.5–3.5
D	>3.5–4.5
E	>4.5–5.5
F	>5.5

3. MOTORIZED VEHICLE METHODOLOGY

SCOPE OF THE METHODOLOGY

This chapter's methodology addresses the analysis of directional two-lane highway segments or facilities with varying horizontal or vertical alignment. The methodology is most directly used to determine the LOS on a uniform directional segment of two-lane highway, or a series of contiguous segments, by estimating the performance measures that are used to determine LOS. Such an analysis can also be used to determine the capacity of the directional segment or the service flow rate that can be accommodated at any given LOS.

Spatial and Temporal Limits

This chapter's methodology applies to uniform directional segments of a two-lane highway. While the two directions of flow interact through passing maneuvers (and limitations on passing maneuvers), each direction must be analyzed separately. Directional segments should have the same or similar traffic and roadway conditions in the direction being studied. Segment boundaries should be established at points where a change occurs in any of the following in the study direction: terrain, lane widths, shoulder width, facility classification, or demand flow rate. An analysis segment can contain no more than one passing or climbing lane in the study direction.

The recommended length of the analysis period is the HCM standard of 15 min (although longer periods can be examined).

Performance Measures

This motor-vehicle method produces the following performance measures:

- Free-flow speed,

- Average speed,
- Percent followers, and
- Follower density.

Strengths of the Methodology

The methodology provides a straightforward way to analyze uninterrupted-flow segments of two-lane highways and produces several useful performance measures as outputs. The method can evaluate the effects of passing and climbing lanes on two-lane highway operation.

Limitations of the Methodology

The motorized vehicle methodology works best for the analysis of individual segments where the selected analysis segment is immediately downstream of a fairly straight, fairly level, constrained passing segment of sufficient length such that the traffic conditions are in a reasonably stable state.

The motorized vehicle methodology for evaluating *facilities* is able to model some interactions between upstream and downstream segments but only under limited conditions (e.g., the downstream effects of a single passing lane). For example, the method does not consider the impacts of upgrades that begin before the analysis segment and continue through it, nor does it consider the additive impacts of multiple passing lanes. In such situations, a microsimulation analysis is recommended to better capture the complex system effects.

The facility analysis methodology does not address two-lane highways with signalized intersections or other types of intersections requiring traffic on the highway to stop or yield. For these situations, the reader is referred to reference (*3*) for more analysis guidance. Isolated intersections on two-lane highways may be evaluated with the intersection methodologies given in Volume 3. Two-lane highways in urban and suburban areas with multiple signalized intersections spaced 2 mi or less apart should be analyzed as urban streets using Chapter 17, Urban Street Segments. Operations of two-lane highways with signalized intersections closer than 2 mi apart are dominated by issues of signal progression and other factors associated with urban streets.

Even isolated intersections can have a significant effect on two-lane highway operations where queuing on the highway immediately upstream of the signalized intersection is significant. This effect is especially likely in cases where the intersection approach fails for any period of time; that is, has a d/c ratio > 1.00. Again, in such complex situations, a microsimulation analysis is recommended.

Alternative Tool Considerations

Appendix I of the final report for NCHRP Project 17-65, Improved Analysis of Two-Lane Highway Capacity and Operational Performance (*2*), describes simulation methods for two-lane highways. Situations in which simulation should be considered include:

- Segment lengths falling outside the method's specified minimum and maximum lengths;
- Long upgrades spanning multiple segments;
- Multiple passing lanes with overlapping effective lengths;
- Volumes differing more than 10% between segments;
- Demand exceeding capacity; and
- Traffic signals, roundabouts, or other forms of intersection traffic control that may cause highway traffic to stop or yield.

REQUIRED DATA AND SOURCES

Exhibit 15-8 lists the information necessary to apply the motorized vehicle methodology and suggests potential sources for obtaining these data. It also suggests default values for use when segment-specific information is not available. The user is cautioned that every use of a default value instead of a field-measured, segment-specific value may make the analysis results more approximate and less related to the specific conditions that describe the highway. HCM defaults should only be used when (*a*) field data cannot be collected and (*b*) locally derived defaults do not exist.

Exhibit 15-8: Required Input Data, Potential Data Sources, and Default Values for Two-Lane Highway Motorized Vehicle Analysis

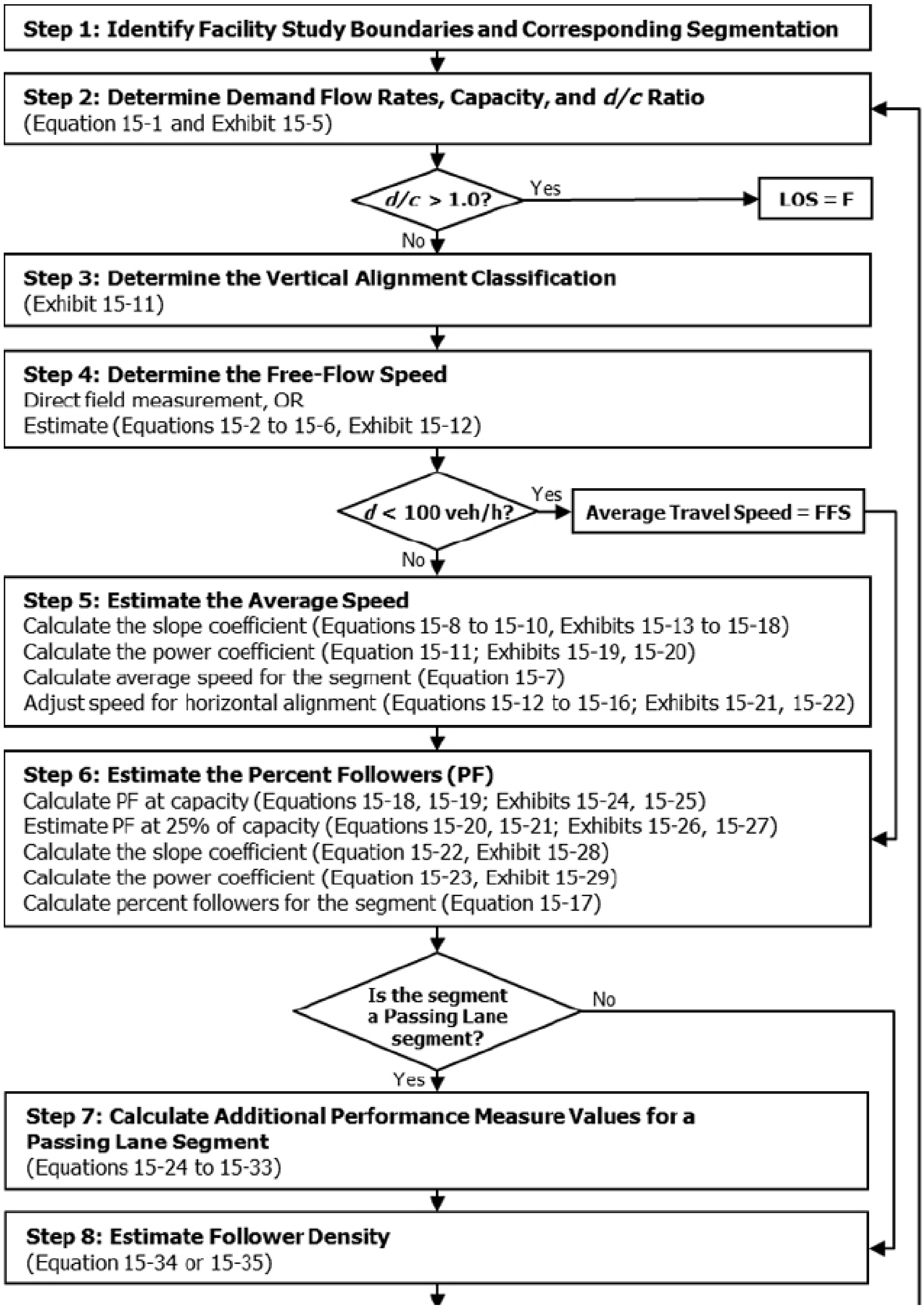
Required Data and Units	Potential Data Source(s)	Suggested Default Value
	Geometric Data	
Lane width (ft)	Design plans, field inspection	12 ft
Shoulder width (ft)	Design plans, field inspection	6 ft
Access points	Design plans, field inspection	0
Posted speed limit (mi/h)	Design plans, field inspection	Must be provided
Passing zones	Design plans, field inspection	Must be provided
Vertical grades	Design plans, field inspection	Must be provided
Horizontal curves	Design plans, field inspection	Must be provided
Passing lane length (mi)	Design plans, field inspection	Must be provided
	Demand Data	
Analysis direction demand volume (veh/h)	Field data, demand forecasts	Must be provided
Opposing direction demand volume (veh/h)	Field data, demand forecasts	Must be provided
Analysis period length (min)	Set by analyst	15 min (0.25 h)
Peak hour factor (decimal)	Field data	0.94
Heavy vehicle percentage (%)	Field data	6%[a]

Notes: [a] See Chapter 26 in Volume 4 for state-specific default heavy vehicle percentages.

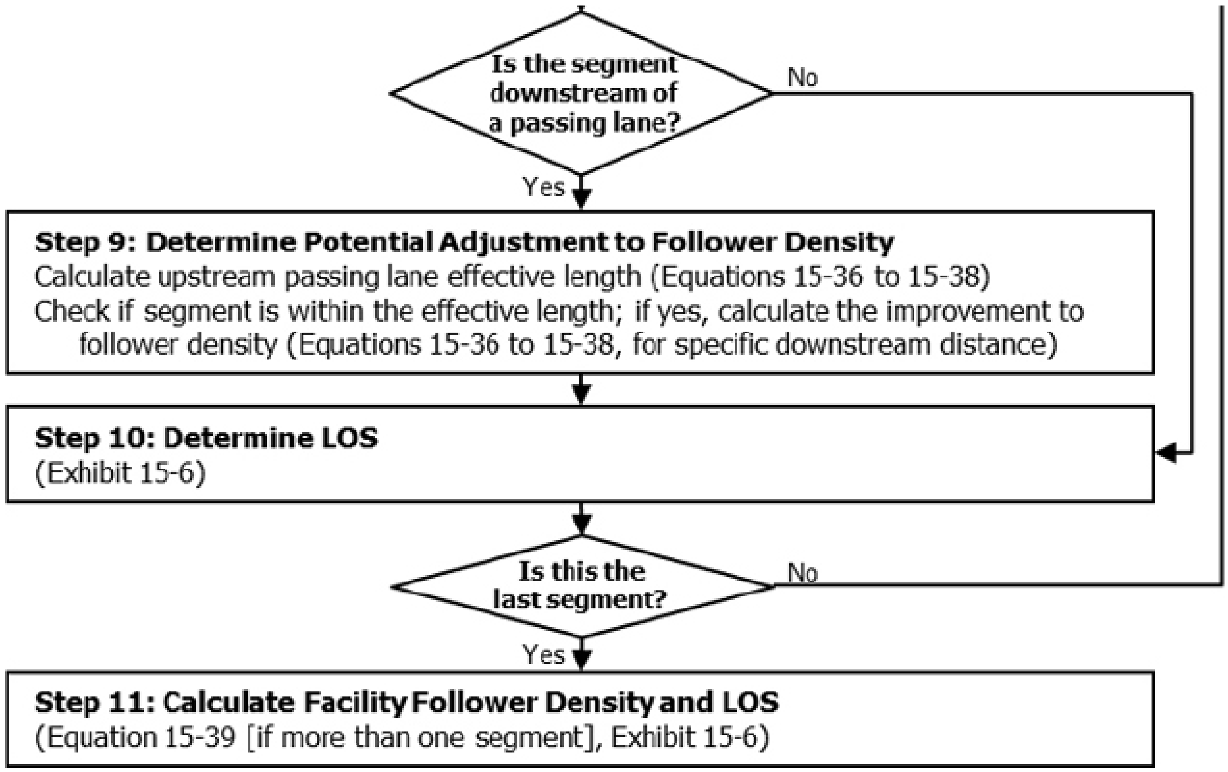
OVERVIEW OF THE METHODOLOGY

Exhibit 15-9 illustrates the basic steps in the core methodology for two-lane highways. The directional facility is segmented and each segment is classified in Step 1. Next, the segments are analyzed by repeating Steps 2–10 for each segment in upstream-to-downstream order. Finally, the results of the segment analyses are combined in Step 11 to produce results for the directional facility.

Exhibit 15-9: Flowchart of the Core Two-Lane Highway Methodology



Step 1: Identify Facility Study Boundaries and Corresponding Segmentation
Step 2: Determine Demand Flow Rates, Capacity, and d/c Ratio
(Equation 15-1 and Exhibit 15-5)
$d/c > 1.0$?
Yes
LOS = F
No
Step 3: Determine the Vertical Alignment Classification
(Exhibit 15-11)
Step 4: Determine the Free-Flow Speed
Direct field measurement, OR
Estimate (Equations 15-2 to 15-6, Exhibit 15-12)
$d < 100$ veh/h?
Yes
Average Travel Speed = FFS
No
Step 5: Estimate the Average Speed
Calculate the slope coefficient (Equations 15-8 to 15-10, Exhibits 15-13 to 15-18)
Calculate the power coefficient (Equation 15-11; Exhibits 15-19, 15-20)
Calculate average speed for the segment (Equation 15-7)
Adjust speed for horizontal alignment (Equations 15-12 to 15-16; Exhibits 15-21, 15-22)
Step 6: Estimate the Percent Followers (PF)
Calculate PF at capacity (Equations 15-18, 15-19; Exhibits 15-24, 15-25)
Estimate PF at 25% of capacity (Equations 15-20, 15-21; Exhibits 15-26, 15-27)
Calculate the slope coefficient (Equation 15-22, Exhibit 15-28)
Calculate the power coefficient (Equation 15-23, Exhibit 15-29)
Calculate percent followers for the segment (Equation 15-17)
Is the segment a Passing Lane segment?
No
Yes
Step 7: Calculate Additional Performance Measure Values for a Passing Lane Segment
(Equations 15-24 to 15-33)
Step 8: Estimate Follower Density
(Equation 15-34 or 15-35)



COMPUTATIONAL STEPS

As the analysis is directional, it is assumed that all variable values correspond to the chosen direction of analysis. Thus, for simplicity, variables are not subscripted to indicate direction, except for demand flow rate variables, as some equations contain inputs for both directions of travel.

Step 1: Identify Facility Study Boundaries and Corresponding Segmentation

Classify the study segment, or each segment being analyzed as part of a facility, as a Passing Constrained, Passing Zone, or Passing Lane segment. Each segment should have homogeneous properties with respect to traffic demand, grade, lane and shoulder widths, posted speed limit, etc. Varying horizontal curvature can be included within a single segment, as described in Step 5d.

Signalized intersections, all-way STOP-controlled intersections, and roundabouts are logical locations to end one segment and start another. Two-way STOP-controlled intersections, with control on the crossroad only, that have a significant amount of traffic entering or exiting the highway are also logical locations for ending one segment and starting another.

Minimum and Maximum Segment Lengths for Use in Steps 2–9

This methodology does not explicitly adjust performance measure results for a segment downstream of a non–passing lane segment on the basis of the range of the speed, platooning, and vehicle composition conditions of the entering traffic stream. As mentioned previously, performance measure results for a segment are estimated at the end of the segment. Those results are not particularly sensitive to the specific flow profile entering the segment, except in the cases of very short segments or a substantial change in the vertical geometry from one segment to the next. Likewise, after a certain length, the performance measure values do not change appreciably over longer lengths. For example, once trucks reach crawl speed on a grade, performance measure values will remain fairly consistent beyond that point, assuming the downstream highway characteristics also remain consistent.

Exhibit 15-10 provides recommended minimum and maximum segment lengths for use in computing segment speeds and percent followers. To the extent consistent with conditions in the field, the roadway should be segmented such that each segment exceeds these minimum lengths. However, there may be cases where these minima cannot be met.

Passing lanes shorter than the minima given in Exhibit 15-10 should be ignored and treated as Passing Constrained segments instead. For a segment with an actual length less than the minimum length given in Exhibit 15-10, the minimum value from this exhibit should be used in Steps 2–9 of the methodology. Similarly, if the actual segment length is greater than the maximum length in Exhibit 15-10, the maximum value from this exhibit should be used in Steps 2–9. Later, when facility performance is computed in Step 10, the actual segment lengths should be used. The analyst may also consider microsimulation for facilities whose segment lengths fall outside these limits.

Exhibit 15-10: Minimum and Maximum Segment Lengths for Use in Computing Segment Speeds and Percent Followers

Vertical Class	Passing Constrained		Passing Zone		Passing Lane*	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum

	(mi)	(mi)	(mi)	(mi)	(mi)	(mi)
1	0.25	3.0	0.25	2.0	0.5	3.0**
2	0.25	3.0	0.25	2.0	0.5	3.0**
3	0.25	1.1	0.25	1.1	0.5	1.1**
4	0.5	3.0	0.5	2.0	0.5	3.0**
5	0.5	3.0	0.5	2.0	0.5	3.0**

Notes: See Step 3 for how to determine the vertical class.

* If a passing lane exceeds 3 mi in length, it may be more appropriate to analyze the segment as a multilane highway using the methods described in Chapters 12 and 26.

** Class 3 segments have a shorter maximum length than the other vertical classifications, due to the transitional nature of the severity of truck operational impacts on Class 3 segments. Any segment longer than 1.1 mi will be vertical class 1, 2, 4, or 5, as seen in the last row of Exhibit 15-11.

Check for Volume Differences for Segments Downstream of a Passing Lane

The analysis methodology for adjusting for the downstream effects of passing lanes was developed for facilities where the entry volumes in the downstream segments did not differ by more than 10% from the volume in the passing lane segment. Should the downstream volumes differ by more than 10% from the passing lane segment volumes (e.g., due to a driveway), the analyst should consider whether a microsimulation approach might be more accurate.

Step 2: Determine Demand Flow Rates, Capacity, and d/c Ratio

At the entrance to the segment being analyzed, adjust hourly demand volumes in both directions (analysis direction and opposing direction) to account for the peak 15-min volume within the analysis hour, using Equation 15-1:

Equation 15-1:

$$v_i = \frac{V_i}{PHF}$$

where

= demand flow rate in direction *i* (veh/h),

v_i

i = "d" (analysis direction) or "o" (opposing direction),

V_i = demand volume for direction i (veh/h), and

PHF = peak hour factor (decimal).

The segment capacity is set at 1,700 veh/h for Passing Constrained and Passing Zone segments and is determined from Exhibit 15-5 for Passing Lane segments. If the demand flow rate exceeds capacity, the segment and facility LOS are set to F and the analysis stops at this point.

Step 3: Determine Vertical Alignment Classification

The calculations for free-flow speed, average speed, and percent followers require classifying the vertical alignment on the basis of the segment's length and grade. Exhibit 15-11 is used for this purpose. The vertical alignment classification value is used to identify the appropriate set of coefficient values used in many of the ensuing calculations.

Exhibit 15-11: Classifications for Vertical Alignment (Downgrades in Parentheses)

Segment Length (mi)	Segment Percent Grade (%) ≤1	>1 ≤2	>2 ≤3	>3 ≤4	>4 ≤5	>5 ≤6	>6 ≤7	>7 ≤8	>8 ≤9	>9
≤0.1	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	2 (1)	2 (2)	2 (2)
>0.1 ≤0.2	1 (1)	1 (1)	1 (1)	1 (1)	2 (1)	2 (2)	2 (2)	3 (2)	3 (3)	3 (3)
>0.2 ≤0.3	1 (1)	1 (1)	1 (1)	2 (1)	2 (2)	3 (2)	3 (3)	4 (3)	4 (4)	5 (5)
>0.3 ≤0.4	1 (1)	1 (1)	2 (1)	2 (2)	3 (2)	3 (3)	4 (4)	5 (4)	5 (5)	5 (5)
>0.4 ≤0.5	1 (1)	1 (1)	2 (1)	2 (2)	3 (3)	4 (3)	5 (4)	5 (5)	5 (5)	5 (5)
>0.5 ≤0.6	1 (1)	1 (1)	2 (1)	3 (2)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)
>0.6 ≤0.7	1 (1)	1 (1)	2 (1)	3 (2)	4 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)
>0.7 ≤0.8	1 (1)	1 (1)	2 (1)	3 (3)	4 (4)	5 (4)	5 (5)	5 (5)	5 (5)	5 (5)
>0.8 ≤0.9	1 (1)	1 (1)	2 (1)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)

>0.9 ≤1.0	1 (1)	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
>1.0 ≤1.1	1 (1)	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)
>1.1	1 (1)	1 (1)	2 (2)	4 (4)	4 (4)	5 (5)	5 (5)	5 (5)	5 (5)	5 (5)

Step 4: Determine the Free-Flow Speed

The free-flow speed (FFS) can be determined either through direct field measurement (preferred) or by estimation.

Direct Field Measurement

Measurements are made for the direction under analysis; if both directions are to be analyzed, then separate measurements in each direction are made. If the analysis segment cannot be directly observed, then measurements from a similar facility (same highway configuration, same speed limit, similar environment, etc.) may be used. Each directional measurement should be based on a sample of at least 100 vehicle speeds. The FFS can be directly measured as the mean speed under low-demand conditions (i.e., the two-way flow rate is less than or equal to 200 veh/h).

Estimating FFS

The FFS can be estimated indirectly if field data are not available. This is a greater challenge on two-lane highways than on other types of uninterrupted-flow facilities. FFS on two-lane highways covers a significant range, from as low as 40 mi/h to as high as 75 mi/h. To estimate the FFS, the analyst must characterize the operating conditions of the facility in terms of a base free-flow speed (BFFS) that reflects the facility's geometric characteristics. As part of this estimation process, it is recognized that the posted speed limit is intended to inform motorists of appropriate operating speeds for the given geometric conditions. Thus, the posted speed limit serves as a surrogate for identifying FFS for base geometric conditions (i.e., lane width ≥ 12 ft, shoulder width ≥ 6 ft, no access points) and no heavy vehicles in the traffic stream. Research performed in the development of this chapter's methodology (*2*) indicated that FFS is approximately 14% higher than the posted speed limit. The BFFS is estimated with Equation 15-2.

Equation 15-2:

$$BFFS = 1.14 \times S_{pl}$$

where *BFFS* is the base free-flow speed (mi/h) and S_{pl} is the posted speed limit (mi/h).

The *FFS* is calculated with Equation 15-3 through Equation 15-6.

Equation 15-3:

$$FFS = BFFS - a\,(HV\%)$$

with

Equation 15-4:

$$a = \max\left[0.0333, a_0 + a_1 \times BFFS + a_2 \times L + \max\left(0, a_3 + a_4 \times BFF\right.\right.$$

where

FFS	=	free-flow speed in the analysis direction (mi/h);
BFFS	=	base free-flow speed (mi/h);
HV%	=	percentage of heavy vehicles in the analysis direction (%) (e.g., 5% is expressed as 5);
f_{LS}	=	adjustment for lane and shoulder width (mi/h), from Equation 15-5;
f_A	=	adjustment for access-point density (mi/h), from Equation 15-6;
a_0–a_5	=	coefficient values from Exhibit 15-12;
L	=	segment length (mi), subject to minima and maxima given in

Step 1; and

v_o = demand flow rate in opposing direction (veh/h); v_o = 1,500 in Passing Constrained segments and v_o = 0 in Passing Lane segments.

Exhibit 15-12: Coefficient Values for Equation 15-4

Vertical Class	a_0	a_1	a_2	a_3	a_4	a_5
1	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	−0.45036	0.00814	0.01543	0.01358	0.00000	0.00000
3	−0.29591	0.00743	0.00000	0.01246	0.00000	0.00000
4	−0.40902	0.00975	0.00767	−0.18363	0.00423	0.00000
5	−0.38360	0.01074	0.01945	−0.69848	0.01069	0.12700

The adjustment for lane and shoulder width f_{LS} is calculated with Equation 15-5.

Equation 15-5:

$$f_{LS} = 0.6 \times (12 - LW) + 0.7 \times (6 - SW)$$

where

f_{LS} = adjustment for lane and shoulder width (mi/h);

LW = lane width (ft), constrained to minimum and maximum values of 9 ft and 12 ft, respectively; and

SW = shoulder width (ft), constrained to minimum and maximum values of 0 ft and 6 ft, respectively.

The adjustment for access points f_A is calculated with Equation 15-6.

Equation 15-6:

$$f_A = \min\left(\frac{APD}{4}, 10\right)$$

where f_A is in units of mi/h and *APD* is the access-point density (access points/mi). The Access Points subsection of Section 2 (page 15-6) provides guidance on counting access points.

Step 5: Estimate the Average Speed

If the demand flow rate is less than or equal to 100 veh/h, the average speed is equal to the free-flow speed and Step 5 can be skipped. Otherwise, the average speed is computed from the second formulation of Equation 15-7:

Equation 15-7:

$$S = \begin{cases} FFS & v_d \leq 100 \\ FFS - m\left(\frac{v_d}{1{,}000} - 0.1\right)^p & v_d > 100 \end{cases}$$

where

S = average speed in the analysis direction (mi/h);

v_d = flow rate in the analysis direction (veh/h);

m = slope coefficient, from Step 5a; and

p = power coefficient, from Step 5b.

Step 5a: Calculate the Slope Coefficient

The slope coefficient *m* in Equation 15-7 is calculated by Equation 15-8.

Equation 15-8:

$$m = \max\left[b_5, b_0 + b_1 \times FFS + b_2 \times \sqrt{\frac{v_o}{1,000}} + \max(0, b_3) \times \sqrt{L} + \mathrm{m}\right.$$

where

m = slope coefficient (decimal);

b_0–b_5 = coefficients for speed–flow slope model, from Exhibit 15-13 for Passing Constrained and Passing Zone segments, and from Exhibit 15-14 for Passing Lane segments;

FFS = free-flow speed in the analysis direction (mi/h);

v_o = demand flow rate in opposing direction (veh/h); v_o = 1,500 in Passing Constrained segments and v_o = 0 in Passing Lane segments;

L = segment length (mi), subject to minima and maxima given in Step 1; and

$HV\%$ = percentage of heavy vehicles in the analysis direction (%).

Exhibit 15-13: Coefficient Values for Equation 15-8 for Passing Constrained and Passing Zone Segments

Vertical Class	b_0	b_1	b_2	b_3	b_4	b_5
1	0.0558	0.0542	0.3278	0.1029	0.0000	0.0000
2	5.7280	−0.0809	0.7404	Equation 15-9	Equation 15-10	3.1155
3	9.3079	−0.1706	1.1292	Equation 15-9	Equation 15-10	3.1155
4	9.0115	−0.1994	1.8252	Equation 15-9	Equation 15-10	3.2685
5	23.9144	−0.6925	1.9473	Equation 15-9	Equation 15-10	3.5115

Exhibit 15-14: Coefficient Values for Equation 15-8 for Passing Lane Segments

Vertical Class	b_0	b_1	b_2	b_3	b_4	b_5
1	−1.1379	0.0941	0.0000	Equation 15-9	Equation 15-10	0.0000
2	−2.0688	0.1053	0.0000	Equation 15-9	Equation 15-10	0.0000
3	−0.5074	0.0935	0.0000	0.0000	Equation 15-10	0.0000
4	8.0354	−0.0860	0.0000	Equation 15-9	Equation 15-10	4.1900
5	7.2991	−0.3535	0.0000	Equation 15-9	Equation 15-10	4.8700

Equation 15-9 is used to determine the segment length coefficient b_3 for the combinations of vertical alignment class and segment type identified in Exhibit 15-13 and Exhibit 15-14.

Equation 15-9:

$$b_3 = c_0 + c_1 \times \sqrt{L} + c_2 \times FFS + c_3 \times \left(FFS \times \sqrt{L}\right)$$

where

b_3 = segment length coefficient for speed–flow slope model (decimal);

c_0–c_3 = coefficients for the b_3 segment length coefficient model, from Exhibit 15-15 for Passing Constrained and Passing Zone segments, and from Exhibit 15-16 for Passing Lane segments;

L = segment length (mi), subject to minima and maxima given in Step 1; and

FFS = free-flow speed in the analysis direction (mi/h).

Exhibit 15-15: Coefficient Values for Equation 15-9 for Passing Constrained and Passing Zone Segments

Vertical Class	c_0	c_1	c_2	c_3
1	0.1029	0.0000	0.0000	0.0000
2	−13.8036	0.0000	0.2446	0.0000
3	−11.9703	0.0000	0.2542	0.0000
4	−12.5113	0.0000	0.2656	0.0000
5	−14.8961	0.0000	0.4370	0.0000

Exhibit 15-16: Coefficient Values for Equation 15-9 for Passing Lane Segments

Vertical Class	c_0	c_1	c_2	c_3
1	0.0000	0.2667	0.0000	0.0000
2	0.0000	0.4479	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000
4	−27.1244	11.5196	0.4681	−0.1873
5	−45.3391	17.3749	1.0587	−0.3729

Equation 15-10 is used to determine the heavy vehicle percentage coefficient b_4 for the combinations of vertical alignment class and segment type identified in Exhibit 15-13 and Exhibit 15-14.

Equation 15-10:

$$b_4 = d_0 + d_1 \times \sqrt{HV\%} + d_2 \times FFS + d_3 \times \left(FFS \times \sqrt{HV\%}\right)$$

where

b_4 = heavy vehicle percentage coefficient for speed–flow slope model (decimal);

d_0–d_3 = coefficients for the b_4 heavy vehicle percentage coefficient model, from Exhibit 15-17 for Passing Constrained and Passing Zone segments, and from Exhibit 15-18 for Passing Lane segments; and

all other terms as defined previously.

Exhibit 15-17: Coefficient Values for Equation 15-10 for Passing Constrained and Passing Zone Segments

Vertical Class	d_0	d_1	d_2	d_3
1	0.0000	0.0000	0.0000	0.0000
2	−1.7765	0.0000	0.0392	0.0000
3	−3.5550	0.0000	0.0826	0.0000
4	−5.7775	0.0000	0.1373	0.0000
5	−18.2910	2.3875	0.4494	−0.0520

Exhibit 15-18: Coefficient Values for Equation 15-10 for Passing Lane Segments

Vertical Class	d_0	d_1	d_2	d_3
1	0.0000	0.1252	0.0000	0.0000
2	0.0000	0.1631	0.0000	0.0000
3	0.0000	−0.2201	0.0000	0.0072
4	0.0000	−0.7506	0.0000	0.0193
5	3.8457	−0.9112	0.0000	0.0170

Step 5b: Calculate the Power Coefficient

The power coefficient p in Equation 15-7 is calculated by Equation 15-11.

Equation 15-11:

$$p = \max\left[f_8, f_0 + f_1 \times FFS + f_2 \times L + f_3 \times \frac{v_o}{1{,}000} + f_4 \times \sqrt{\frac{v_o}{1{,}000}}\right.$$

where

p = power coefficient (decimal);

f_0–f_8 = coefficients for the power coefficient model, from Exhibit 15-19 for Passing Constrained and Passing Zone segments, and from Exhibit 15-20 for Passing Lane segments; and

all other terms as defined previously.

Exhibit 15-19: Coefficient Values for Equation 15-11 for Passing Constrained and Passing Zone Segments

Vertical Class	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	
1	0.67576	0.00000	0.00000	0.12060	−0.35919	0.00000	0.00000	0.00000	0.
2	0.34524	0.00591	0.02031	0.14911	−0.43784	−0.00296	0.02956	0.00000	0.
3	0.17291	0.00917	0.05698	0.27734	−0.61893	−0.00918	0.09184	0.00000	0.
4	0.67689	0.00534	−0.13037	0.25699	−0.68465	−0.00709	0.07087	0.00000	0.
5	1.13262	0.00000	−0.26367	0.18811	−0.64304	−0.00867	0.08675	0.00000	0.

Exhibit 15-20: Coefficient Values for Equation 15-11 for Passing Lane Segments

Vertical Class	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	
1	0.91793	−0.00557	0.36862	0.00000	0.00000	0.00611	0.00000	−0.00419	0.0
2	0.65105	0.00000	0.34931	0.00000	0.00000	0.00722	0.00000	−0.00391	0.0
3	0.40117	0.00000	0.68633	0.00000	0.00000	0.02350	0.00000	−0.02088	0.0
4	1.13282	−0.00798	0.35425	0.00000	0.00000	0.01521	0.00000	−0.00987	0.0
5	1.12077	−0.00550	0.25431	0.00000	0.00000	0.01269	0.00000	−0.01053	0.0

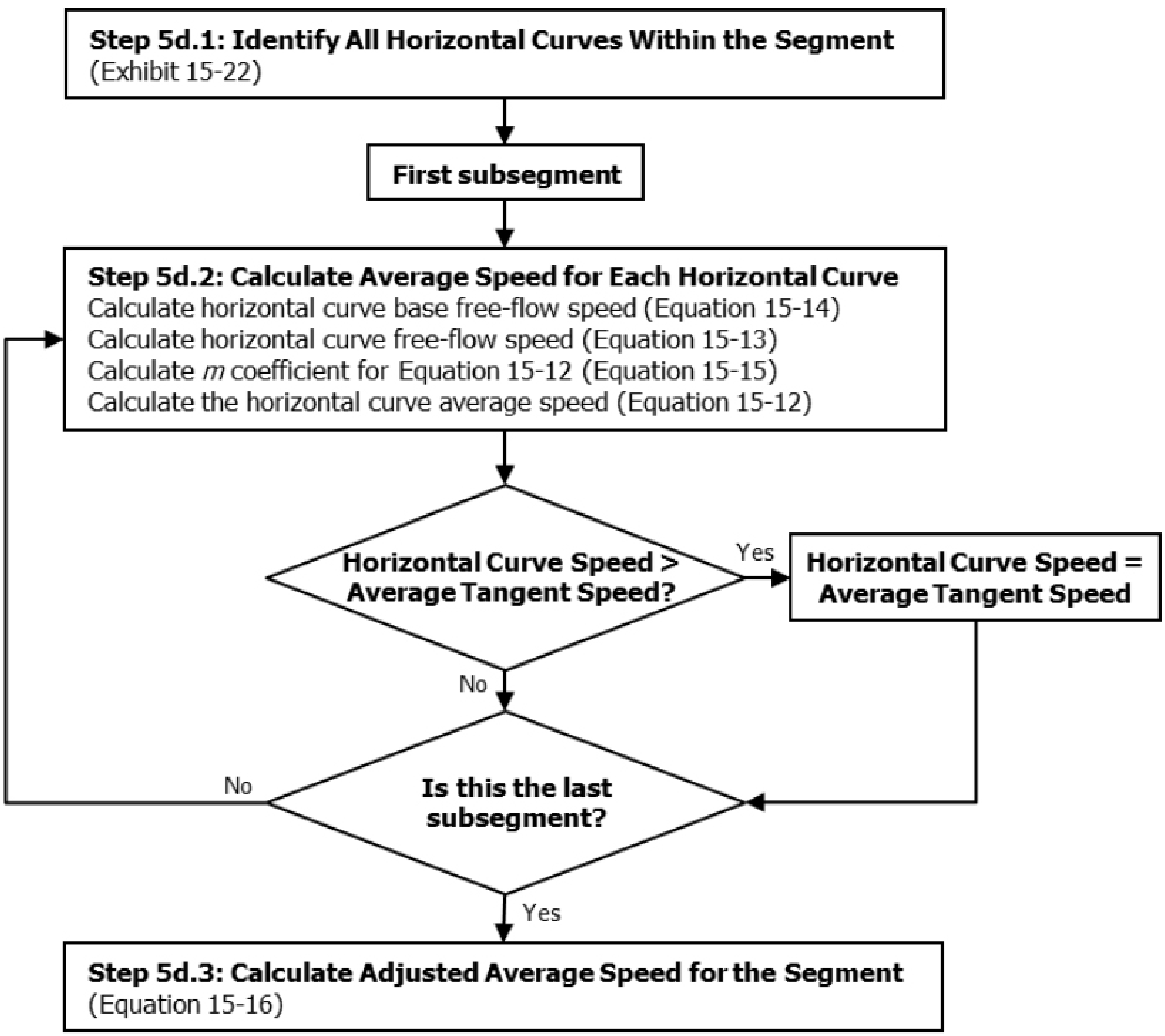
Step 5c: Calculate Average Speed for the Segment

The average segment speed *S* can now be calculated from Equation 15-7.

Step 5d: Adjust Speed for Horizontal Alignment

The calculation in Step 5c assumes that the segment's horizontal alignment has no discernable impact on average speed. Step 5d adjusts the calculated speed to account for horizontal curvature. Note that the segment length minima given in Step 1 do not apply to the subsegments used in this adjustment. The substeps involved in this process are illustrated in Exhibit 15-21.

Exhibit 15-21: Flowchart of the Procedure to Adjust Segment Average Speed for Horizontal Curvature



Step 5d.1: Identify all Horizontal Curves Within the Segment

Each horizontal curve within the segment should be assigned a classification of 1–5 on the basis of radius and superelevation, according to Exhibit 15-22. Entries of "—" mean that the curve does not restrict speeds and can be treated as a tangent. Each horizontal curve will act as a subsegment within the segment.

Exhibit 15-22: Horizontal Alignment Classifications

	Superelevation (%)										
Radius (ft)	<1	≥1 <2	≥2 <3	≥3 <4	≥4 <5	≥5 <6	≥6 <7	≥7 <8	≥8 <9	≥9 <10	≥10
<300	5	5	5	5	5	5	5	5	5	5	5
300–449	4	4	4	4	4	4	4	4	4	4	4
450–599	4	3	3	3	3	3	3	3	3	3	3
600–749	3	3	3	3	3	3	2	2	2	2	2
750–899	2	2	2	2	2	2	2	2	2	2	2
900–1,049	2	2	2	2	2	2	2	2	1	1	1
1,050–1,199	2	2	2	2	1	1	1	1	1	1	1
1,200–1,349	2	2	1	1	1	1	1	1	1	1	1
1,350–1,499	1	1	1	1	1	1	1	1	1	1	—
1,500–1,649	1	1	1	1	1	1	1	1	—	—	—
1,650–1,799	1	1	1	1	1	1	—	—	—	—	—
1,800–1,949	1	1	1	1	1	—	—	—	—	—	—
1,950–2,099	1	1	1	1	—	—	—	—	—	—	—
2,100–2,249	1	1	1	—	—	—	—	—	—	—	—
2,250–2,399	1	1	—	—	—	—	—	—	—	—	—
2,400–2,549	1	—	—	—	—	—	—	—	—	—	—
≥2550	—	—	—	—	—	—	—	—	—	—	—

Note: — means that the curve does not restrict speeds and can be treated as a tangent section.

Step 5d.2: Calculate Average Speed for each Horizontal Curve within the Segment

The average speed on each horizontal curve subsegment is calculated with Equation 15-12 though Equation 15-15.

Equation 15-12:

$$S_{HCi} = \min\left(S, FFS_{HCi} - m \times \sqrt{\frac{v_d}{1,000} - 0.1}\right)$$

with

Equation 15-13:

$$FFS_{HCi} = BFFS_{HCi} - 0.0255 \times HV\%$$

Equation 15-14:

$$BFFS_{Hci} = \min\left(BFFS_T, 44.32 + 0.3728 \times BFFS_T - 6.868 \times Horiz$$

Equation 15-15:

$$m = \max\left(0.277, -25.8993 - 0.7756 \times FFS_{HCi} + 10.6294 \times \sqrt{FFS_{H}}\right.$$

where

S_{HCi}	=	average speed on horizontal curve subsegment i in the analysis direction (mi/h);
FFS_{HCi}	=	free-flow speed on horizontal curve subsegment i in the analysis direction (mi/h), from Equation 15-13;
$BFFS_{HCi}$	=	base free-flow speed on horizontal curve subsegment i in the analysis direction (mi/h), from Equation 15-14;
$BFFS_T$	=	base free-flow speed on preceding tangent subsegment in the analysis direction (mi/h);
$HorizClass_i$	=	horizontal classification for subsegment i;
m	=	slope coefficient for Equation 15-12, from Equation 15-15; and

all other terms as defined previously.

Step 5d.3: Calculate Adjusted Average Speed for the Segment

In this step, Equation 15-16 is used to calculate a new average speed for the segment as a function of the length-weighted average speeds of all the subsegments.

Equation 15-16:

$$S = \frac{\sum_i (SubsegSpeed_i \times SubsegLength_i)}{L}$$

where

S	=	average speed in the analysis direction (mi/h), with consideration of horizontal curvature;
$SubsegSpeed_i$	=	speed of subsegment (horizontal curve or tangent) i (mi/h);
$SubsegLength_i$	=	length of subsegment (horizontal curve or tangent) i (mi); and
L	=	actual segment length (mi).

All tangent subsegments use the average speed calculated by Equation 15-7. The tangent average speed also serves as a limiting speed for any calculated horizontal subsegment speeds.

Step 6: Estimate the Percent Followers

The percent followers is computed using Equation 15-17.

Equation 15-17:

$$PF = 100 \times \left[1 - e^{\left(m \times \left\{\frac{v_d}{1000}\right\}^p\right)}\right]$$

where

PF = percent followers in the analysis direction (%);

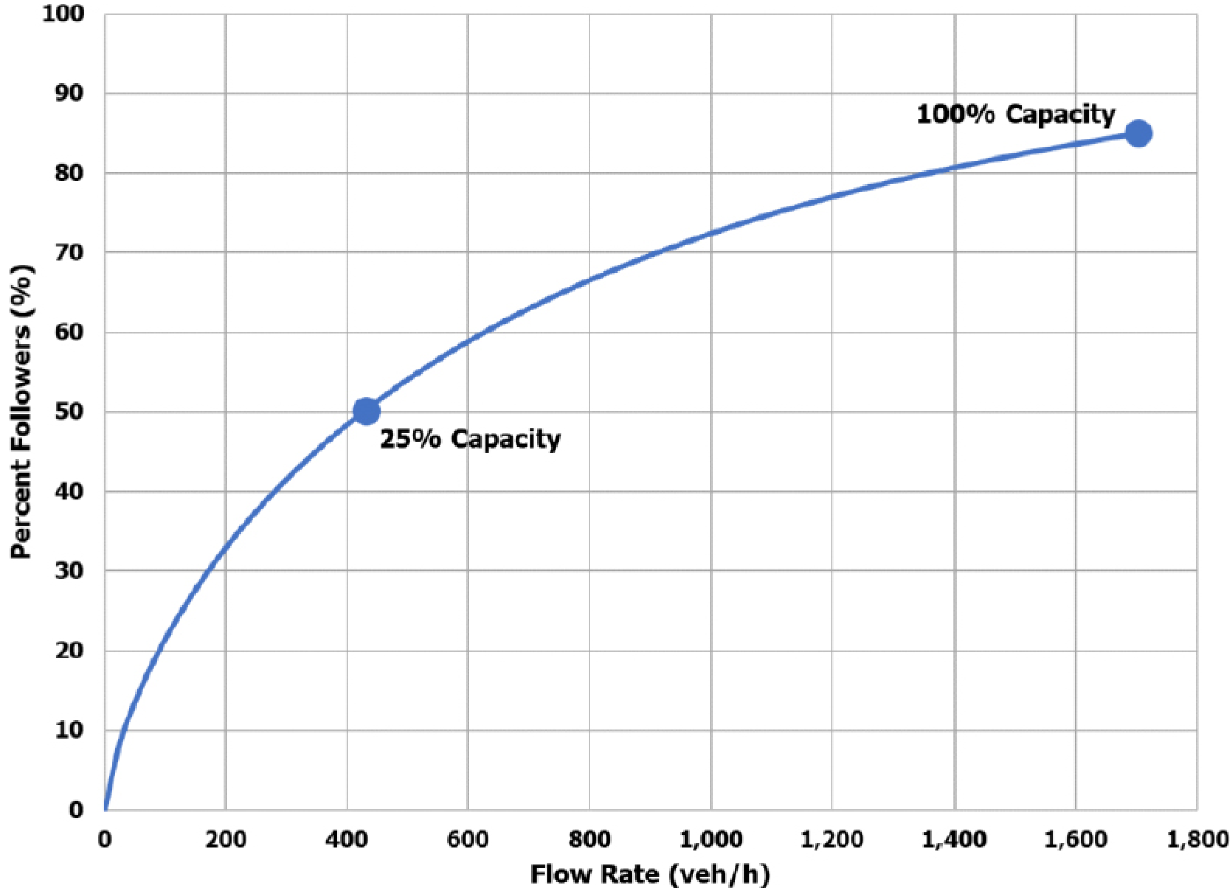
v_d = analysis direction flow rate (veh/h);

m = slope coefficient; and

p = power coefficient.

The m and p coefficients for Equation 15-17 are calculated so that the exponential curve will pass through two specific points, as illustrated in the example in Exhibit 15-23. The first point is the computed percent followers at 25% of capacity PF_{25cap}. The second point is the computed percent followers at 100% of capacity PF_{cap}. Note that the values of PF_{25cap} and PF_{cap} must be constrained to the range of 0 to 100. Values outside this range are generally only possible for very unusual combinations of equation variable values. Nevertheless, a value less than zero should be set to zero and a value greater than 100 should be set to 100. The actual percent followers for the segment is then computed for the actual flow rate using the fitted exponential equation.

Exhibit 15-23: Illustrative Percent Followers Curve Fitted to Two Flow Points



Step 6a: Calculate Percent Followers at Capacity

The percent followers at capacity is computed as a function of the vertical alignment class, segment length, free-flow speed, percent heavy vehicles, and opposing flow rate (if a Passing Zone segment). Equation 15-18 is used for both Passing Constrained and Passing Zone segments. Equation 15-19, which uses different parameters, is used for Passing Lane segments.

Passing Constrained and Passing Zone segments. Equation 15-18 is used to calculate percent followers at capacity for Passing Constrained and Passing Zone segments.

Equation 15-18:

$$PF_{cap} = b_0 + b_1 (L) + b_2 \left(\sqrt{L}\right) + b_3 (FFS) + b_4 \left(\sqrt{FFS}\right) + b_5 (HV\%$$

where

PF_{cap}	=	percent followers at capacity flow rate in the analysis direction (%);
b_0–b_7	=	coefficient values for Equation 15-18, from Exhibit 15-24;
L	=	segment length (mi), subject to minima and maxima given in Step 1;
FFS	=	free-flow speed in the analysis direction (mi/h);
$HV\%$	=	percentage of heavy vehicles in the analysis direction (%); and
v_o	=	demand flow rate in opposing direction (veh/h); v_o = 1,500 in Passing Constrained segments and v_o = 0 in Passing Lane segments.

Exhibit 15-24: Coefficient Values for Equation 15-18

Vertical Class	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7
1	37.68080	3.05089	–7.90866	–0.94321	13.64266	–0.00050	–0.05500	7.137
2	58.21104	5.73387	–13.66293	–0.66126	9.08575	–0.00950	–0.03602	7.146
3	113.20439	10.01778	–18.90000	0.46542	–6.75338	–0.03000	–0.05800	10.032
4	58.29978	–0.53611	7.35076	–0.27046	4.49850	–0.01100	–0.02968	8.896
5	3.32968	–0.84377	7.08952	–1.32089	19.98477	–0.01250	–0.02960	9.994

Passing Lane segments. Equation 15-19 is used to calculate percent followers at capacity for Passing Lane segments.

Equation 15-19:

$$PF_{cap} = b_0 + b_1\left(L\right) + b_2\left(\sqrt{L}\right) + b_3\left(FFS\right) + b_4\left(\sqrt{FFS}\right) + b_5\left(HV\%\right.$$

where b_0 through b_7 are coefficient values for Equation 15-19, from Exhibit 15-25, and all other terms are as defined previously.

Exhibit 15-25: Coefficient Values for Equation 15-19

Vertical Class	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b
1	61.73075	6.73922	–23.68853	–0.84126	11.44533	–1.05124	1.50390	0.0
2	12.30096	9.57465	–30.79427	–1.79448	25.76436	–0.66350	1.26039	–0.0
3	206.07369	–4.29885	0.00000	1.96483	–30.32556	–0.75812	1.06453	–0.0
4	263.13428	5.38749	–19.04859	2.73018	–42.76919	–1.31277	–0.32242	0.0
5	126.95629	5.95754	–19.22229	0.43238	–7.35636	–1.03017	–2.66026	0.0

Step 6b: Calculate Percent Followers at 25% of Capacity

The percent followers at 25% of capacity is computed using a similar procedure as for 100% capacity, but with a different set of formulas and parameters.

Passing Constrained and Passing Zone segments. Equation 15-20 is used to calculate percent followers at 25 percent of capacity for Passing Constrained and Passing Zone segments.

Equation 15-20:

$$PF_{25cap} = c_0 + c_1\left(L\right) + c_2\left(\sqrt{L}\right) + c_3\left(FFS\right) + c_4\left(\sqrt{FFS}\right) + c_5\left(HV\right.$$

where PF_{25cap} is the percent followers of 25% of the capacity flow rate in the analysis direction, c_0 through c_7 are coefficient values for Equation 15-20, from Exhibit 15-26, and all other terms are as defined previously.

Exhibit 15-26: Coefficient Values for Equation 15-20

Vertical Class	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c
1	18.01780	10.00000	21.60000	–0.97853	12.05214	0.00750	–0.06700	11.6
2	47.83887	12.80000	–28.20000	–0.61758	5.80000	–0.04550	–0.03344	11.3
3	125.40000	19.50000	–34.90000	0.90672	–16.10000	–0.11000	–0.06200	14.7
4	103.13534	14.68459	–23.72704	0.66444	–11.95763	–0.10000	0.00172	14.7
5	89.00000	19.02642	–34.54240	0.29792	–6.62528	–0.16000	0.00480	17.5

Passing Lane segments. Equation 15-21 is used to calculate percent followers at 25 percent of capacity for Passing Lane segments.

Equation 15-21:

$$PF_{25cap} = c_0 + c_1\left(L\right) + c_2\left(\sqrt{L}\right) + c_3\left(FFS\right) + c_4\left(\sqrt{FFS}\right) + c_5\left(HV\right.$$

where c_0 through c_7 are coefficient values for Equation 15-21, from Exhibit 15-27, and all other terms are as defined previously.

Exhibit 15-27: Coefficient Values for Equation 15-21

Vertical Class	c_0	c_1	c_2	c_3	c_4	c_5	c_6	c_7
1	80.37105	14.44997	–46.41831	–0.23367	0.84914	–0.56747	0.89427	0.00
2	18.37886	14.71856	–47.78892	–1.43373	18.32040	–0.13226	0.77217	–0.00
3	239.98930	15.90683	–46.87525	2.73582	–42.88130	–0.53746	0.76271	–0.00
4	223.68435	10.26908	–35.60830	2.31877	–38.30034	–0.60275	–0.67758	0.00
5	137.37633	11.00106	–38.89043	0.78501	–14.88672	–0.72576	–2.49546	0.00

Step 6c: Calculate the Slope Coefficient

At this point, the capacity of the segment in the subject direction is required. For segments without passing lanes, a capacity of 1,700 veh/h should be used. For Passing Lane segments, the capacity is obtained from Exhibit 15-5.

Equation 15-22 is used to calculate the slope coefficient m used in Equation 15-17.

Equation 15-22:

$$m = d_1 \left(\frac{0 - \ln\left[1 - \frac{PF_{25cap}}{100}\right]}{0.25\left[\frac{cap}{1{,}000}\right]} \right) + d_2 \left(\frac{0 - \ln\left[1 - \frac{PF_{cap}}{100}\right]}{\left[\frac{cap}{1{,}000}\right]} \right)$$

where d_1 and d_2 are coefficient values for Equation 15-22, from Exhibit 15-28, *cap* is the directional capacity (veh/h), and all other terms are as defined previously.

Exhibit 15-28: Coefficient Values for Equation 15-22

Segment Type	d_1	d_2
Passing Constrained and Passing Zone	–0.29764	–0.71917
Passing Lane	–0.15808	–0.83732

Step 6d: Calculate the Power Coefficient

Equation 15-23 is used to calculate the power coefficient p used in Equation 15-17.

Equation 15-23:

$$p = e_0 + e_1 \left(\frac{0 - \ln\left[1 - \frac{PF_{25cap}}{100}\right]}{0.25\left[\frac{cap}{}\right]} \right) + e_2 \left(\frac{0 - \ln\left[1 - \frac{PF_{cap}}{100}\right]}{\left[\frac{cap}{}\right]} \right) + e_3$$

$$\Big\backslash \quad 0.25 \left\lfloor 1{,}000 \right\rfloor \quad \Big/ \qquad \Big\backslash \quad \left\lfloor 1{,}000 \right\rfloor \quad \Big/$$

where e_0 through e_4 are coefficient values for Equation 15-23, from Exhibit 15-29, and all other terms are as defined previously.

Exhibit 15-29: Coefficient Values for Equation 15-23

Segment Type	e_0	e_1	e_2	e_3	e_4
Passing Constrained and Passing Zone	0.81165	0.37920	–0.49524	–2.11289	2.41146
Passing Lane	–1.63246	1.64960	–4.45823	–4.89119	10.33057

Step 6e: Calculate Percent Followers for the Segment

The percent followers *PF* can now be calculated from Equation 15-17. Horizontal curvature is not considered when estimating percent followers, because its impact on percent followers is much smaller than its impact on travel speed.

Step 7: Calculate Additional Performance Measure Values for a Passing Lane Segment

As mentioned in the Analysis Approach of Section 2, the performance of each segment is estimated at the end of the segment. For passing lane segments, this endpoint is immediately downstream of the merge point. To provide more information about the operating conditions within the passing lane segment, and to provide a more realistic estimate of the impact of the passing lane on the facility follower density, additional performance measure values are calculated. Specifically, the performance of each of the two lanes in the passing lane segment is determined at the midpoint of the passing lane segment. These measures are used as being representative of performance along the full length of the passing lane segment, prior to the merge point.

Step 7a: Calculate the Flow Rate in Each Lane of the Passing Lane Segment

Equation 15-24 through Equation 15-27 are applied.

Equation 15-24:

$$\mathrm{NumHV} = \mathrm{v_d} \times \frac{\mathrm{HV\%}}{100}$$

Equation 15-25:

$$PropFlowRate_{FL} = 0.92183 - 0.05022 \times \ln(v_d) - 0.00030 \times NumHV$$

Equation 15-26:

$$FlowRate_{FL} = v_d \times PropFlowRate_{FL}$$

Equation 15-27:

$$FlowRate_{SL} = v_d \times (1 - PropFlowRate_{FL})$$

where

NumHV	=	number of heavy vehicles entering the passing lane segment (veh);
v_d	=	demand flow rate entering the passing lane segment (veh/h);
HV%	=	percentage of heavy vehicles entering the passing lane segment (%);
$PropFlowRate_{FL}$	=	proportion of the demand flow in the faster lane (i.e., the lane used by passing vehicles) (decimal);
$FlowRate_{FL}$	=	demand flow rate in the faster lane (veh/h); and
$FlowRate_{SL}$	=	demand flow rate in the slower lane (i.e., the lane used by non-passing vehicles) (veh/h).

Step 7b: Calculate the Percentage of Heavy Vehicles in Each Lane of the Passing Lane Segment

Equation 15-28 through Equation 15-30 are applied.

Equation 15-28:

$$HV\%_{FL} = HV\% \times HVPropMultiplier_{FL}$$

Equation 15-29:

$$NumHV_{SL} = NumHV - \left(FlowRate_{FL} \times \frac{HV\%_{FL}}{100}\right)$$

Equation 15-30:

$$HV\%_{SL} = \frac{NumHV_{SL}}{FlowRate_{SL}} \times 100$$

where

$HV\%_{FL}$	=	percentage of heavy vehicles in the faster lane (%),
$HVPropMultiplier_{FL}$	=	0.4,
$NumHV_{SL}$	=	number of heavy vehicles in the slower lane (veh),
$HV\%_{SL}$	=	percentage of heavy vehicles in the slower lane (%), and

all other terms are as defined previously.

Step 7c: Calculate the Average Speed in Each Lane of the Passing Lane Segment

Apply the equations and passing lane coefficient tables of Step 5 (Estimate the Average Speed), with the corresponding flow rate and heavy vehicle percentage for each lane. These results are assigned to the following variables:

S_{init_FL} = initial average speed in the faster lane (mi/h), and

S_{init_SL} = initial average speed in the slower lane (mi/h).

Calculate the average speed lane differential adjustment *AvgSpeedDiffAdj* (mi/h) with Equation 15-31.

Equation 15-31:

$$AvgSpeedDiffAdj = 2.750 + 0.00056 \times v_d + 3.8521 \times \frac{HV\%}{100}$$

Next, calculate the average speed for each lane at the passing lane segment midpoint with Equation 15-32 and Equation 15-33.

Equation 15-32:

$$S_{PLmid\_FL} = S_{init\_FL} + \frac{AvgSpeedDiffAdj}{2}$$

Equation 15-33:

$$S_{PLmid\_SL} = S_{init\_SL} - \frac{AvgSpeedDiffAdj}{2}$$

where

S_{PLmid_FL} = average speed in the faster lane at the midpoint of the passing lane segment (mi/h),

S_{PLmid_SL} = average speed in the slower lane at the midpoint of the passing lane segment (mi/h), and all other terms are as defined previously.

Step 7d: Calculate the Percent Followers in Each Lane of the Passing Lane Segment

Apply the equations and passing lane coefficient tables of Step 6 (Estimate the Percent Followers), with the corresponding flow rate and heavy vehicle percentage for each lane. These results are assigned to the following variables:

PF_{PLmid_FL} = percent followers in the faster lane at the midpoint of the passing lane segment (%), and

PF_{PLmid_SL} = percent followers in the slower lane at the midpoint of the passing lane segment (%).

Step 8: Calculate Follower Density

Apply Equation 15-34 to determine the follower density at the passing lane segment midpoint FD_{PLmid} in followers/mi/ln.

Equation 15-34:

$$FD_{PLmid} = \frac{\left(\frac{PF_{PLmid\_FL}}{100} \times \frac{FlowRate_{FL}}{S_{PLmid\_FL}}\right) + \left(\frac{PF_{PLmid\_SL}}{100} \times \frac{FlowRate_{SL}}{S_{PLmid\_SL}}\right)}{2}$$

where all terms are as defined previously.

For non-passing lane segments, or the endpoint of a passing lane segment, apply Equation 15-35 to determine the follower density FD in followers/mi/ln.

Equation 15-35:

$$FD = \frac{PF}{100} \times \frac{v_d}{S}$$

where all terms are as defined previously.

Step 9: Determine Potential Adjustment to Follower Density

If no Passing Lane segment is located upstream of the subject segment, Step 9 is skipped. Otherwise, if the subject segment is located within the effective length of the upstream passing lane, an adjustment is made to the follower density of the subject segment (calculated from Step 8). Equation 15-36 through Equation 15-38 are used to both determine the passing lane's effective length and the improvement in performance measures in downstream segments within the effective length.

Equation 15-36:

$$\%Improve_{PF} = \max\left(0, 27 - 8.75 \times \ln\left[\max(0.1, DownstreamDistan\right.\right.$$

Equation 15-37:

$$\%Improve_{S} = \max\left(0, 3 - 0.8 \times DownstreamDistance + 0.1 \times \max\left[\right.\right.$$

Equation 15-38:

$$FD_{adj} = \frac{PF}{100} \times \left(1 - \frac{\%Improve_{PF}}{100}\right) \times \frac{FlowRate}{S \times \left(1 + \frac{\%Improve_{S}}{100}\right)}$$

where

$\%Improve_{PF}$	=	% improvement to percent followers on a segment downstream of a Passing Lane segment;
$\%Improve_{S}$	=	% improvement to the average speed on a segment downstream of a Passing Lane segment;
FD_{adj}	=	adjusted follower density on a segment downstream of a Passing Lane segment

(followers/mi);

DownstreamDistance = distance downstream from the start of the passing lane segment (mi);

PassLaneLength = length of passing lane segment (mi);

S = average speed in the analysis direction for the analysis segment (mi/h);

PF = percent followers (%), determined as follows:

- When calculating passing lane effective length or downstream segment $\%Improve_{PF}$ or $\%Improve_{S}$, use PF entering the passing lane segment (i.e., PF estimated at the end of the segment just upstream of the passing lane segment), and
- When calculating *FDadj* downstream of the passing lane, use PF for the analysis segment; and

FlowRate = demand flow rate (veh/h), determined as follows:

- When calculating passing lane effective length, use the flow rate entering the passing lane segment, and
- When calculating downstream segment $\%Improve_{PF}$, $\%Improve_{S}$, or FD_{adj}, use the flow rate for the analysis segment.

The effective length is the distance downstream from the start of the passing lane to the point where operational performance returns to its levels just prior to the start of the passing lane. For the purposes of this methodology, that point is identified as of one of the following:

- The percentage improvement to the percent followers becomes zero, or
- Follower density is at least 95% of the level entering the passing lane.

Whichever of these two distances is shorter is taken as the effective length. For any downstream segments within the effective length, Equation 15-36 through Equation 15-38 are applied to determine the improvement in follower density for the subject segment. This adjusted follower density value is then used in Steps 10 and 11.

Only the effect of the closest upstream Passing Lane segment is considered when determining the improvement to follower density. In other words, the analysis of segments downstream of a passing lane “resets” with each new passing lane.

Step 10: Determine LOS

The LOS is found by comparing the follower density value with the criteria of Exhibit 15-6, for the appropriate type of two-lane highway—higher-speed or lower-speed.

Step 11: Facility Analysis

Facility Follower Density

If the analysis consists of multiple contiguous segments, repeat steps 2–10 for each segment. Use the resulting follower densities and lengths for each segment with Equation 15-39 to obtain an average follower density for the facility. Note that the Step 1 segment length minima and maxima do not apply to this computation.

Equation 15-39:

$$FD_F = \frac{\sum_{i=1}^{n} FD_i \times L_i}{\sum_{i=1}^{n} L_i}$$

where

FD_F = average follower density for the facility in the analysis direction (followers/mi);

FD_i = follower density, or adjusted follower density, for segment i in the analysis direction (followers/mi); and

L_i = actual segment length for segment i (mi).

For passing lane segments, FD_{PLmid} is used for the segment follower density value. FD_F is used with Exhibit 15-6 to determine the facility LOS.

Intersections

This methodology does not explicitly consider the effect of traffic control (e.g., traffic signal, roundabout, or STOP sign controlling highway traffic) on two-lane highway performance. However, reference (*3*) provides additional guidance on this topic.

4. BICYCLE METHODOLOGY

The calculation of bicycle LOS on multilane and two-lane highways shares the same methodology, since multilane and two-lane highways operate in fundamentally the same manner for bicyclists. Cyclists travel much more slowly than the prevailing traffic flow, staying as far to the right as possible and using paved shoulders when available, which indicates the need for only one model.

The bicycle LOS model for two-lane and multilane highways uses a traveler perception model calibrated by using linear regression (*4*). The model fits independent variables associated with roadway characteristics to the results of a field-based user survey that rated the comfort of various bicycle facilities. The resulting bicycle LOS score generally ranges from 0.5 to 6.5 and is stratified to produce a LOS A–F result, on the basis of Exhibit 15-7.

SCOPE OF THE METHODOLOGY

Spatial and Temporal Limits

The bicycle method applies to paved shoulders, bicycle lanes, and shared lanes on two-lane highways. These facility types were illustrated in Exhibit 3-24 in Chapter 3, Modal Characteristics. Side paths are not addressed by the method, but they could be treated as an off-street facility, if located sufficiently far away from the highway, as described in Section 1 of Chapter 24, Off-Street Pedestrian and Bicycle Facilities.

Segment boundaries should be established at points where a change occurs in any of the following: terrain, lane widths, shoulder width, facility classification, or demand flow rate. If both a bicycle and a motorized vehicle analysis are being performed for the two-lane highway, the segments used for the two analyses should be identical. The recommended length of the analysis period is the HCM standard of 15 min (although longer periods can be examined).

Performance Measures

This method produces the following performance measures:

- Bicycle LOS score, and
- LOS based on the bicycle LOS score.

Strengths of the Methodology

The bicycle LOS score and letter produced by this method are sensitive to bicyclist separation from motor vehicle traffic, motorized traffic volumes and speed, heavy vehicle presence, and pavement condition. The bicycle LOS score and letter can be directly compared with the modal LOS scores and letters produced by other HCM traveler perception–based methods, such as those found in many of the urban street and intersection chapters in Volume 3.

Limitations of the Methodology

This methodology was developed with data collected on urban and suburban streets, including facilities that would be defined as suburban two-lane highways. Although the methodology has been successfully applied to rural two-lane highways in different parts of the United States, users should be aware that conditions on many rural two-lane highways will be outside the range of values used to develop the bicycle LOS model. The ranges of values used in the development of the bicycle LOS model (*4*) are shown below:

- Width of the outside through lane: 10 to 16 ft;
- Shoulder width: 0 to 6 ft;
- Motorized vehicle volumes: up to 36,000 annual average daily traffic (AADT);
- Posted speed: 25 to 50 mi/h;
- Heavy vehicle percentage: 0% to 2%; and
- Pavement condition: 2 to 5 on the Federal Highway Administration (FHWA) 5-point pavement rating scale (*5*).

The bicycle LOS methodology does not take differences in prevalent driver behavior into consideration, although driver behavior may vary considerably both regionally and by facility. In particular, the likelihood of drivers slowing down or providing additional horizontal clearance while passing cyclists plays a significant role in the perceived quality of service of a facility.

REQUIRED DATA AND SOURCES

Exhibit 15-30 lists the information necessary to apply the bicycle methodology and suggests potential sources for obtaining these data. As can be seen in the exhibit, many of the input data required for a bicycle analysis are also required for a motorized vehicle analysis.

Exhibit 15-30 also suggests default values for use when segment-specific information is not available. The user is cautioned that every use of a default value instead of a field-measured, segment-specific value may make the analysis results more approximate and less related to the specific conditions that describe the highway. HCM defaults should only be used when (*a*) field data cannot be collected and (*b*) locally derived defaults do not exist.

Exhibit 15-30: Required Input Data, Potential Data Sources, and Default Values for Two-Lane and Multilane Highway Bicycle Analysis

Required Data	Potential Data Source(s)	Suggested Default Value
	Geometric Data	
Lane width (ft)*	Road inventory, aerial photo	12 ft
Shoulder width (ft)*	Road inventory, aerial photo	6 ft
Speed limit (mi/h)	Field data, road inventory	Must be provided
Number of directional through lanes	Field data, road inventory	1 (two-lane highways) 2 (multilane highways)
Pavement condition[a] (FHWA 5-point scale)	Field data, pavement condition inventory	4 (good)
	Demand Data	
Hourly motor vehicle demand (veh/h)*	Field data, past counts, models	Must be provided

Directional volume split (%)*	Field data, past counts, models	Must be provided
Analysis period length (min)*	Set by analyst	15 min (0.25 h)
Peak hour factor (decimal)*	Field data	0.88
Heavy vehicle percentage (decimal)*	Field data, past counts	0.06[b]
Percent of segment with occupied on-highway parking (decimal)[c]	Field data	0.00

Notes: ***Bold italic*** indicates high sensitivity (±2 LOS letters) of LOS to the choice of default value.
Bold indicates moderate sensitivity (±1 LOS letter) of LOS to the choice of default value.
*Also used by the two-lane highway motorized vehicle method.
[a] Sensitivity reflects pavement conditions 2–5. Very poor pavement (i.e., 1) typically results in LOS F, regardless of other input values.
[b] See Chapter 26 in Volume 4 for state-specific default heavy vehicle percentages.
[c] Generally applicable only to highway sections passing through small communities.

OVERVIEW OF THE METHODOLOGY

Exhibit 15-31 illustrates the steps involved in the bicycle methodology.

Exhibit 15-31: Flowchart of the Bicycle Methodology for Two-Lane and Multilane Highways

Step 1: Gather Input Data
Lane and shoulder width
Number of directional lanes
Speed limit
Pavement condition
Automobile demand data
On-highway parking occupancy

↓

Step 2: Calculate the Directional Flow Rate in the Outside Lane
(Equation 15-40)

↓

Step 3: Calculate the Effective Width
(Equations 15-41 through 15-45)

↓

Step 4: Calculate the Effective Speed Factor
(Equation 15-46)

↓

Step 5: Determine the LOS
(Equation 15-47 and Exhibit 15-7)

COMPUTATIONAL STEPS

Step 1: Gather Input Data

Exhibit 15-30 listed the information that must be available before a two-lane or multilane highway segment can be analyzed and potential sources for that information. The exhibit also suggested default values for use when neither site-specific data nor local default values are available.

Pavement rating is determined by using FHWA's 5-point present serviceability rating scale (5): 1 (very poor), 2 (poor), 3 (fair), 4 (good), and

5 (very good).

Step 2: Calculate the Directional Flow Rate in the Outside Lane

On the basis of the hourly directional volume, the peak hour factor, and the number of directional lanes (one for Passing Constrained and Passing Zone segments of two-lane highways, two or more for Passing Lane segments on two-lane highways or for multilane highways), calculate the directional demand flow rate of motorized traffic in the outside lane with Equation 15-40:

Equation 15-40:

$$v_{OL} = \frac{V}{PHF \times N}$$

where

v_{OL}	=	directional demand flow rate in the outside lane (veh/h),
V	=	hourly directional volume (veh/h),
PHF	=	peak hour factor, and
N	=	number of directional lanes (=1 for two-lane highways).

Step 3: Calculate the Effective Width

The effective width of the outside through lane depends on both the actual width of the outside through lane and the shoulder width, since cyclists will be able to travel on the shoulder where one is provided. Moreover, striped shoulders of 4 ft or greater provide more security to cyclists by giving cyclists a dedicated place to ride outside of the motorized vehicle travelway. Thus, an 11-ft lane and adjacent 5-ft paved shoulder results in a larger effective width for cyclists than a 16-ft lane with no adjacent shoulder.

Parking occasionally exists along two-lane highways, particularly in developed areas and near entrances to recreational areas where a fee is charged for off-highway parking or where the off-highway parking is inadequate for the parking demand. On-highway parking reduces the effective width, because parked vehicles take up shoulder space and bicyclists leave some shy distance between themselves and the parked cars.

Equation 15-41 through Equation 15-45 are used to calculate the effective width W_e on the basis of the paved shoulder width W_s and the hourly directional volume V:

If W_s is greater than or equal to 8 ft:

Equation 15-41:

$$W_e = W_v + W_s - (\%OHP \times 10 \text{ ft})$$

If W_s is greater than or equal to 4 ft and less than 8 ft:

Equation 15-42:

$$W_e = W_v + W_s - 2 \times [\%OHP\,(2 \text{ ft} + W_s)]$$

If W_s is less than 4 ft:

Equation 15-43:

$$W_e = W_v - [\%OHP\,(2 \text{ ft} + W_s)]$$

with, if V is greater than 160 veh/h:

Equation 15-44:

$$W_v = W_{OL} + W_s$$

Otherwise,

Equation 15-45:

$$W_v = (W_{OL} + W_s) \times (2 - 0.005V)$$

where

W_v = effective width as a function of traffic volume (ft),

W_{OL} = outside lane width (ft),

W_s = paved shoulder width (ft),

V = hourly directional volume per lane (veh/h),

W_e = average effective width of the outside through lane (ft), and

$\%OHP$ = percentage of segment with occupied on-highway parking (decimal).

Step 4: Calculate the Effective Speed Factor

The effect of motor vehicle speed on bicycle quality of service is primarily related to the differential between motor vehicle and bicycle travel speeds. For example, a typical cyclist may travel in the range of 15 mi/h. An increase in motor vehicle speeds from 20 to 25 mi/h is more readily perceived than a speed increase from 60 to 65 mi/h, since the speed differential increases by 100% in the first instance compared with only 11% in the latter. Equation 15-46 shows the calculation of the effective speed factor that accounts for this diminishing effect.

Equation 15-46:

$$S_t = 1.1199 \ln(S_{pl} - 20) + 0.8103$$

where

S_t = effective speed factor, and

S_{pl} = posted speed limit (mi/h).

Step 5: Determine the LOS

With the results of Steps 1–4, the bicycle LOS score can be calculated from Equation 15-47:

Equation 15-47:

$$BLOS = 0.507 \ln(v_{OL}) + 0.1999 S_t (1 + 10.38 HV)^2 + 7.066 (1/P)^2 - 0.0$$

where

$BLOS$	=	bicycle level of service score;
v_{OL}	=	directional demand flow rate in the outside lane (veh/h);
S_t	=	effective speed factor;
HV	=	proportion of heavy vehicles (decimal); if $V < 200$ veh/h, then HV should be limited to a maximum of 0.5 (i.e., 50%);
P	=	FHWA's 5-point pavement surface condition rating; and
W_e	=	average effective width of the outside through lane (ft).

Finally, the BLOS score value is used in Exhibit 15-7 to determine the bicycle LOS for the segment.

5. APPLICATIONS

EXAMPLE PROBLEMS

Section 8 of Chapter 26, Freeway and Highway Segments: Supplemental, provides five example problems that go through each of the computational steps involved in applying the motorized vehicle and bicycle methods:

1. Level, Straight, Passing Constrained Segment;
2. Passing Constrained Segment with Horizontal Curves;
3. Facility Analysis—Level Terrain;
4. Facility Analysis—Mountain Road; and
5. Two-Lane Highway Bicycle LOS.

SENSITIVITIES

This subsection gives a high-level overview of the sensitivity of bicycle and motor-vehicle LOS to changes in traffic flow rates for various geometric conditions.

Sensitivity of Motor-Vehicle Performance

The sensitivity of motor-vehicle performance on two-lane highways to traffic volumes was presented in Exhibit 15-2 through Exhibit 15-4 in the Applicable Performance Measures and Their Sensitivities subsection of Section 2.

Sensitivity of Bicycle Mode Performance

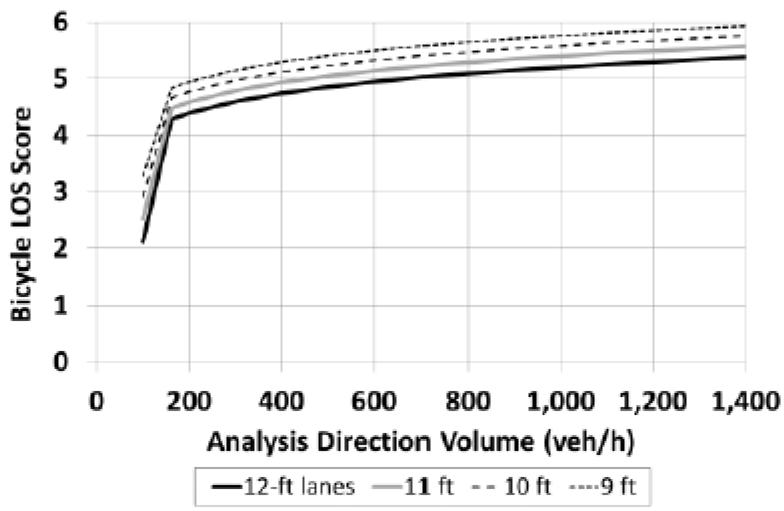
Sensitivity of Results to Lane and Shoulder Width

Exhibit 15-32 depicts how the bicycle level-of-service (BLOS) score is affected by different lane and shoulder widths at different directional volumes. As was shown in Exhibit 15-7, lower BLOS score values indicate that bicyclists perceive better conditions, with the LOS A/B threshold set at a BLOS score of 1.5, the LOS E/F threshold set at 5.5, and each 1.0 increase in the BLOS score indicating a one-letter drop in the level of service.

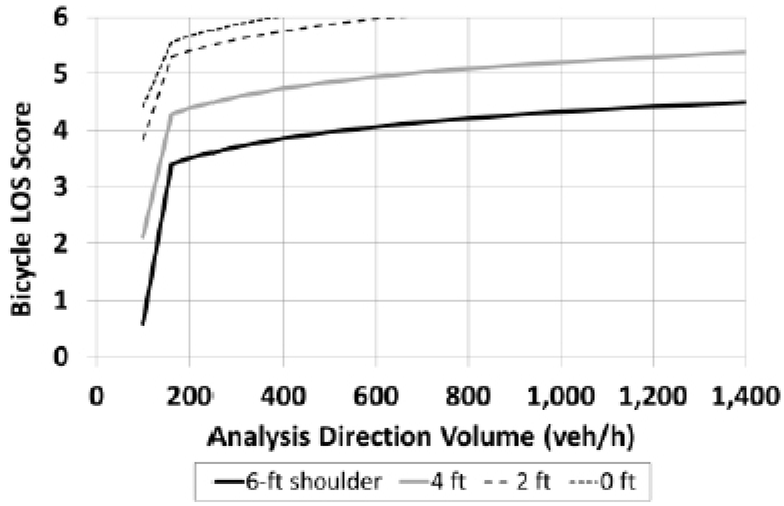
Comparison of Exhibit 15-32(a) with Exhibit 15-32(b) indicates that the relative change in the BLOS score with either a reduced lane width or a reduced shoulder width is the same at any volume. In addition, shoulder width has a greater impact on the BLOS score than does the lane width.

Finally, the effect of low volumes on the BLOS score can be seen clearly in both graphs as a sharp drop in the score when the volume is 160 veh/h or less. This effect is a result of Equation 15-45, where the effective width as a function of traffic volume can be as much as twice the physical width.

Exhibit 15-32: Illustrative Effect of Volume, Lane Width, and Shoulder Width on BLOS Score



(a) Lane Width



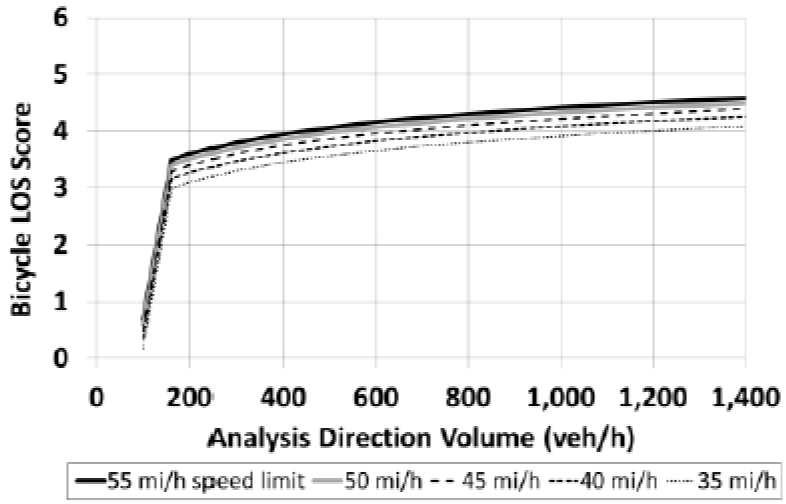
(b) Shoulder Width

Note: Calculated by using this chapter's methods. Fixed values include pavement condition = 4 (good), speed limit = 50 mi/h, PHF = 0.88, 6% heavy vehicles, and no on-highway parking. In Exhibit 15-32(a), shoulder width = 4 ft. In Exhibit 15-32(b), lane width = 12 ft.

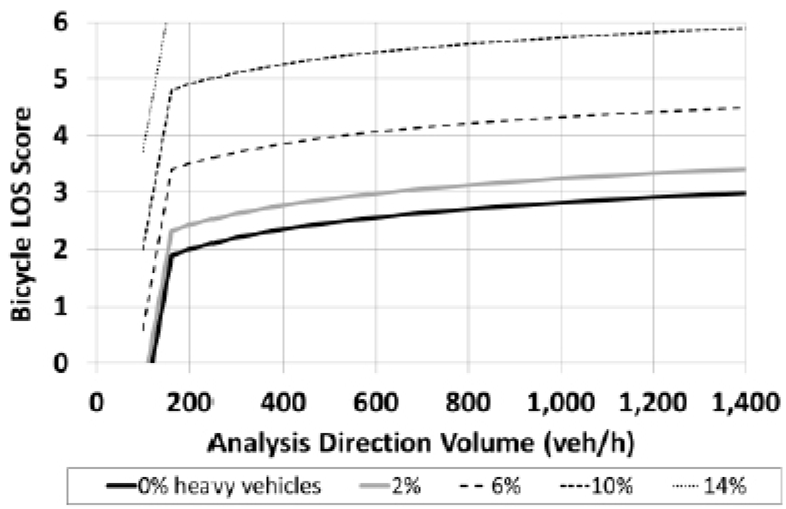
Sensitivity of Results to Traffic Speed and Heavy Vehicles

Exhibit 15-33(a) shows that traffic speed has a relatively small effect on the BLOS score, within the range of speed limits typically found on two-lane highways. On the other hand, Exhibit 15-33(b) shows that the heavy vehicle percentage has a large effect on the BLOS score. When heavy vehicles form 14% of the traffic volume, LOS F (i.e., BLOS score > 5.5) conditions result at any traffic volume over 160 veh/h, for the conditions shown in the note accompanying the exhibit.

Exhibit 15-33: Illustrative Effect of Volume, Speed Limit, and Heavy Vehicles on BLOS Score



(a) Speed Limit



(b) Heavy Vehicle Percentage

Note: Calculated by using this chapter's methods. Fixed values include 12-ft lane width, 6-ft shoulder, pavement condition = 4 (good), PHF = 0.88, no on-highway parking. In Exhibit 15-33(a), the heavy vehicle percentage is 6%. In Exhibit 15-33(b), the speed limit is 50 mi/h.

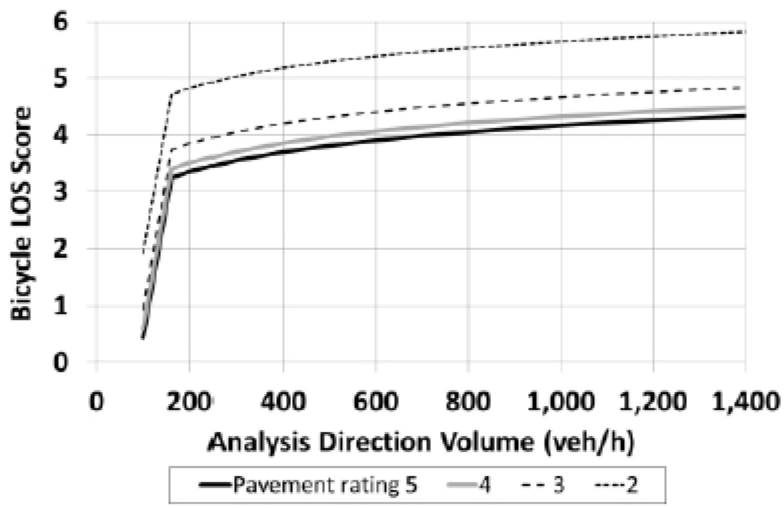
Sensitivity of Results to Pavement Condition and On-Highway Parking

Exhibit 15-34(a) shows that the BLOS score is sensitive to the pavement condition rating. Furthermore, when the pavement rating is 1 (very poor), the

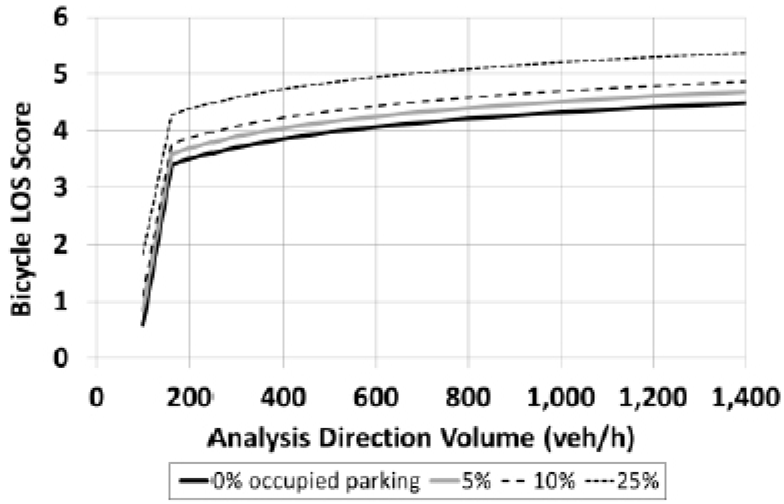
BLOS score is off the graph, well into the LOS F range (e.g., BLOS = 6.51 with no traffic volume, for the conditions shown with the exhibit).

Exhibit 15-34(b) shows that, within the range of occupied parking that might be found along most two-lane highways, on-highway parking has a small impact on the BLOS score. However, at the higher percentages of on-highway parking that might be found along a highway section passing through a small community, the impact of parking is greater.

Exhibit 15-34: Illustrative Effect of Volume, Pavement Condition, and On-Highway Parking on BLOS Score



(a) Pavement Condition



(b) On-Highway Parking

Note: Calculated by using this chapter’s methods. Fixed values include 12-ft lane width, 6-ft shoulder, 6% heavy vehicles, 50-mi/h speed limit, and PHF = 0.88. In Exhibit 15-34 (a), there is no on-highway parking. In Exhibit 15-34(b), the pavement condition rating is 4 (good).
When the pavement condition is 1 (very poor), BLOS score > 5.5 (LOS F) across the full range of directional volumes, for the conditions listed above.

GENERALIZED DAILY SERVICE VOLUMES

Daily service volume tables have not yet been estimated for this updated two-lane highway method. The user can follow the guidance given in *NCHRP Report 825* (*6*) to generate service volume tables, as needed.

USE OF ALTERNATIVE TOOLS

Appendix C of the NCHRP Project 17-65 final report (*2*) describes how motor-vehicle operations can be simulated for two-lane highways. The use of a simulation model should be considered when the situation being analyzed falls outside the recommended limits of this chapter’s methodology.

FIELD MEASUREMENT OF MOTOR-VEHICLE PERFORMANCE MEASURES

The analyst has the option of measuring segment motor-vehicle performance directly in the field, as described below.

Average Speed

The average speed is measured in the field by averaging the measured spot speeds observed over one hour at the endpoint of the segment.

Percent Followers

The percent followers is measured in the field at the downstream end of each segment. The total number of vehicles passing the segment endpoint in the subject direction is counted over a one-hour period. The front-bumper to front-bumper time headways between vehicles is noted in tenths of seconds for each vehicle after the first vehicle. The number of followers is determined by summing up the number of headways equal to or less than 2.5 s. The percent followers is the number of followers divided by the total number of vehicles passing the point.

Follower Density

The follower density is the percent followers multiplied by the density of all vehicles at the endpoint of the segment. It can be computed from the counted volume and the number of followers counted at the downstream endpoint of the segment. The number of followers divided by the average segment speed (mi/h) (measured over the full length of the segment) gives the follower density.

CALIBRATION OF THE MOTOR-VEHICLE METHODOLOGY

The motor-vehicle methodology can be calibrated to local conditions to improve the quality of the results produced by the method. However, calibration should be done with care, and not used as a method to gloss over data entry errors, computational errors, or field observation errors.

Calibration of Capacity

It is rare to be able to observe the capacity of a two-lane highway segment in the field. Caution should be used, as what may appear to be a segment capacity situation in the field may be, in reality, be an intersection capacity issue.

If the counted volume in one direction of a segment exceeds 1,700 veh/h, it is recommended that the analyst recheck the count and ideally repeat the count for a few more days to verify that directional volumes in excess of 1,700 veh/h are regularly obtained. If it is verified that directional volumes regularly exceed 1,700 veh/h, the field-observed value should be substituted for this chapter's recommended capacity value.

Similarly, if the analyst regularly observes mainline queuing on the segment at volumes below 1,700 veh/h, the analyst may consider reducing the value of capacity used in the motor-vehicle methodology accordingly. Before doing so, however, other possible causes of the queuing should be investigated and ruled out, such as intersection delays or transitory roadside distractions.

Calibration of Speed and Percent Followers

In situations where the analyst is able to directly measure free-flow speed, average travel speed, and percent followers in the field, it is desirable to calibrate the speed and percent-following estimates produced by this chapter's methodology. Once calibrated, the motor-vehicle methodology can then be used to predict how changes in demand and design would affect average travel speeds, follower density, and LOS.

Calibration consists of applying multiplicative factors to each of the following HCM-estimated performance measures: free-flow speed, average travel speed, and percent followers. The factors are different for each performance measure and may also vary by segment, as indicated by Equation 15-48 through Equation 15-50.

Equation 15-48:

$$FFS_{\text{field},i} = SAF_{FFS,i} \times FFS_{HCM,i}$$

Equation 15-49:

$$S_{\text{field},i} = SAF_{S,i} \times S_{HCM,i}$$

Equation 15-50:

$$PF_{\text{field},i} = PFAF_i \times PF_{HCM,i}$$

where

$FFS_{\text{field},i}$	=	field-measured free-flow speed for segment i (mi/h),
$SAF_{FFS,i}$	=	speed adjustment factor for free-flow speed for segment i (decimal),
$FFS_{HCM,i}$	=	free-flow speed estimated by Chapter 15 method for segment i (mi/h),
$S_{\text{field},i}$	=	field-measured average speed for segment i (mi/h),
$SAF_{S,i}$	=	speed adjustment factor for average speed for segment i (decimal),
$S_{HCM,i}$	=	average speed estimated by Chapter 15 method for segment i (mi/h),
$PF_{\text{field},i}$	=	field-measured percent followers for segment i (%),
$PFAF_i$	=	calibration adjustment factor for percent followers for segment i (decimal), and
$PF_{HCM,i}$	=	percent followers estimated by Chapter 15 method for segment i (%).

These calibration factors should preferably fall in the range of 0.85–1.15. Should the values fall outside that range, the analyst should recheck the field measurements and the data inputs to the HCM method to rule out errors. If the calibration factors still are not within the preferred range after error-checking, it is possible that this chapter's method is not well-suited for the segment's specific conditions, and simulation analysis should be considered instead.

Results obtained using these calibration factors should be checked for reasonableness. For example, percent followers after adjustment for calibration should not exceed 100%.

6. REFERENCES

1. *Traffic Monitoring Guide,* Appendix C, Vehicle Types. Report FHWA-PL-17-003. Federal Highway Administration, Washington, D.C., Oct. 2016.

2. Washburn, S. S., A. Al-Kaisy, T. Luttinen, R. Dowling, D. Watson, A. Jafari, Z. Bian, and A. Elias. *NCHRP Web-Only Document 255: Improved Analysis of Two-Lane Highway Capacity and Operational Performance.* Final Report for NCHRP Project 17-65, March 2018. http://www.trb.org/main/blurbs/177835.aspx. Accessed September 14, 2020.

3. Li, J., and S. S. Washburn. Improved Operational Performance Assessment for Two-Lane Highway Facilities. *Journal of Transportation Engineering,* Vol. 140, Issue 6, June 2014. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000666

4. Petritsch, T. A., B. W. Landis, H. F. Huang, P. S. McLeod, D. R. Lamb, W. Farah, and M. Guttenplan. Bicycle Level of Service for Arterials. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2031,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 34–42.

5. *Highway Performance Monitoring System Field Manual*, Chapter 4. Federal Highway Administration, Washington, D.C., May 2005.

6. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, and T. Creasey. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the HCM.* Transportation Research Board, Washington, D.C., 2016.

APPENDIX A: GUIDANCE ON OPTIMIZING PASSING LANE PERFORMANCE

Passing is an important operational phenomenon on two-lane, two-way highways. Platoons form on these highways as a result of infrequent passing opportunities. Vehicle speeds in platoons are restricted by the speed of slow-moving platoon leaders. As the amount of platooning increases, the highway's LOS deteriorates. Providing a passing lane on a two-lane highway can improve operational performance and LOS, as it provides passing opportunities that help break up vehicular platoons. Passing lanes on steep upgrades are also referred to as *climbing lanes,* which are also discussed in this appendix.

OPTIMUM LENGTH OF PASSING LANES

Exhibit 15-A1 presents results from simulation that show values of the reduction in percent followers in level terrain for different combinations of passing lane lengths and directional traffic flow rates (i.e., the total demand across the two directional lanes within the Passing Lane segment). It can be seen that the slopes of the curves are higher at shorter passing lane lengths, and take on a linear (constant slope) form at longer passing lane lengths. The length at which the relationship between percent followers and passing lane length transitions from curvilinear to linear is largely a function of traffic volume, with the transition occurring at greater lengths when higher traffic volumes are present.

Exhibit 15-A1: Illustrative Percent Reduction in Percent Followers by Passing Lane Length in Level Terrain

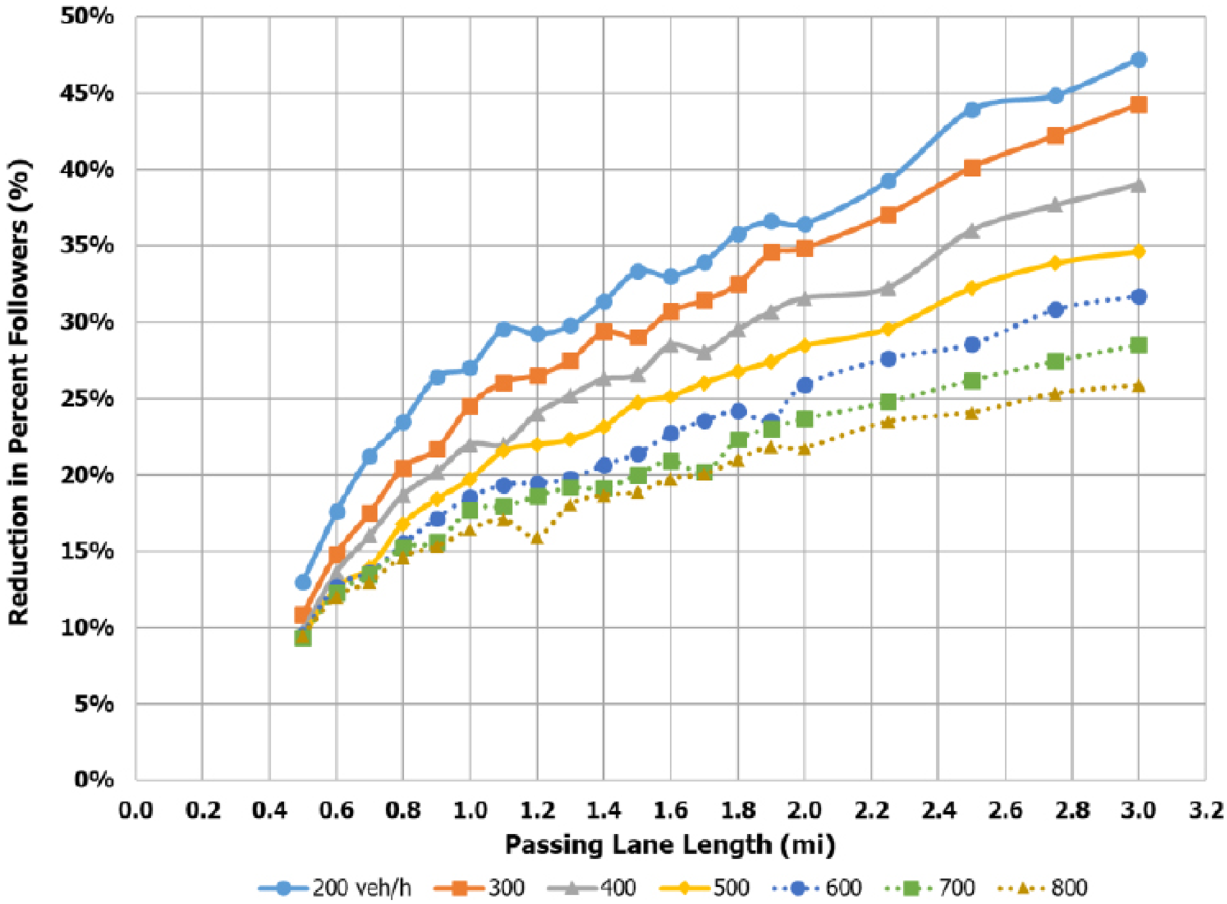


Exhibit 15-A2 shows optimum passing lane lengths derived from simulation, with the optimum length defined as the point where the relationship between the reduction in percent followers and the passing lane length transitions from curvilinear to linear. These lengths are in the range of 0.9–2.0 mi, depending on directional traffic flow rate.

Exhibit 15-A2: Optimum Passing Lane Lengths

Traffic flow rate entering passing lane (veh/h)	200	300	400	500	600	700	800
Optimum passing lane length (mi)	0.9	1.0	1.2	1.2	1.6	1.9	2.0

CLIMBING LANES

Overview

Climbing lane sections are similar to passing lane sections in that they provide an added lane that allows faster vehicles to pass slower vehicles without using the oncoming lane. Both climbing and passing lanes also serve to break up platoons. However, the considerations for implementing a climbing lane are distinctly different from the considerations for adding a passing lane. As their name implies, climbing lanes are implemented on upgrades and are intended to allow slower-moving trucks to move out of the way of faster vehicles on the grade, as the speed differential between passenger vehicles and large trucks can be substantial when the grade exceeds 3%.

AASHTO provides the following criteria for when a climbing lane should be considered (*A-1*):

- Upgrade traffic flow rate exceeds 200 veh/h;
- Upgrade truck flow rate exceeds 20 veh/h; and
- One or more of the following conditions exists:
  - A 10 mi/h or greater speed reduction is expected for a typical heavy truck;
  - LOS E or F exists on the grade; or
  - A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

Truck Speed Reductions on Upgrades

Base Method

The truck speed–distance curves in Exhibit 15-A3 through Exhibit 15-A5 can be used to determine speed reductions on different lengths of grade for three truck types (single-unit, intermediate semitrailer, and interstate semitrailer). Alternatively, Equation 15-A1 can be used to estimate the speed reduction. No set of curves are provided for double semitrailer trucks, because field data indicated that this truck type was not prevalent on two-lane highways.

Exhibit 15-A3: Upgrade Speed–Distance Curves for Single-Unit Trucks

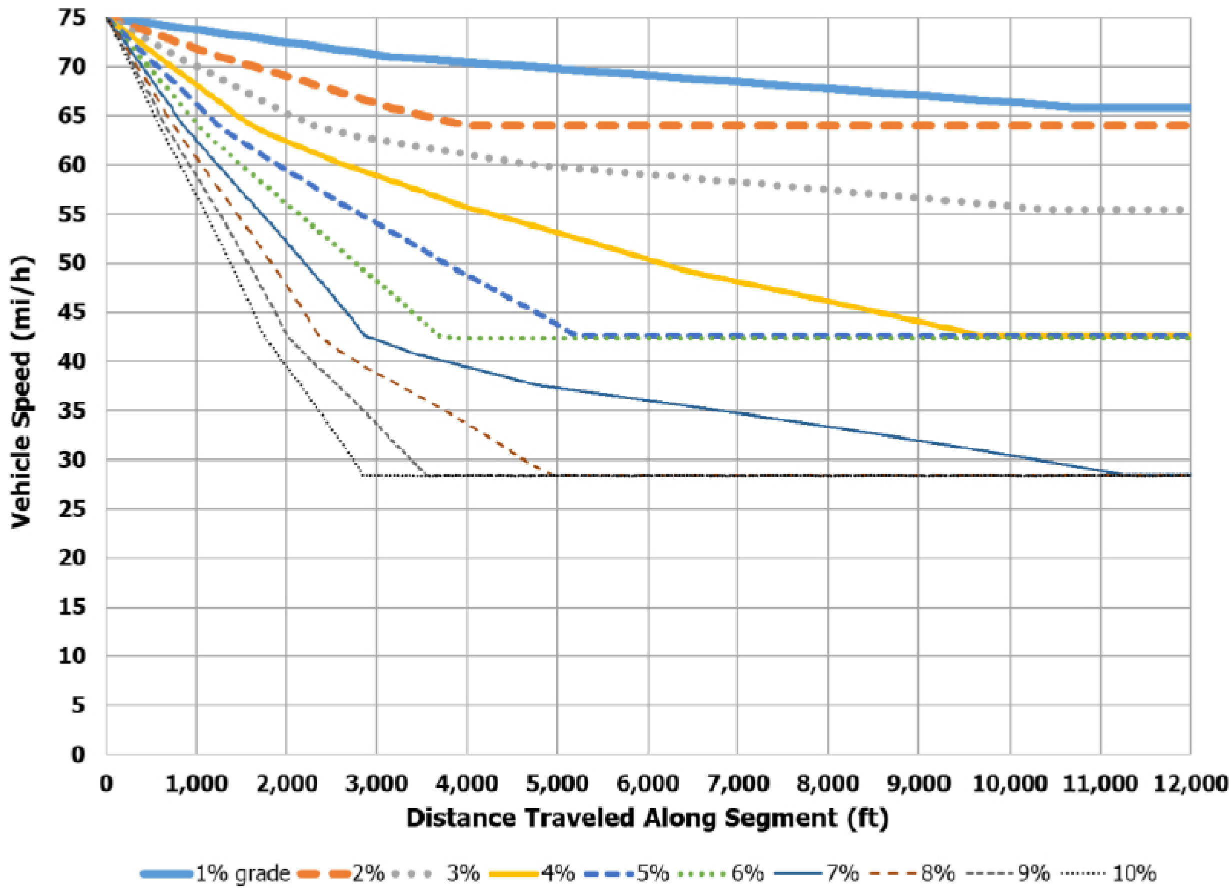


Exhibit 15-A4: Upgrade Speed–Distance Curves for Intermediate Semitrailer Trucks

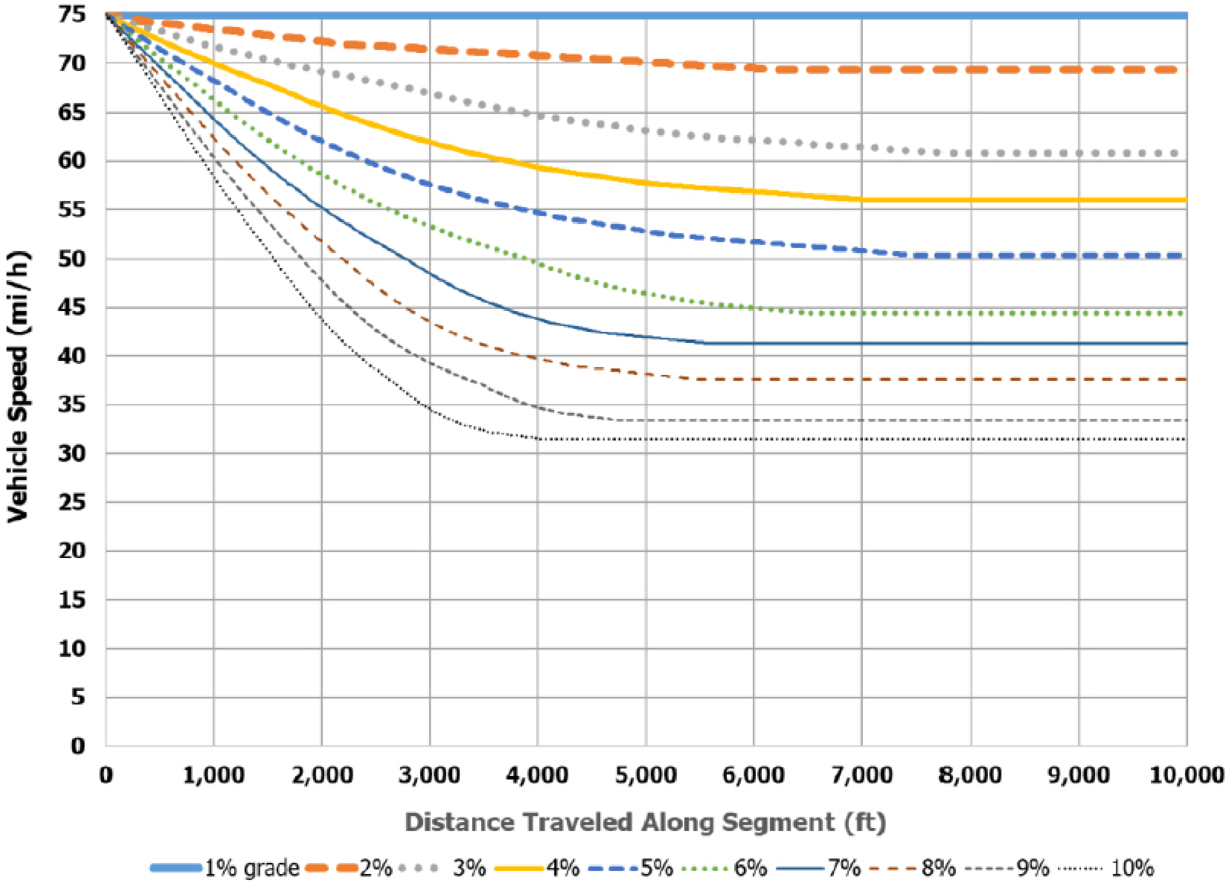
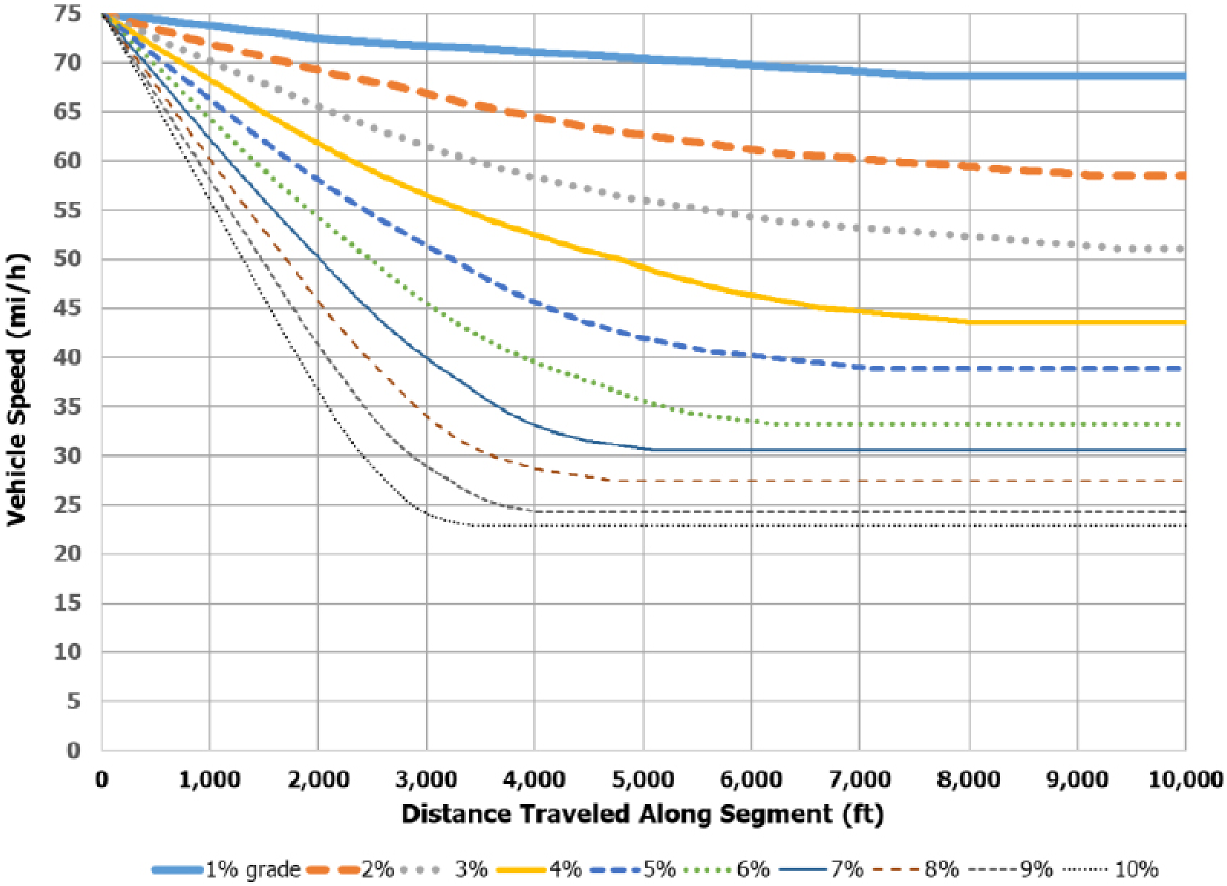


Exhibit 15-A5: Upgrade Speed–Distance Curves for Interstate Semitrailer Trucks



Equation 15-A1:

$$V = 75 + a \times L + b \times L^2 + c \times L^3$$

where

V	=	speed of heavy vehicle at the end of the upgrade segment (mi/h),
L	=	length of the upgrade segment (mi),
a, b, c	=	model coefficients (decimal), from Exhibit 15-A6, Exhibit 15-A7, or Exhibit 15-A8 for single-unit, intermediate semitrailer, and interstate semitrailer trucks, respectively.

Exhibit 15-A6: Upgrade Speed Model Coefficients for Single-Unit Trucks

Grade Slope (%)	*a*	*b*	*c*

1	−7.99117	3.34943	−0.80873
2	−16.79550	1.90540	1.36780
3	−32.09620	21.98800	−5.51770
4	−39.03610	21.53390	−5.45420
5	−52.54130	37.09590	−17.43770
6	−61.54480	38.29370	−22.79690
7	−80.51610	54.45520	−12.78160
8	−88.40130	47.70330	−5.71440
9	−97.19730	41.85210	0.00000
10	−93.95550	−33.73320	93.20230

Exhibit 15-A7: Upgrade Speed Model Coefficients for Intermediate Semitrailer Trucks

Grade Slope (%)	*a*	*b*	*c*
1	0.00000	0.00000	0.00000
2	−9.11990	6.63672	−2.51232
3	−17.52110	5.44550	0.00000
4	−29.10240	11.41810	0.00000
5	−42.79200	24.99010	−4.85490
6	−52.06060	26.76310	−3.74860
7	−63.70110	30.18420	0.00000
8	−77.24510	40.32630	0.00000
9	−89.75260	48.34020	0.00000
10	−90.21160	1.41830	56.44760

Exhibit 15-A8: Upgrade Speed Model Coefficients for Interstate Semitrailer Trucks

Grade Slope (%)	*a*	*b*	*c*
1	−7.92121	4.78662	−1.63570
2	−16.71740	3.63040	0.37130
3	−29.79650	11.81370	−1.39070
4	−39.51320	13.24520	−0.52500
5	−49.57050	11.49140	4.32190
6	−60.94040	12.96240	7.63790
7	−66.62850	−9.65440	32.62600
8	−75.89060	−24.93370	57.74360
9	−82.36480	−55.27030	101.05490
10	−85.01500	−114.73900	188.34900

Adjustment for Upgrades With Initial Speeds Less Than 75 mi/h

The upgrade speed versus distance functions were developed assuming an initial speed of 75 mi/h. These functions can be modified to produce upgrade speeds for different initial speeds. Rather than creating new functions with different initial speeds, the length of the upgrade segment used in the equation can be extended to account for the difference in the initial speed.

For example, assume that an interstate semi-trailer truck is approaching a 0.5-mi, 6 percent upgrade at an initial speed of 60 mi/h. Based on the speed versus distance function for a 6 percent grade and initial speed of 75 mi/h (shown in Exhibit 15-A5), the vehicle does not reach a speed of 60 mi/h until it has traveled a distance of 1,426 ft (0.27 mi). To account for the 15 mi/h difference in initial speed, this distance can be added to the original segment length of 0.5 mi. Therefore, the adjusted upgrade segment length is 0.77 mi. This segment length is input into the speed versus distance function for a 6 percent grade (Equation 15-A1), which returns a final speed on the upgrade of 40 mi/h. Had the segment length not been adjusted, the final speed would have equaled 50 mi/h. Therefore, the 15 mi/h difference in initial speed created a 10 mi/h difference in the final speed on the upgrade.

Exhibit 15-A9 through Exhibit 15-A11 provide additional upgrade segment lengths for various combinations of initial speed and grade slope, for single-unit, intermediate semitrailer, and interstate semitrailer trucks, respectively. "N/A" in the exhibits indicates a situation where the truck initial speed is less than the truck crawl speed for a particular upgrade. Equation 15-A1 only models the non-constant portion of a speed-distance curve that is prior to the constant crawl speed portion. Exhibit 15-A12 provides the segment lengths at which crawl speed is reached if the truck enters the segment with an initial speed of 75 mi/h. Exhibit 15-A12 can be used to check if a truck would reach its crawl speed for a given adjusted segment length. If the adjusted segment length exceeds the value in Exhibit 15-A12, the crawl speed can be used directly rather than using Equation 15-A1.

Exhibit 15-A9: Additional Upgrade Segment Lengths (mi) for Different Initial Speeds of Single-Unit Trucks

	Grade Slope (%)									
Initial Speed (mi/h)	1	2	3	4	5	6	7	8	9	10

75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70	0.89	0.32	0.18	0.14	0.11	0.09	0.07	0.06	0.06	0.06
65	N/A	0.68	0.42	0.31	0.23	0.19	0.14	0.13	0.11	0.11
60	N/A	N/A	0.89	0.51	0.37	0.29	0.22	0.19	0.17	0.16
55	N/A	N/A	N/A	0.79	0.53	0.41	0.31	0.27	0.23	0.21
50	N/A	N/A	N/A	1.18	0.72	0.53	0.42	0.35	0.30	0.26
45	N/A	N/A	N/A	1.63	0.91	0.65	0.56	0.44	0.37	0.32
40	N/A	N/A	N/A	N/A	N/A	N/A	0.75	0.55	0.45	0.38
35	N/A	N/A	N/A	N/A	N/A	N/A	1.15	0.69	0.54	0.45
30	N/A	N/A	N/A	N/A	N/A	N/A	1.98	0.90	0.64	0.53
25	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: N/A: not applicable; the initial speed is less than the truck crawl speed. Use Exhibit 15-A12 instead.

Exhibit 15-A10: Additional Upgrade Segment Lengths (mi) for Different Initial Speeds of Intermediate Semitrailer Trucks

	Grade Slope (%)									
Initial Speed (mi/h)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70	N/A	1.01	0.32	0.19	0.13	0.11	0.09	0.07	0.06	0.06
65	N/A	N/A	0.75	0.41	0.28	0.22	0.18	0.14	0.12	0.12
60	N/A	N/A	N/A	0.72	0.47	0.35	0.28	0.22	0.19	0.17
55	N/A	N/A	N/A	N/A	0.75	0.51	0.39	0.31	0.26	0.24
50	N/A	N/A	N/A	N/A	N/A	0.72	0.53	0.42	0.35	0.30
45	N/A	N/A	N/A	N/A	N/A	1.12	0.71	0.55	0.44	0.37
40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.74	0.56	0.45
35	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.75	0.56
30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
25	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: N/A: not applicable; the initial speed is less than the truck crawl speed. Use Exhibit 15-A12 instead.

Exhibit 15-A11: Additional Upgrade Segment Lengths (mi) for Different Initial Speeds of Interstate Semitrailer Trucks

	Grade Slope (%)									
Initial Speed (mi/h)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70	1.08	0.33	0.19	0.14	0.11	0.09	0.08	0.07	0.06	0.06
65	N/A	0.72	0.40	0.28	0.22	0.18	0.15	0.13	0.12	0.11
60	N/A	1.35	0.67	0.45	0.34	0.27	0.23	0.20	0.17	0.16
55	N/A	N/A	1.07	0.65	0.47	0.37	0.31	0.26	0.23	0.20

50	N/A	N/A	N/A	0.89	0.62	0.48	0.39	0.33	0.28	0.25
45	N/A	N/A	N/A	1.29	0.80	0.60	0.47	0.40	0.34	0.30
40	N/A	N/A	N/A	N/A	1.12	0.75	0.57	0.47	0.40	0.35
35	N/A	N/A	N/A	N/A	N/A	0.98	0.70	0.56	0.47	0.40
30	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.69	0.55	0.46
25	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.70	0.55
20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: N/A: not applicable; the initial speed is less than the truck crawl speed. Use Exhibit 15-A12 instead.

Exhibit 15-A12: Crawl Speeds and Corresponding Segment Lengths for Different Truck Types

	Single-Unit Trucks		Intermediate Semitrailer Trucks		Interstate Semitrailer Trucks	
.Grade Slope (%)	Segment Length (mi)	Crawl Speed (mi/h)	Segment Length (mi)	Crawl Speed (mi/h)	Segment Length (mi)	Crawl Speed (mi/h)
1	2.03	65.82	N/A	N/A	1.43	68.68
2	0.76	63.94	1.17	69.39	1.77	58.84
3	1.91	55.46	1.57	60.91	1.85	51.50
4	1.81	42.55	1.25	56.46	1.57	43.58
5	0.99	42.42	1.58	50.62	1.25	39.43
6	0.72	42.03	1.24	44.45	1.16	33.67
7	2.07	28.30	1.05	41.39	0.93	30.93
8	1.02	28.40	0.95	38.01	0.82	27.84
9	0.68	28.26	0.90	33.38	0.73	24.73
10	0.56	28.17	0.72	31.85	0.64	22.97

Note: N/A: not applicable; truck crawl speed is greater than 75 mi/h.

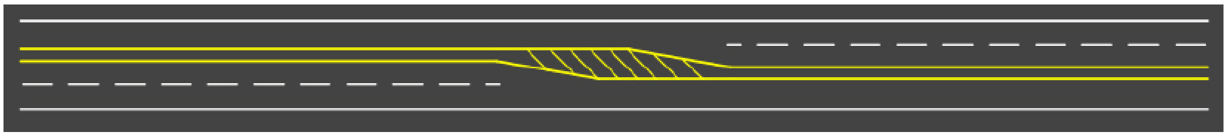
AASHTO indicates that climbing lanes should be extended beyond the crest of the curve for a distance that allows a truck to accelerate to a speed that is (*a*) within 10 mi/h of the passenger vehicle speed and (*b*) at least 40 mi/h (*A-1*).

2+1 CONFIGURATION

The 2+1 configuration is a continuous three-lane cross section, with the middle lane being a passing lane that alternates direction. An example of this configuration is illustrated in Exhibit 15-A13. Modern designs also include a transition area where the passing lane reverses direction. An example of a typical European transition area is illustrated in Exhibit 15-A14.

Exhibit 15-A13: Illustrative Schematic of a 2+1 Configuration

Exhibit 15-A14: Illustrative Schematic of Transition Area Typical of European 2+1 Configurations



The 2+1 design is popular in parts of Europe. Although this design has some similarities with the typical three-lane cross section with a passing lane used in the U.S., there are some significant differences. The 2+1 design typically extends for many miles, with several changes of direction for the passing lane provided within this distance. Additionally, passing vehicles always use the center lane. This design is intended to be an intermediate option between a two-lane highway with or without occasional passing lanes and a four-lane highway.

The 2+1 configuration is currently rare in the U.S. Note that two-lane highways referred to as “Super 2” sections by some agencies are not necessarily the same as a “2+1” section. The “Super 2” label is sometimes applied to two-lane highways with frequent passing lanes, but not necessarily to continuously alternating passing lanes. “Super 2” is also sometimes used to refer to a fully access-controlled two-lane highway, regardless of passing lane presence.

Equation 15-A2 through Equation 15-A4 can be used to estimate the change in performance between a 2+1 configuration and a comparable two-lane highway with no passing lanes, approximately 50% passing zones, and 16-18 mi in length.

Equation 15-A2:

$$\%Improve_{\text{\%Followers,2+1}} = 147.5 - 15.8 \times \ln\left(FlowRate\right) + 0.05 \times FFS$$

Equation 15-A3:

$$\%Improve_{AvgSpeed,2+1} = \max\left(0, 21.8 - 1.86 \times \ln\left(FlowRate\right) - 0.1 \times \mathrm{r}\right.$$

Equation 15-A4:

$$FollowerDensity_{adj,2+1} = \frac{\%Followers_{2+1}}{100} \times \left(1 - \frac{\%Improve_{\%\text{Follower}}}{100}\right.$$

where

$\%Improve_{\%\text{Followers},2+1}$	=	% improvement to percent followers,
$\%Improve_{AvgSpeed,2+1}$	=	% improvement to the average speed,
$FollowerDensity_{adj,2+1}$	=	adjusted follower density (followers/mi),
$FlowRate_{2+1}$	=	flow rate entering the 2+1 configuration (veh/h),
FFS	=	free-flow speed (mi/h),
$HV\%$	=	percentage of heavy vehicles in the analysis direction (%),
$PassLaneLength$	=	Passing lane length (mi),
$\%Followers_{2+1}$	=	percent followers entering the 2+1 configuration (i.e., percent followers estimated at the end of the segment just upstream of the first passing lane), and
S	=	average speed in the analysis direction (mi/h).

Note that these models are intended to apply to a range of passing lane lengths of 0.75–2.0 mi. The improvement of percent followers is inversely related to the passing lane length. This result is a consequence of the unique configuration of 2+1 sections—increasing the length of the passing lanes also increases the length of the in-between non-passing lane segments due to the symmetry of the opposing direction.

REFERENCES

A-1. *A Policy on Geometric Design of Highways and Streets,* 6th ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2011.