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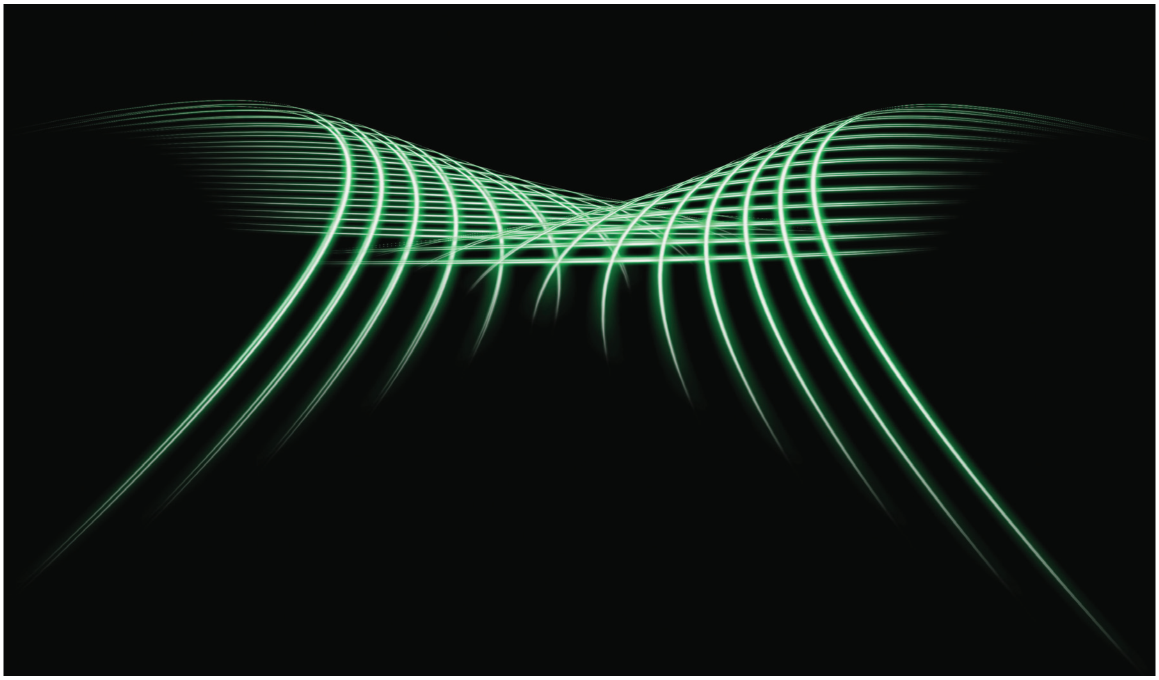

CHAPTER 15

TWO-LANE HIGHWAYS

TRB TRANSPORTATION RESEARCH BOARD
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HCM2010

HIGHWAY CAPACITY MANUAL

The HCM 2010 significantly enhances how engineers and planners assess the traffic and environmental effects of highway projects by

- Providing an integrated multimodal approach to the analysis and evaluation of urban streets from the points of view of automobile drivers, transit passengers, bicyclists, and pedestrians;
- Addressing the proper application of microsimulation analysis and the evaluation of the results;
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- Exploring specific tools and generalized service volume tables to assist planners in quickly sizing future facilities.

The HCM 2010 consists of four volumes:

Volume 1: Concepts;
Volume 2: Uninterrupted Flow;
Volume 3: Interrupted Flow; and
Volume 4: Applications Guide (electronic only).

The four-volume format provides information at several levels of detail, to help users more easily apply and understand the concepts, methodologies, and potential applications.

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CHAPTER 15
TWO-LANE HIGHWAYS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Two-lane highways have one lane for the use of traffic in each direction. The principal characteristic that separates motor vehicle traffic on two-lane highways from other uninterrupted-flow facilities is that passing maneuvers 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.

Two-lane highways have one lane for the use of traffic in each direction. Passing takes place in the opposing lane of traffic when sight distance is appropriate and safe gaps in the opposing traffic stream are available.

Because passing capacity decreases as passing demand increases, two-lane highways exhibit a unique characteristic: operating quality often decreases precipitously as demand flow increases, and operations can become "unacceptable" at relatively low volume-to-capacity ratios. For this reason, few two-lane highways ever operate at flow rates approaching capacity; in most cases, poor operating quality has led to improvements or reconstruction long before capacity demand is reached.

The quality of service for bicycles is primarily affected by the speed and volume of adjacent traffic flows and by the degree of separation between bicyclist and motor vehicle traffic allowed by the roadway geometry.

Chapter 15, Two-Lane Highways, 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. In general, any segment that is 2.0 to 3.0 mi from the nearest signalized intersection would fit into this category. Where signalized intersections are less than 2.0 mi apart, the facility should be classified as an urban street and analyzed with the methodologies of Chapter 16, Urban Street Facilities, and Chapter 17, Urban Street Segments, which are located in Volume 3. It is assumed that no passing in the opposing lane occurs on urban streets.

Chapter 15 also includes a methodology for predicting the effect of passing and truck climbing lanes on two-lane highways.

CHARACTERISTICS OF TWO-LANE HIGHWAYS

Functions of Two-Lane Highways in Highway Systems

Two-lane highways are a key element in the highway systems of most states and counties. They are located in many different geographical areas and serve a wide variety of traffic functions. Two-lane highways also serve a number of bicycle trips, particularly recreational trips. Any consideration of operating quality criteria must account for these disparate functions.

The functions of two-lane highways include efficient mobility, accessibility, scenic and recreational enjoyment, and service to small towns and communities.

Efficient mobility is the principal function of major two-lane highways that connect major trip generators or that serve as primary links in state and national highway networks. These routes tend to serve long-distance commercial and recreational travelers, and long sections may pass through rural areas without traffic control interruptions. Consistent high-speed operations and infrequent passing delays are desirable for these types of facilities.

Other paved, two-lane rural highways primarily provide *accessibility* to remote or sparsely populated areas. Such highways provide reliable all-weather access and often serve low traffic demands. Cost-effective access is a primary concern. Although high speed is beneficial, it is not the principal objective. Delay, as indicated by the formation of platoons, is a more relevant measure of service quality.

Two-lane roads also serve *scenic and recreational* areas in which the vista and environment are meant to be experienced and enjoyed without traffic interruption or delay. High-speed operation is neither expected nor desired. Passing delays, however, significantly distract from the scenic enjoyment of trips and should be minimized whenever possible.

Two-lane roads may also pass through and serve *small towns and communities*. Such areas have higher-density development than would normally be expected along a rural highway, and speed limits in these areas are often lower. In these cases, drivers expect to be able to maintain speeds close to the posted limit. Since two-lane highway segments serving such developed areas are usually of limited length, passing delays are not a significant issue.

Two-lane highways serve a wide range of functions and serve a variety of rural areas, as well as more developed areas. Therefore, this chapter's methodology and level of service (LOS) criteria provide flexibility to encompass the resulting range of driver expectations.

Classification of Two-Lane Highways

Because of the wide range of functions served by two-lane highways, the automobile methodology establishes three classes of highways.

The first two classes address *rural two-lane highways*. The methodology for them was developed as part of National Cooperative Highway Research Program (NCHRP) Project 3-55(3) in 1999 (*1*) and revised as part of NCHRP Project 20-7(160) in 2003 (*2*).

The third class addresses two-lane highways in *developed areas*. The analysis approach for these highways is a modification of the rural highway method noted previously and was developed by the Florida Department of Transportation (FDOT) (*3*). This modification has not been subjected to a national calibration study and is based on the procedure developed and adopted by FDOT. It is presented here as an alternative procedure, since it is based entirely on information collected in Florida. For clarity, however, the material is integrated into the overall presentation and is not discussed separately as an alternative procedure.

The three classes of two-lane highways are defined as follows:

- *Class I two-lane highways* are highways where motorists expect to travel at relatively high speeds. Two-lane highways that are major intercity routes, primary connectors of major traffic generators, daily commuter routes, or major links in state or national highway networks are generally assigned to Class I. These facilities serve mostly long-distance trips or provide the connections between facilities that serve long-distance trips.
- *Class II two-lane highways* are highways where motorists do not necessarily expect to travel at high speeds. Two-lane highways functioning as access routes to Class I facilities, serving as scenic or recreational routes (and not as primary arterials), or passing through rugged terrain (where high-speed operation would be impossible) are assigned to Class II. Class II facilities most often serve relatively short trips, the beginning or ending portions of longer trips, or trips for which sightseeing plays a significant role.
- *Class III two-lane highways* are highways serving moderately developed areas. They may be portions of a Class I or Class II highway that pass through small towns or developed recreational areas. On such segments, local traffic often mixes with through traffic, and the density of unsignalized roadside access points is noticeably higher than in a purely rural area. Class III highways may also be longer segments passing through more spread-out recreational areas, also with increased roadside densities. Such segments are often accompanied by reduced speed limits that reflect the higher activity level.

Exhibit 15-1 shows examples of the three classes of two-lane highway.

The definition of two-lane highway classes is based on their function. Most arterials or trunk roads are considered to be Class I highways, while most collectors and local roads are considered to be Class II or Class III highways. The primary determinant of a facility's classification is the motorist's expectation, which might not agree with the overall functional category of the route. For example, a major intercity route passing through a rugged mountainous area might be described as Class II if drivers recognize that high-speed operation is not feasible due to the terrain, but the route could still be considered to be in Class I.

Even Class III highways incorporate only uninterrupted-flow segments of two-lane highways. Occasional signalized or unsignalized intersections on any two-lane highway must be separately analyzed with the appropriate *Highway Capacity Manual* (HCM) methodologies in Chapter 18, Signalized Intersections, Chapter 20, All-Way STOP-Controlled Intersections, or Chapter 21, Roundabouts. The results must be carefully considered in conjunction with those of uninterrupted-flow portions of the facility to obtain a complete picture of probable operations.

Exhibit 15-1
Two-Lane Highway
Classification Illustrated

(a) Examples of Class I Two-Lane Highways

(b) Examples of Class II Two-Lane Highways

(c) Examples of Class III Two-Lane Highways

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). The methodology of this chapter 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 shoulders wider than or equal to 6 ft,
- No no-passing zones,
- All passenger cars in the traffic stream,

- Level terrain, and
- No impediments to through traffic (e.g., traffic signals, turning vehicles).

Traffic can operate ideally 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 they may increase percent time-spent-following (PTSF) as well.

The length and frequency of no-passing zones are a result of the roadway alignment. No-passing zones may be marked by barrier centerlines in one or both directions, but any segment with a passing sight distance of less than 1,000 ft should also be considered to be a no-passing zone.

On a two-lane highway, passing in the opposing lane of flow may be necessary. It is the only way to fill gaps forming in front of slow-moving vehicles in the traffic stream. Restrictions on the ability to pass significantly increase the rate at which platoons form in the traffic stream, since motorists are unable to pass slower vehicles in front of them.

Basic Relationships

Exhibit 15-2 shows the relationships among flow rate, average travel speed (ATS), and PTSF for an extended directional segment of two-lane highway under base conditions. While the two directions of flow interact on a two-lane highway (because of passing maneuvers), the methodology of this chapter analyzes each direction separately.

Exhibit 15-2(b) illustrates a critical characteristic that affects two-lane highways. Low directional volumes create high values of PTSF. With only 800 pc/h, PTSF ranges from 60% (with 200 pc/h opposing flow) to almost 80% (with 1,600 pc/h opposing flow).

In multilane uninterrupted flow, typically acceptable speeds can be maintained at relatively high proportions of capacity. On two-lane highways, service quality (as measured by PTSF) begins to deteriorate at relatively low demand flows.

CAPACITY AND LOS

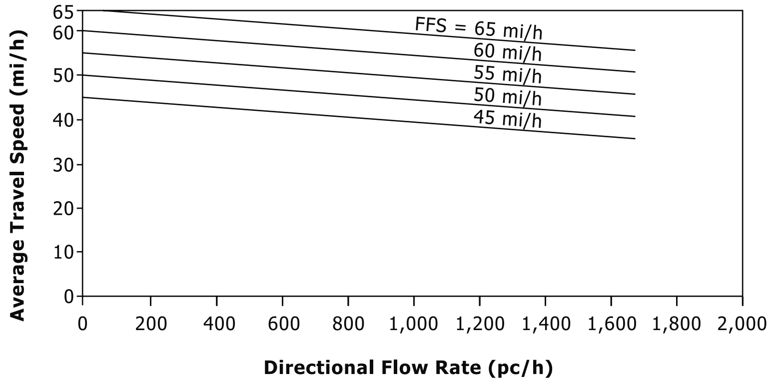
Capacity

The capacity of a two-lane highway under base conditions is 1,700 pc/h in one direction, with a limit of 3,200 pc/h for the total of the two directions. Because of the interactions between directional flows, when a capacity of 1,700 pc/h is reached in one direction, the maximum opposing flow would be limited to 1,500 pc/h.

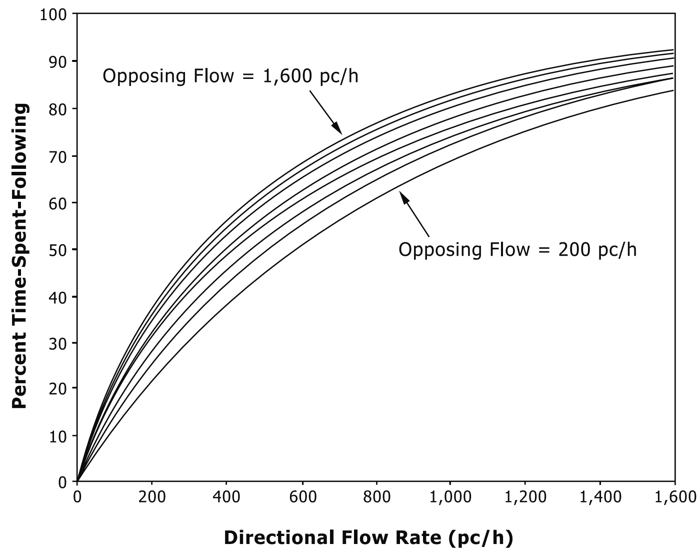
Capacity of a two-lane highway under base conditions is 1,700 pc/h in one direction, with a maximum of 3,200 pc/h in the two directions.

Capacity conditions, however, are rarely observed—except in short segments. Because service quality deteriorates at relatively low demand flow rates, most two-lane highways are upgraded before demand approaches capacity.

Exhibit 15-2
Speed–Flow and PTSF Relationships for Directional Segments with Base Conditions



(a) ATS Versus Directional Flow Rate



(b) PTSF Versus Directional Flow Rate

Capacity is important for evacuation and special event planning.

However, estimation of capacity conditions is important for evacuation planning, special event planning, and evaluation of the downstream impacts of incident bottlenecks once cleared.

Two-way flow rates as high as 3,400 pc/h can be observed for short segments fed by high demands from multiple or multilane facilities. This may occur at tunnels or bridges, for example, but such flow rates cannot be expected over extended segments.

Capacity is not defined for bicycles on two-lane highways because of lack of data. Bicycle volumes approaching capacity do not often occur on two-lane highways except during special bicycle events, and little information is available on which to base a definition.

Levels of Service

Automobile Mode

Because of the wide range of situations in which two-lane highways are found, three measures of effectiveness are incorporated into the methodology of this chapter to determine automobile LOS.

1. *ATS* reflects mobility on a two-lane highway. It is defined as the highway segment length divided by the average travel time taken by vehicles to traverse it during a designated time interval.
2. *PTSF* represents the freedom to maneuver and the comfort and convenience of travel. It is the average percentage of time that vehicles must travel in platoons behind slower vehicles due to the inability to pass. Because this characteristic is difficult to measure in the field, a surrogate measure is the percentage of vehicles traveling at headways of less than 3.0 s at a representative location within the highway segment. PTSF also represents the approximate percentage of vehicles traveling in platoons.
3. *Percent of free-flow speed* (*PFFS*) represents the ability of vehicles to travel at or near the posted speed limit.

On Class I two-lane highways, speed and delay due to passing restrictions are both important to motorists. Therefore, on these highways, LOS is defined in terms of both ATS and PTSF. On Class II highways, travel speed is not a significant issue to drivers. Therefore, on these highways, LOS is defined in terms of PTSF only. On Class III highways, high speeds are not expected. Because the length of Class III segments is generally limited, passing restrictions are also not a major concern. In these cases, drivers would like to make steady progress at or near the speed limit. Therefore, on these highways, PFFS is used to define LOS. The LOS criteria for two-lane highways are shown in Exhibit 15-3.

Exhibit 15-3
Automobile LOS for Two-Lane Highways

LOS	Class I Highways		Class II Highways	Class III Highways
	ATS (mi/h)	PTSF (%)	PTSF (%)	PFFS (%)
A	>55	≤35	≤40	>91.7
B	>50–55	>35–50	>40–55	>83.3–91.7
C	>45–50	>50–65	>55–70	>75.0–83.3
D	>40–45	>65–80	>70–85	>66.7–75.0
E	≤40	>80	>85	≤66.7

Because driver expectations and operating characteristics on the three categories of two-lane highways are quite different, it is difficult to provide a single definition of operating conditions at each LOS.

Two characteristics, however, have a significant impact on actual operations and driver perceptions of service:

- *Passing capacity*: Since passing maneuvers on two-lane highways are made in the opposing direction of flow, the ability to pass is limited by the opposing flow rate and by the distribution of gaps in the opposing flow.
- *Passing demand*: As platooning and PTSF increase in a given direction, the demand for passing maneuvers increases. As more drivers are caught in a

platoon behind a slow-moving vehicle, they will desire to make more passing maneuvers.

Both passing capacity and passing demand are related to flow rates. If flow in both directions increases, a difficult trend is established: as passing demand increases, passing capacity decreases.

At LOS A, motorists experience high operating speeds on Class I highways and little difficulty in passing. Platoons of three or more vehicles are rare. On Class II highways, speed would be controlled primarily by roadway conditions. A small amount of platooning would be expected. On Class III highways, drivers should be able to maintain operating speeds close or equal to the free-flow speed (FFS) of the facility.

At LOS B, passing demand and passing capacity are balanced. On both Class I and Class II highways, the degree of platooning becomes noticeable. Some speed reductions are present on Class I highways. On Class III highways, it becomes difficult to maintain FFS operation, but the speed reduction is still relatively small.

At LOS C, most vehicles are traveling in platoons. Speeds are noticeably curtailed on all three classes of highway.

At LOS D, platooning increases significantly. Passing demand is high on both Class I and II facilities, but passing capacity approaches zero. A high percentage vehicles are now traveling in platoons, and PTSF is quite noticeable. On Class III highways, the fall-off from FFS is now significant.

At LOS E, demand is approaching capacity. Passing on Class I and II highways is virtually impossible, and PTSF is more than 80%. Speeds are seriously curtailed. On Class III highways, speed is less than two-thirds the FFS. The lower limit of this LOS represents capacity.

LOS F exists whenever demand flow in one or both directions exceeds the capacity of the segment. Operating conditions are unstable, and heavy congestion exists on all classes of two-lane highway.

Bicycle Mode

Bicycle LOS is based on a traveler-perception model.

Bicycle levels of service for two-lane 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 highways are given in Exhibit 15-4. The same LOS score is used for multilane highways, as described in Chapter 14.

Exhibit 15-4
Bicycle LOS for Two-Lane 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

REQUIRED INPUT DATA AND DEFAULT VALUES

Exhibit 15-5 lists the information necessary to apply the methodology. It also contains suggested default values for use when segment-specific information is not available. The user is cautioned, however, that every use of a default value instead of a field-measured, segment-specific variable makes the analysis results more approximate and less related to the specific conditions that describe the study site. Defaults should be used only when field measurements cannot be collected.

Exhibit 15-5
Required Input Data and Default Values for Two-Lane Highways

Required Data	Recommended Default Value	Relevant Modes
	Geometric Data	
Highway class	Must select as appropriate	Auto
Lane width	12 ft	Auto, bicycle
Shoulder width	6 ft	Auto, bicycle
Access-point density (one side)	Classes I and II: 8/mi, Class III: 16/mi	Auto
Terrain	Level or rolling	Auto
Percent no-passing zone[a]	Level: 20%, rolling: 40%, more extreme: 80%	Auto
Speed limit	Speed limit	Bicycle
Base design speed	Speed limit + 10 mi/h	Auto
Length of passing lane (if present)	Must be site-specific	Auto
Pavement condition	4 on FHWA 5-point rating scale (good)	Bicycle
	Demand Data	
Hourly automobile volume	Must be site-specific	Auto, bicycle
Length of analysis period	15 min (0.25 h)	Auto, bicycle
Peak hour factor	0.88	Auto, bicycle
Directional split	60/40	Auto, bicycle
Heavy vehicle percentage[b]	6% trucks	Auto, bicycle
Percent occupied on-highway parking	0%	Bicycle

Notes: [a] Percent no-passing zone may be different in each direction.
[b] See Chapter 26 in Volume 4 for state-specific default heavy vehicle percentages.

The use of some default values is less problematic than others. Lane and shoulder widths of 12 and 6 ft, respectively, are common, particularly on Class I highways. However, these variables have large impacts on bicycle LOS, increasing the importance of segment-specific data. A general assessment of terrain is usually straightforward and requires only general knowledge of the area through which the highway is built. Access-point densities are more difficult and tend to vary widely on a site-by-site basis. Estimating the percent no-passing zones on the basis of a generalized assessment of terrain is also challenging, since the details of vertical and horizontal alignment can have a significant impact on this factor.

FFS is best measured at the site or at a similar site. While adjustments to a base free-flow speed (BFFS) are provided as part of the methodology, no firm guidance on determining the BFFS is given. The default suggestions of Exhibit 15-5 are highly approximate.

In terms of demand data, the length of the analysis period is a recommended HCM standard of 15 min (although longer periods can be examined). The peak hour factor (PHF) is typical but could vary significantly on the basis of localized trip generation characteristics. The directional split is best observed directly, since it can vary widely over time, even at the same location. The recommended default for heavy vehicle presence is also highly approximate. This factor varies widely with local conditions; Chapter 26, Freeway and Highway Segments: Supplemental, provides state-specific default values (*4*).

As is the case with all default values, these values should be used with care, and only when site-specific data cannot be acquired by any reasonable means.

DEMAND VOLUMES AND FLOW RATES

Demand volumes are generally stated in vehicles per hour under prevailing conditions. They are converted in the methodology to demand flow rates in passenger cars per hour under base conditions. The PHF, in particular, is used to convert hourly volumes to flow rates.

If demand volumes are measured in 15-min increments, use of the PHF to convert to flow rates is unnecessary. The worst 15-min period is selected, and flow rates are the 15-min volumes multiplied by 4. When this is done, the PHF is set at 1.00 for the rest of the application.

In measuring demand volumes or flow rates, flow may be restricted by upstream bottlenecks or even signals that are more than 2 mi away from the study site (if they are closer, this methodology is not applicable). Downstream congestion may also affect flows in a study segment. Insofar as is possible, demand volumes and flow rates should reflect the situation that would exist with no upstream or downstream limiting factors.

2. METHODOLOGY

This section presents the details of the methodology for two-lane highways and documents its use in planning and operational analysis applications.

SCOPE OF THE METHODOLOGY

This chapter presents an operational analysis methodology for directional segments of two-lane highways for automobiles and bicyclists. Both directions may be analyzed separately on the facility or segment to obtain a full estimate of operating conditions.

This chapter's automobile methodology addresses the analysis of

- Directional segments in general terrain (level or rolling),
- Directional segments on specific grades, and
- Directional segments including passing and truck climbing lanes.

All segments in mountainous terrain, and all grades of 3% or more that cover a length of 0.6 mi or more, must be analyzed as specific grades.

The methodology is most directly used to determine the LOS on a uniform directional segment of two-lane highway by estimating the measures of effectiveness that define LOS (ATS, PTSF, PFFS). 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.

This chapter includes an appendix that addresses specialized treatments for two-lane highways that cannot be evaluated with the basic methodology. Special procedures are also provided to determine the impact of passing lanes or truck climbing lanes in two-lane highway segments.

LIMITATIONS OF THE METHODOLOGY

The operational analysis methodologies in this chapter do not address two-lane highways with signalized intersections. Isolated signalized intersections on two-lane highways may be evaluated with the methodology of Chapter 18, Signalized Intersections. Two-lane highways in urban and suburban areas with multiple signalized intersections 2 mi or less apart should be analyzed as urban streets or arterials with the methodology of Chapter 17, Urban Street Segments.

The bicycle 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 (*5*) 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: 45 to 50 mi/h;
- Heavy vehicle percentage: 0% to 2%; and
- Pavement condition: 1 to 5 on the Federal Highway Administration (FHWA) 5-point pavement rating scale.

The bicycle LOS methodology also 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.

AUTOMOBILE MODE

Overview

Exhibit 15-6 illustrates the basic steps in the methodology for two-lane highways. Because the three classes of highways use different service measures to determine LOS, not all steps are applied to each class of facility.

Note that the computational step for estimating ATS applies only to Class I and Class III highways, while the step for estimating PTSF applies only to Class I and Class II highways. The step for estimating PFFS applies only to Class III highways.

Segments for Analysis

The methodology of this chapter applies to uniform directional segments of two-lane highway. While the two directions of flow interact through passing maneuvers (and limitations on passing maneuvers), each direction must be analyzed separately.

Uniform segments have the same or similar traffic and roadway conditions. Segment boundaries should be established at points where a change occurs in any of the following: terrain, lane widths or shoulder width, facility classification, or demand flow rate.

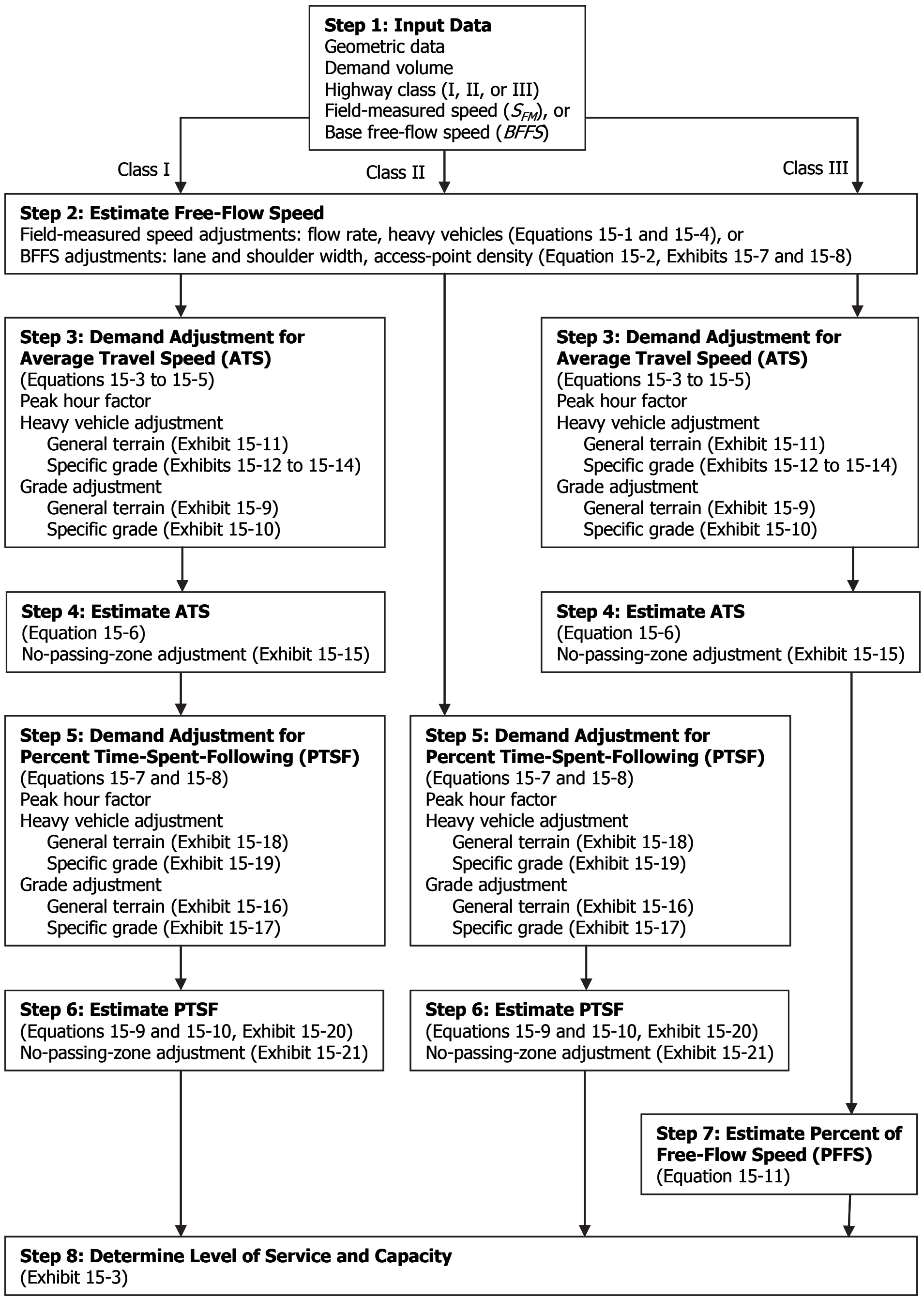


Exhibit 15-6
Flowchart of the Two-Lane Highway Methodology

Computational Steps

Step 1: Input Data

Exhibit 15-5 lists the information that must be available before a two-lane highway segment can be analyzed. The exhibit also lists default values suggested for use when site-specific data are not available.

Step 2: Estimate the FFS

A key step in the analysis of a two-lane highway is the determination of the FFS for the segment. There are three ways to estimate FFS.

Direct Field Measurement

Direct field measurement on the subject highway segment is preferred. Measurements should be taken only in the direction under analysis; if both directions are to be analyzed, then separate measurements in each direction are made. Each directional measurement should be based on a random 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).

If the analysis segment cannot be directly observed, then measurements from a similar facility (same highway class, same speed limit, similar environment, etc.) may be used.

Field Measurements at Higher Flow Rates

For some highways, it may be difficult or impossible to observe total flow rates less than 200 veh/h. In such cases, a speed sample may be taken at higher flow rates and adjusted accordingly. The same sampling approach is taken: each direction is separately observed, with each directional sample including at least 100 observed speeds. The measured mean speed is then adjusted with Equation 15-1:

Equation 15-1

$$FFS = S_{FM} + 0.00776\left(\frac{v}{f_{HV,ATS}}\right)$$

where

FFS = free-flow speed (mi/h);

S_{FM} = mean speed of sample ($v > 200$ veh/h) (mi/h);

v = total demand flow rate, both directions, during period of speed measurements (veh/h); and

$f_{HV,ATS}$ = heavy vehicle adjustment factor for ATS, from Equation 15-4 or Equation 15-5.

Estimating FFS

FFS on two-lane highways ranges from 45 mi/h to as high as 70 mi/h. BFFS reflects alignment of the facility and the nature of traffic.

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 45 mi/h to as high as 70 mi/h. To estimate the FFS, the analyst must characterize the operating conditions of the facility in terms of a BFFS that reflects the nature of the traffic and the alignment of the facility. Unfortunately, because of the broad range of speeds that occur and the importance of local and regional factors that influence driver-desired speeds, little guidance on estimating the BFFS can be given.

Estimates of BFFS can be developed on the basis of speed data and local knowledge of operating conditions on similar facilities. As will be seen, once the BFFS is determined, adjustments for lane and shoulder widths and for the density of unsignalized access points are applied to estimate the FFS. In concept, the BFFS is the speed that would be expected on the basis of the facility's horizontal and vertical alignment, if standard lane and shoulder widths were present and there were no roadside access points. Thus, the *design speed* of the facility might be an acceptable estimator of BFFS, since it is based primarily on horizontal and vertical alignment. Posted speed limits may not reflect current conditions or driver desires. A rough estimate of BFFS might be taken as the posted speed limit plus 10 mi/h.

Once a BFFS is determined, the actual FFS may be estimated as follows:

Equation 15-2

$$FFS = BFFS - f_{LS} - f_A$$

where

FFS = free-flow speed (mi/h),

$BFFS$ = base free-flow speed (mi/h),

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

f_A = adjustment for access-point density (mi/h).

When field measurements are used to estimate FFS, standard approaches and sampling techniques should be applied. Guidance on field speed studies is provided in standard traffic engineering texts and elsewhere (*3*).

Adjustment factors for use in Equation 15-2 are found in Exhibit 15-7 (lane and shoulder width) and Exhibit 15-8 (access-point density).

Exhibit 15-7
Adjustment Factor for Lane and Shoulder Width (f_{LS})

Lane Width (ft)	Shoulder Width (ft)			
	≥0 <2	≥2 <4	≥4 <6	≥6
≥9 <10	6.4	4.8	3.5	2.2
≥10 <11	5.3	3.7	2.4	1.1
≥ 11 <12	4.7	3.0	1.7	0.4
≥12	4.2	2.6	1.3	0.0

Exhibit 15-8
Adjustment Factor for Access-Point Density (f_A)

Access Points per Mile (Two Directions)	Reduction in FFS (mi/h)
0	0.0
10	2.5
20	5.0
30	7.5
40	10.0

Note: Interpolation to the nearest 0.1 is recommended.

The access-point density is computed by dividing the total number of unsignalized intersections and driveways on *both* sides of the roadway segment by the length of the segment (in miles). Thus, in analyzing the two directions of the highway and estimating the FFS, the FFS will be the same in *both* directions. If the FFS is measured in the field, the value could be different in each direction.

If a highway contains sharp horizontal curves with design speeds substantially below those of the rest of the segment, it may be desirable to determine the FFS separately for curves and tangents and to compute a weighted-average FFS for the segment as a whole.

The data for FFS relationships in this chapter include both commuter and noncommuter traffic. There were no significant differences between the two. However, it is expected that commuters and other regular users will use a facility more efficiently than recreational and other occasional users. If the effect of driver population is a concern, the FFS should be measured in the field.

Step 3: Demand Adjustment for ATS

This computational step is applied only in cases of Class I and Class III two-lane highways. LOS on Class II highways is not based on ATS, and therefore this step is skipped for those highways.

Demand volumes in both directions (analysis direction and opposing direction) must be converted to flow rates under equivalent base conditions with Equation 15-3:

Equation 15-3

$$v_{i,ATS} = \frac{V_i}{PHF \times f_{g,ATS} \times f_{HV,ATS}}$$

where

$v_{i,ATS}$ = demand flow rate i for ATS estimation (pc/h);

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

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

$f_{g,ATS}$ = grade adjustment factor, from Exhibit 15-9 or Exhibit 15-10; and

$f_{HV,ATS}$ = heavy vehicle adjustment factor, from Equation 15-4 or Equation 15-5.

PHF

The PHF represents the variation in traffic flow within the hour. Two-lane highway analysis is based on the demand flow rates for a peak 15-min period within the analysis hour—usually (but not necessarily) the peak hour. If flow rates for the peak 15 min have been directly measured, the PHF used in Equation 15-3 is set equal to 1.00.

ATS Grade Adjustment Factor

The grade adjustment factor $f_{g,ATS}$ depends on the terrain. Factors are defined for

- Extended segments (≥2 mi) of level terrain,
- Extended segments (≥2 mi) of rolling terrain,
- Specific upgrades, and
- Specific downgrades.

Any grade of 3% or steeper and 0.6 mi or longer *must* be analyzed as a specific upgrade or downgrade, depending on the analysis direction being considered. However, a grade of 3% or more *may* be analyzed as a specific grade if it is 0.25 mi or longer.

Exhibit 15-9 shows grade adjustment factors for extended segments of level and rolling terrain, as well as for specific downgrades. Exhibit 15-9 is entered with the one-direction demand flow rate v_{vph}, in vehicles per hour.

Exhibit 15-9
ATS Grade Adjustment Factor ($f_{g,ATS}$) for Level Terrain, Rolling Terrain, and Specific Downgrades

One-Direction Demand Flow Rate, v_{vph} (veh/h)	Adjustment Factor	
	Level Terrain and Specific Downgrades	Rolling Terrain
≤100	1.00	0.67
200	1.00	0.75
300	1.00	0.83
400	1.00	0.90
500	1.00	0.95
600	1.00	0.97
700	1.00	0.98
800	1.00	0.99
≥900	1.00	1.00

Note: Interpolation to the nearest 0.01 is recommended.

If demand is expressed as an hourly volume, it must be divided by the PHF ($v_{vph} = V/PHF$) to obtain the appropriate factor. Other adjustment factor tables associated with Equation 15-3 are entered with this value as well.

Note that the adjustment factor for level terrain is 1.00, since level terrain is one of the base conditions. For the purposes of grade adjustment, specific downgrade segments are treated as level terrain.

Exhibit 15-10 shows grade adjustment factors for specific upgrades. The negative impact of upgrades on two-lane highway speeds increases as both the severity of the upgrade and its length increase. The impact, however, declines as demand flow rate increases. At higher demand flow rates, lower speeds would already result, and the additional impact of the upgrades is less severe.

ATS Heavy Vehicle Adjustment Factor

The base conditions for two-lane highways include 100% passenger cars in the traffic stream. This is a rare occurrence, and the presence of heavy vehicles in the traffic stream reduces the ATS.

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 are classified as trucks or recreational vehicles (RVs). Trucks cover a wide variety of vehicles from small pickup and panel trucks with more than four wheels to double and triple tractor–trailer units. Small pickup and panel trucks with only four wheels are classified as passenger cars. All school, transit, or intercity buses are classified as trucks. The RV classification also covers a wide range of vehicles, including motorized campers, motor homes, and cars or small trucks that are towing trailers.

Exhibit 15-10
ATS Grade Adjustment Factor ($f_{g,ATS}$) for Specific Upgrades

Grade (%)	Grade Length (mi)	Directional Demand Flow Rate, v_{vph} (veh/h)								
		≤100	**200**	**300**	**400**	**500**	**600**	**700**	**800**	**≥900**
≥3 <3.5	0.25	0.78	0.84	0.87	0.91	1.00	1.00	1.00	1.00	1.00
	0.50	0.75	0.83	0.86	0.90	1.00	1.00	1.00	1.00	1.00
	0.75	0.73	0.81	0.85	0.89	1.00	1.00	1.00	1.00	1.00
	1.00	0.73	0.79	0.83	0.88	1.00	1.00	1.00	1.00	1.00
	1.50	0.73	0.79	0.83	0.87	0.99	0.99	1.00	1.00	1.00
	2.00	0.73	0.79	0.82	0.86	0.98	0.98	0.99	1.00	1.00
	3.00	0.73	0.78	0.82	0.85	0.95	0.96	0.96	0.97	0.98
	≥4.00	0.73	0.78	0.81	0.85	0.94	0.94	0.95	0.95	0.96
≥3.5 <4.5	0.25	0.75	0.83	0.86	0.90	1.00	1.00	1.00	1.00	1.00
	0.50	0.72	0.80	0.84	0.88	1.00	1.00	1.00	1.00	1.00
	0.75	0.67	0.77	0.81	0.86	1.00	1.00	1.00	1.00	1.00
	1.00	0.65	0.73	0.77	0.81	0.94	0.95	0.97	1.00	1.00
	1.50	0.63	0.72	0.76	0.80	0.93	0.95	0.96	1.00	1.00
	2.00	0.62	0.70	0.74	0.79	0.93	0.94	0.96	1.00	1.00
	3.00	0.61	0.69	0.74	0.78	0.92	0.93	0.94	0.98	1.00
	≥4.00	0.61	0.69	0.73	0.78	0.91	0.91	0.92	0.96	1.00
≥4.5 <5.5	0.25	0.71	0.79	0.83	0.88	1.00	1.00	1.00	1.00	1.00
	0.50	0.60	0.70	0.74	0.79	0.94	0.95	0.97	1.00	1.00
	0.75	0.55	0.65	0.70	0.75	0.91	0.93	0.95	1.00	1.00
	1.00	0.54	0.64	0.69	0.74	0.91	0.93	0.95	1.00	1.00
	1.50	0.52	0.62	0.67	0.72	0.88	0.90	0.93	1.00	1.00
	2.00	0.51	0.61	0.66	0.71	0.87	0.89	0.92	0.99	1.00
	3.00	0.51	0.61	0.65	0.70	0.86	0.88	0.91	0.98	0.99
	≥4.00	0.51	0.60	0.65	0.69	0.84	0.86	0.88	0.95	0.97
≥5.5 <6.5	0.25	0.57	0.68	0.72	0.77	0.93	0.94	0.96	1.00	1.00
	0.50	0.52	0.62	0.66	0.71	0.87	0.90	0.92	1.00	1.00
	0.75	0.49	0.57	0.62	0.68	0.85	0.88	0.90	1.00	1.00
	1.00	0.46	0.56	0.60	0.65	0.82	0.85	0.88	1.00	1.00
	1.50	0.44	0.54	0.59	0.64	0.81	0.84	0.87	0.98	1.00
	2.00	0.43	0.53	0.58	0.63	0.81	0.83	0.86	0.97	0.99
	3.00	0.41	0.51	0.56	0.61	0.79	0.82	0.85	0.97	0.99
	≥4.00	0.40	0.50	0.55	0.61	0.79	0.82	0.85	0.97	0.99
≥6.5	0.25	0.54	0.64	0.68	0.73	0.88	0.90	0.92	1.00	1.00
	0.50	0.43	0.53	0.57	0.62	0.79	0.82	0.85	0.98	1.00
	0.75	0.39	0.49	0.54	0.59	0.77	0.80	0.83	0.96	1.00
	1.00	0.37	0.45	0.50	0.54	0.74	0.77	0.81	0.96	1.00
	1.50	0.35	0.45	0.49	0.54	0.71	0.75	0.79	0.96	1.00
	2.00	0.34	0.44	0.48	0.53	0.71	0.74	0.78	0.94	0.99
	3.00	0.34	0.44	0.48	0.53	0.70	0.73	0.77	0.93	0.98
	≥4.00	0.33	0.43	0.47	0.52	0.70	0.73	0.77	0.91	0.95

Note: Straight-line interpolation of $f_{g,ATS}$ for length of grade and demand flow permitted to the nearest 0.01.

Exhibit 15-11
ATS Passenger Car Equivalents for Trucks (E_T) and RVs (E_R) for Level Terrain, Rolling Terrain, and Specific Downgrades

Vehicle Type	Directional Demand Flow Rate, v_{vph} (veh/h)	Level Terrain and Specific Downgrades	Rolling Terrain
Trucks, E_T	≤100	1.9	2.7
	200	1.5	2.3
	300	1.4	2.1
	400	1.3	2.0
	500	1.2	1.8
	600	1.1	1.7
	700	1.1	1.6
	800	1.1	1.4
	≥900	1.0	1.3
RVs, E_R	All flows	1.0	1.1

Note: Interpolation to the nearest 0.1 is recommended.

Determining the heavy vehicle adjustment factor is a two-step process:

1. Passenger car equivalents are found for trucks (E_T) and RVs (E_R) under prevailing conditions.
2. A heavy vehicle adjustment factor is computed from the passenger car equivalents with Equation 15-4:

$$f_{HV,ATS} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

Equation 15-4

where

$f_{HV,ATS}$ = heavy vehicle adjustment factor for ATS estimation,

P_T = proportion of trucks in the traffic stream (decimal),

P_R = proportion of RVs in the traffic stream (decimal),

E_T = passenger car equivalent for trucks from Exhibit 15-11 or Exhibit 15-12, and

E_R = passenger car equivalent for RVs from Exhibit 15-11 or Exhibit 15-13.

The passenger car equivalent is the number of passenger cars displaced from the traffic stream by one truck or RV. Passenger car equivalents are defined for several situations:

- Extended sections of general level or rolling terrain,
- Specific upgrades, and
- Specific downgrades.

Exhibit 15-11 contains passenger car equivalents for trucks and RVs in general terrain segments and for specific downgrades, which are treated as level terrain in most cases. A special procedure is provided in the next section to evaluate specific downgrades on which significant numbers of trucks must reduce their speed to crawl speed to maintain control.

Exhibit 15-12 and Exhibit 15-13 show passenger car equivalents for trucks and RVs, respectively, on specific upgrades.

ATS Passenger Car Equivalents for Specific Downgrades Where Trucks Travel at Crawl Speed

As noted previously, any downgrade of 3% or more *and* 0.6 mi or longer must be analyzed as a specific downgrade. If the slope of the downgrade varies, it should be analyzed as a single composite by using an average grade computed by dividing the total change in elevation by the total length of grade and expressing the result as a percentage.

Most specific downgrades will be treated as level terrain for analysis purposes. Some downgrades, however, are severe enough to force some trucks into crawl speed. In such cases, the truck drivers are forced to operate in a low gear to apply engine braking, since the normal brake system would not be sufficient to slow or stop a heavy vehicle from gaining too much momentum as it travels down a sharp downgrade. There are no general guidelines for identifying when or where these situations will occur, other than direct observation of heavy vehicle operations.

Exhibit 15-12
ATS Passenger Car Equivalents for Trucks (E_T) on Specific Upgrades

Grade (%)	Grade Length (mi)	Directional Demand Flow Rate, v_{vph} (veh/h) ≤100	200	300	400	500	600	700	800	≥900
≥3 <3.5	0.25	2.6	2.4	2.3	2.2	1.8	1.8	1.7	1.3	1.1
	0.50	3.7	3.4	3.3	3.2	2.7	2.6	2.6	2.3	2.0
	0.75	4.6	4.4	4.3	4.2	3.7	3.6	3.4	2.4	1.9
	1.00	5.2	5.0	4.9	4.9	4.4	4.2	4.1	3.0	1.6
	1.50	6.2	6.0	5.9	5.8	5.3	5.0	4.8	3.6	2.9
	2.00	7.3	6.9	6.7	6.5	5.7	5.5	5.3	4.1	3.5
	3.00	8.4	8.0	7.7	7.5	6.5	6.2	6.0	4.6	3.9
	≥4.00	9.4	8.8	8.6	8.3	7.2	6.9	6.6	4.8	3.7
≥3.5 <4.5	0.25	3.8	3.4	3.2	3.0	2.3	2.2	2.2	1.7	1.5
	0.50	5.5	5.3	5.1	5.0	4.4	4.2	4.0	2.8	2.2
	0.75	6.5	6.4	6.5	6.5	6.3	5.9	5.6	3.6	2.6
	1.00	7.9	7.6	7.4	7.3	6.7	6.6	6.4	5.3	4.7
	1.50	9.6	9.2	9.0	8.9	8.1	7.9	7.7	6.5	5.9
	2.00	10.3	10.1	10.0	9.9	9.4	9.1	8.9	7.4	6.7
	3.00	11.4	11.3	11.2	11.2	10.7	10.3	10.0	8.0	7.0
	≥4.00	12.4	12.2	12.2	12.1	11.5	11.2	10.8	8.6	7.5
≥4.5 <5.5	0.25	4.4	4.0	3.7	3.5	2.7	2.7	2.7	2.6	2.5
	0.50	6.0	6.0	6.0	6.0	5.9	5.7	5.6	4.6	4.2
	0.75	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
	1.00	9.2	9.2	9.1	9.1	9.0	9.0	9.0	8.9	8.8
	1.50	10.6	10.6	10.6	10.6	10.5	10.4	10.4	10.2	10.1
	2.00	11.8	11.8	11.8	11.8	11.6	11.6	11.5	11.1	10.9
	3.00	13.7	13.7	13.6	13.6	13.3	13.1	13.0	11.9	11.3
	≥4.00	15.3	15.3	15.2	15.2	14.6	14.2	13.8	11.3	10.0
≥5.5 <6.5	0.25	4.8	4.6	4.5	4.4	4.0	3.9	3.8	3.2	2.9
	0.50	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
	0.75	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
	1.00	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.2	10.1
	1.50	11.9	11.9	11.9	11.9	11.8	11.8	11.8	11.7	11.6
	2.00	12.8	12.8	12.8	12.8	12.7	12.7	12.7	12.6	12.5
	3.00	14.4	14.4	14.4	14.4	14.3	14.3	14.3	14.2	14.1
	≥4.00	15.4	15.4	15.3	15.3	15.2	15.1	15.1	14.9	14.8
≥6.5	0.25	5.1	5.1	5.0	5.0	4.8	4.7	4.7	4.5	4.4
	0.50	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8
	0.75	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	1.00	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.3	10.2
	1.50	12.0	12.0	12.0	12.0	11.9	11.9	11.9	11.8	11.7
	2.00	12.9	12.9	12.9	12.9	12.8	12.8	12.8	12.7	12.6
	3.00	14.5	14.5	14.5	14.5	14.4	14.4	14.4	14.3	14.2
	≥4.00	15.4	15.4	15.4	15.4	15.3	15.3	15.3	15.2	15.1

Note: Interpolation for length of grade and demand flow rate to the nearest 0.1 is recommended.

Exhibit 15-13
ATS Passenger Car Equivalents for RVs (E_R) on Specific Upgrades

Grade (%)	Grade Length (mi)	Directional Demand Flow Rate, v_{vph} (veh/h) ≤100	200	300	400	500	600	700	800	≥900
≥3 <3.5	≤0.25	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0
	>0.25 ≤0.75	1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.0	1.0
	>0.75 ≤1.25	1.3	1.2	1.2	1.1	1.0	1.0	1.0	1.0	1.0
	>1.25 ≤2.25	1.4	1.3	1.2	1.1	1.0	1.0	1.0	1.0	1.0
	>2.25	1.5	1.4	1.3	1.2	1.0	1.0	1.0	1.0	1.0
≥3.5 <4.5	≤0.75	1.3	1.2	1.2	1.1	1.0	1.0	1.0	1.0	1.0
	>0.75 ≤3.50	1.4	1.3	1.2	1.1	1.0	1.0	1.0	1.0	1.0
	>3.50	1.5	1.4	1.3	1.2	1.0	1.0	1.0	1.0	1.0
≥4.5 <5.5	≤2.50	1.5	1.4	1.3	1.2	1.0	1.0	1.0	1.0	1.0
	>2.50	1.6	1.5	1.4	1.2	1.0	1.0	1.0	1.0	1.0
≥5.5 <6.5	≤0.75	1.5	1.4	1.3	1.1	1.0	1.0	1.0	1.0	1.0
	>0.75 ≤2.50	1.6	1.5	1.4	1.2	1.0	1.0	1.0	1.0	1.0
	>2.50 ≤3.50	1.6	1.5	1.4	1.3	1.2	1.1	1.0	1.0	1.0
	>3.50	1.6	1.6	1.6	1.5	1.5	1.4	1.3	1.2	1.1
≥6.5	≤2.50	1.6	1.5	1.4	1.2	1.0	1.0	1.0	1.0	1.0
	>2.50 ≤3.50	1.6	1.5	1.4	1.2	1.3	1.3	1.3	1.3	1.3
	>3.50	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4

Note: Interpolation in this exhibit is not recommended.

When this situation exists, the heavy vehicle adjustment factor $f_{HV,ATS}$ is found with Equation 15-5 instead of Equation 15-4:

$$f_{HV,ATS} = \frac{1}{1 + P_{TC} \times P_T(E_{TC} - 1) + (1 - P_{TC}) \times P_T \times (E_T - 1) + P_R(E_R - 1)}$$

Equation 15-5

where

P_{TC} = proportion of trucks operating at crawl speed (decimal); and

E_{TC} = passenger car equivalent for trucks operating at crawl speed, from Exhibit 15-14.

All other variables are as previously defined. Note that P_{TC} is the flow rate of trucks traveling at crawl speed divided by the flow rate of all trucks.

Exhibit 15-14
ATS Passenger Car Equivalents (E_{TC}) for Trucks on Downgrades Traveling at Crawl Speed

Difference Between FFS and Truck Crawl Speed (mi/h)	Directional Demand Flow Rate, v_{vph} (veh/h)								
	≤100	200	300	400	500	600	700	800	≥900
≤15	4.7	4.1	3.6	3.1	2.6	2.1	1.6	1.0	1.0
20	9.9	8.7	7.8	6.7	5.8	4.9	4.0	2.7	1.0
25	15.1	13.5	12.0	10.4	9.0	7.7	6.4	5.1	3.8
30	22.0	19.8	17.5	15.6	13.1	11.6	9.2	6.1	4.1
35	29.0	26.0	23.1	20.1	17.3	14.6	11.9	9.2	6.5
≥40	35.9	32.3	28.6	24.9	21.4	18.1	14.7	11.3	7.9

Note: Interpolation against both speed difference and demand flow rate to the nearest 0.1 is recommended.

Step 4: Estimate the ATS

As was the case with Step 3, this step applies only to Class I and Class III two-lane highways. Class II highways do not use ATS as a LOS measure.

The ATS is estimated from the FFS, the demand flow rate, the opposing flow rate, and the percentage of no-passing zones in the analysis direction. The ATS is computed from Equation 15-6:

$$ATS_d = FFS - 0.00776(v_{d,ATS} + v_{o,ATS}) - f_{np,ATS}$$

Equation 15-6

where

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

FFS = free-flow speed (mi/h);

$v_{d,ATS}$ = demand flow rate for ATS determination in the analysis direction (pc/h);

$v_{o,ATS}$ = demand flow rate for ATS determination in the opposing direction (pc/h); and

$f_{np,ATS}$ = adjustment factor for ATS determination for the percentage of no-passing zones in the analysis direction, from Exhibit 15-15.

Exhibit 15-15
ATS Adjustment Factor for No-Passing Zones ($f_{np,ATS}$)

Opposing Demand Flow Rate, v_o (pc/h)	Percent No-Passing Zones ≤ 20	40	60	80	100
	FFS ≥ 65 mi/h				
≤100	1.1	2.2	2.8	3.0	3.1
200	2.2	3.3	3.9	4.0	4.2
400	1.6	2.3	2.7	2.8	2.9
600	1.4	1.5	1.7	1.9	2.0
800	0.7	1.0	1.2	1.4	1.5
1,000	0.6	0.8	1.1	1.1	1.2
1,200	0.6	0.8	0.9	1.0	1.1
1,400	0.6	0.7	0.9	0.9	0.9
≥1,600	0.6	0.7	0.7	0.7	0.8
	FFS = 60 mi/h				
≤100	0.7	1.7	2.5	2.8	2.9
200	1.9	2.9	3.7	4.0	4.2
400	1.4	2.0	2.5	2.7	3.9
600	1.1	1.3	1.6	1.9	2.0
800	0.6	0.9	1.1	1.3	1.4
1,000	0.6	0.7	0.9	1.1	1.2
1,200	0.5	0.7	0.9	0.9	1.1
1,400	0.5	0.6	0.8	0.8	0.9
≥1,600	0.5	0.6	0.7	0.7	0.7
	FFS = 55 mi/h				
≤100	0.5	1.2	2.2	2.6	2.7
200	1.5	2.4	3.5	3.9	4.1
400	1.3	1.9	2.4	2.7	2.8
600	0.9	1.1	1.6	1.8	1.9
800	0.5	0.7	1.1	1.2	1.4
1,000	0.5	0.6	0.8	0.9	1.1
1,200	0.5	0.6	0.7	0.9	1.0
1,400	0.5	0.6	0.7	0.7	0.9
≥1,600	0.5	0.6	0.6	0.6	0.7
	FFS = 50 mi/h				
≤100	0.2	0.7	1.9	2.4	2.5
200	1.2	2.0	3.3	3.9	4.0
400	1.1	1.6	2.2	2.6	2.7
600	0.6	0.9	1.4	1.7	1.9
800	0.4	0.6	0.9	1.2	1.3
1,000	0.4	0.4	0.7	0.9	1.1
1,200	0.4	0.4	0.7	0.8	1.0
1,400	0.4	0.4	0.6	0.7	0.8
≥1,600	0.4	0.4	0.5	0.5	0.5
	FFS ≤ 45 mi/h				
≤100	0.1	0.4	1.7	2.2	2.4
200	0.9	1.6	3.1	3.8	4.0
400	0.9	0.5	2.0	2.5	2.7
600	0.4	0.3	1.3	1.7	1.8
800	0.3	0.3	0.8	1.1	1.2
1,000	0.3	0.3	0.6	0.8	1.1
1,200	0.3	0.3	0.6	0.7	1.0
1,400	0.3	0.3	0.6	0.6	0.7
≥1,600	0.3	0.3	0.4	0.4	0.6

Note: Interpolation of $f_{np,ATS}$ for percent no-passing zones, demand flow rate, and FFS to the nearest 0.1 is recommended.

Exhibit 15-15 is entered with v_o in passenger cars per hour, not v_{vph} in vehicles per hour. At this point in the computational process, fully adjusted demand flow rates are available and are used in the determination of *ATS*. As shown in this exhibit, the effect of no-passing zones is greatest when opposing flow rates are low. As opposing flow rates increase, the effect decreases to zero, since passing and no-passing zones become irrelevant when the opposing flow rate allows no opportunities to pass.

Step 5: Demand Adjustment for PTSF

This computational step is applied only in cases of Class I and Class II two-lane highways. LOS on Class III highways is not based on PTSF, and therefore this step is skipped for those highways.

The demand volume adjustment process for estimating PTSF is structurally similar to that for ATS. The general approach is the same, but different adjustment factors are used, and the resulting adjusted flow rates will be different from those used in estimating ATS. Therefore, a detailed discussion of the process is not included here, since it is the same as that described for ATS estimates.

Equation 15-7 and Equation 15-8 are used to determine demand flow rates for the estimation of PTSF:

$$v_{i,PTSF} = \frac{V_i}{PHF \times f_{g,PTSF} \times f_{HV,PTSF}}$$

Equation 15-7

$$f_{HV,PTSF} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

Equation 15-8

where

$v_{i,PTSF}$ = demand flow rate i for determination of PTSF (pc/h);

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

$f_{g,PTSF}$ = grade adjustment factor for PTSF determination, from Exhibit 15-16 or Exhibit 15-17; and

$f_{HV,PTSF}$ = heavy vehicle adjustment factor for PTSF determination, from Exhibit 15-18 or Exhibit 15-19.

All other variables are as previously defined.

PTSF Grade Adjustment Factor

As was the case for the ATS adjustment process, grade adjustment factors are defined for general terrain segments (level or rolling), specific upgrades, and specific downgrades. Exhibit 15-16 gives the adjustment factors for general terrain segments and specific downgrades (which are treated as level terrain). Exhibit 15-17 shows adjustment factors for specific upgrades. These adjustments are used to compute demand flow rates, and the exhibits are again entered with $v_{vph} = V/PHF$.

Exhibit 15-16
PTSF Grade Adjustment Factor ($f_{g,PTSF}$) for Level Terrain, Rolling Terrain, and Specific Downgrades

Directional Demand Flow Rate, v_{vph} (veh/h)	Level Terrain and Specific Downgrades	Rolling Terrain
≤100	1.00	0.73
200	1.00	0.80
300	1.00	0.85
400	1.00	0.90
500	1.00	0.96
600	1.00	0.97
700	1.00	0.99
800	1.00	1.00
≥900	1.00	1.00

Note: Interpolation to the nearest 0.01 is recommended.

Exhibit 15-17
PTSF Grade Adjustment Factor ($f_{g,PTSF}$) for Specific Upgrades

Grade (%)	Grade Length (mi)	Directional Demand Flow Rate, v_{vph} (veh/h) ≤100	200	300	400	500	600	700	800	≥900
≥3 <3.5	0.25	1.00	0.99	0.97	0.96	0.92	0.92	0.92	0.92	0.92
	0.50	1.00	0.99	0.98	0.97	0.93	0.93	0.93	0.93	0.93
	0.75	1.00	0.99	0.98	0.97	0.93	0.93	0.93	0.93	0.93
	1.00	1.00	0.99	0.98	0.97	0.93	0.93	0.93	0.93	0.93
	1.50	1.00	0.99	0.98	0.97	0.94	0.94	0.94	0.94	0.94
	2.00	1.00	0.99	0.98	0.98	0.95	0.95	0.95	0.95	0.95
	3.00	1.00	1.00	0.99	0.99	0.97	0.97	0.97	0.96	0.96
	≥4.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.97	0.97
≥3.5 <4.5	0.25	1.00	0.99	0.98	0.97	0.94	0.93	0.93	0.92	0.92
	0.50	1.00	1.00	0.99	0.99	0.97	0.97	0.97	0.96	0.95
	0.75	1.00	1.00	0.99	0.99	0.97	0.97	0.97	0.96	0.96
	1.00	1.00	1.00	0.99	0.99	0.97	0.97	0.97	0.97	0.97
	1.50	1.00	1.00	0.99	0.99	0.97	0.97	0.97	0.97	0.97
	2.00	1.00	1.00	0.99	0.99	0.98	0.98	0.98	0.98	0.98
	3.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	≥4.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
≥4.5 <5.5	0.25	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.97	0.97
	≥0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
≥5.5	All	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Note: Interpolation for length of grade and demand flow rate to the nearest 0.01 is recommended.

PTSF Heavy Vehicle Adjustment Factor

The process for determining the heavy vehicle adjustment factor used in estimating PTSF (Equation 15-8) is similar to that used in estimating ATS. Passenger car equivalents must be found for trucks (E_T) and recreational vehicles (E_R). Equivalents for both trucks and RVs in general terrain segments (level, rolling) and on specific downgrades (which are treated as level terrain) are found in Exhibit 15-18. In estimating PTSF, there is no special procedure for trucks traveling at crawl speed on specific downgrades. Equivalents for trucks and RVs on specific upgrades are found in Exhibit 15-19.

Exhibit 15-18
PTSF Passenger Car Equivalents for Trucks (E_T) and RVs (E_R) for Level Terrain, Rolling Terrain, and Specific Downgrades

Vehicle Type	Directional Demand Flow Rate, v_{vph} (veh/h)	Level and Specific Downgrade	Rolling
Trucks, E_T	≤100	1.1	1.9
	200	1.1	1.8
	300	1.1	1.7
	400	1.1	1.6
	500	1.0	1.4
	600	1.0	1.2
	700	1.0	1.0
	800	1.0	1.0
	≥900	1.0	1.0
RVs, E_R	All	1.0	1.0

Note: Interpolation in this exhibit is not recommended.

Grade (%)	Grade Length (mi)	Directional Demand Flow Rate, v_{vph} (veh/h)								
		≤100	200	300	400	500	600	700	800	≥900
Passenger Car Equivalents for Trucks (E_T)										
≥3 <3.5	≤2.00	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	3.00	1.5	1.3	1.3	1.2	1.0	1.0	1.0	1.0	1.0
	≥4.00	1.6	1.4	1.3	1.3	1.0	1.0	1.0	1.0	1.0
≥3.5 <4.5	≤1.00	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	1.50	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2.00	1.6	1.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	3.00	1.8	1.4	1.1	1.2	1.2	1.2	1.2	1.2	1.2
	≥4.00	2.1	1.9	1.8	1.7	1.4	1.4	1.4	1.4	1.4
≥4.5 <5.5	≤1.00	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	1.50	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2
	2.00	1.7	1.6	1.6	1.6	1.5	1.4	1.4	1.3	1.3
	3.00	2.4	2.2	2.2	2.1	1.9	1.8	1.8	1.7	1.7
	≥4.00	3.5	3.1	2.9	2.7	2.1	2.0	2.0	1.8	1.8
≥5.5 <6.5	≤0.75	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	1.00	1.0	1.0	1.1	1.1	1.2	1.2	1.2	1.2	1.2
	1.50	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6
	2.00	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.8	1.8
	3.00	3.4	3.2	3.0	2.9	2.4	2.3	2.3	1.9	1.9
	≥4.00	4.5	4.1	3.9	3.7	2.9	2.7	2.6	2.0	2.0
≥6.5	≤0.50	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	0.75	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.0	1.0
	1.00	1.3	1.3	1.3	1.4	1.4	1.5	1.5	1.4	1.4
	1.50	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.0	2.0
	2.00	2.9	2.8	2.7	2.7	2.4	2.4	2.3	2.3	2.3
	3.00	4.2	3.9	3.7	3.6	3.0	2.8	2.7	2.2	2.2
	≥4.00	5.0	4.6	4.4	4.2	3.3	3.1	2.9	2.7	2.5
Passenger Car Equivalents for RVs (E_R)										
All	All	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Note: Interpolation for length of grade and demand flow rate to the nearest 0.1 is recommended.

Exhibit 15-19
PTSF Passenger Car Equivalents for Trucks (E_T) and RVs (E_R) on Specific Upgrades

Step 6: Estimate the PTSF

This step is only applied to Class I and Class II two-lane highways. Class III highways do not use PTSF to determine LOS.

Once the demand flows for estimating PTSF are computed, the PTSF is estimated with Equation 15-9:

$$PTSF_d = BPTSF_d + f_{np,PTSF}\left(\frac{v_{d,PTSF}}{v_{d,PTSF} + v_{o,PTSF}}\right)$$

Equation 15-9

where

$PTSF_d$ = percent time-spent-following in the analysis direction (decimal);

$BPTSF_d$ = base percent time-spent-following in the analysis direction, from Equation 15-10;

$f_{np,PTSF}$ = adjustment to PTSF for the percentage of no-passing zones in the analysis segment, from Exhibit 15-21;

$v_{d,PTSF}$ = demand flow rate in the analysis direction for estimation of PTSF (pc/h); and

$v_{o,PTSF}$ = demand flow rate in the opposing direction for estimation of PTSF (pc/h).

The base percent time-spent-following (BPTSF) applies to base conditions and is estimated by Equation 15-10:

Equation 15-10

$$BPTSF_d = 100\left[1 - \exp\left(a v_d^b\right)\right]$$

where a and b are constants drawn from Exhibit 15-20 and all other terms are as previously defined.

Exhibit 15-20 and Exhibit 15-21 are entered with demand flow rates fully converted to passenger cars per hour under base conditions (v_o and v_d).

Exhibit 15-20
PTSF Coefficients for Use in Equation 15-10 for Estimating BPTSF

Opposing Demand Flow Rate, v_o (pc/h)	Coefficient a	Coefficient b
≤200	-0.0014	0.973
400	-0.0022	0.923
600	-0.0033	0.870
800	-0.0045	0.833
1,000	-0.0049	0.829
1,200	-0.0054	0.825
1,400	-0.0058	0.821
≥1,600	-0.0062	0.817

Note: Straight-line interpolation of a to the nearest 0.0001 and b to the nearest 0.001 is recommended.

Exhibit 15-21
No-Passing-Zone Adjustment Factor ($f_{np,PTSF}$) for Determination of PTSF

Total Two-Way Flow Rate, $v = v_d + v_o$ (pc/h)	Percent No-Passing Zones					
	0	20	40	60	80	100
Directional Split = 50/50						
≤200	9.0	29.2	43.4	49.4	51.0	52.6
400	16.2	41.0	54.2	61.6	63.8	65.8
600	15.8	38.2	47.8	53.2	55.2	56.8
800	15.8	33.8	40.4	44.0	44.8	46.6
1,400	12.8	20.0	23.8	26.2	27.4	28.6
2,000	10.0	13.6	15.8	17.4	18.2	18.8
2,600	5.5	7.7	8.7	9.5	10.1	10.3
3,200	3.3	4.7	5.1	5.5	5.7	6.1
Directional Split = 60/40						
≤200	11.0	30.6	41.0	51.2	52.3	53.5
400	14.6	36.1	44.8	53.4	55.0	56.3
600	14.8	36.9	44.0	51.1	52.8	54.6
800	13.6	28.2	33.4	38.6	39.9	41.3
1,400	11.8	18.9	22.1	25.4	26.4	27.3
2,000	9.1	13.5	15.6	16.0	16.8	17.3
2,600	5.9	7.7	8.6	9.6	10.0	10.2
Directional Split = 70/30						
≤200	9.9	28.1	38.0	47.8	48.5	49.0
400	10.6	30.3	38.6	46.7	47.7	48.8
600	10.9	30.9	37.5	43.9	45.4	47.0
800	10.3	23.6	28.4	33.3	34.5	35.5
1,400	8.0	14.6	17.7	20.8	21.6	22.3
2,000	7.3	9.7	11.7	13.3	14.0	14.5
Directional Split = 80/20						
≤200	8.9	27.1	37.1	47.0	47.4	47.9
400	6.6	26.1	34.5	42.7	43.5	44.1
600	4.0	24.5	31.3	38.1	39.1	40.0
800	3.8	18.5	23.5	28.4	29.1	29.9
1,400	3.5	10.3	13.3	16.3	16.9	32.2
2,000	3.5	7.0	8.5	10.1	10.4	10.7
Directional Split = 90/10						
≤200	4.6	24.1	33.6	43.1	43.4	43.6
400	0.0	20.2	28.3	36.3	36.7	37.0
600	-3.1	16.8	23.5	30.1	30.6	31.1
800	-2.8	10.5	15.2	19.9	20.3	20.8
1,400	-1.2	5.5	8.3	11.0	11.5	11.9

Note: Straight-line interpolation of $f_{np,PTSF}$ for percent no-passing zones, demand flow rate, and directional split is recommended to the nearest 0.1.

Note that in Exhibit 15-21, the adjustment factor depends on the total two-way demand flow rate, even though the factor is applied to a single directional analysis. The factor reflects not only the percent of no-passing zones in the analysis segment but also the directional distribution of traffic. The directional distribution measure is the same regardless of the direction being considered. Thus, for example, splits of 70/30 and 30/70 result in the same factor, all other variables being constant. Equation 15-9, however, adjusts the factor to reflect the balance of flows in the analysis and opposing directions.

Step 7: Estimate the PFFS

This step is included only in the analysis of Class III two-lane highways. PFFS is not used in the determination of LOS for Class I or Class II facilities. The computation is straightforward, since both the FFS and the ATS have already been determined in previous steps. PFFS is estimated from Equation 15-11:

$$PFFS = \frac{ATS_d}{FFS}$$

Equation 15-11

where all terms are as previously defined.

Step 8: Determine LOS and Capacity

LOS Determination

At this point in the analysis, the values of any needed measure(s) have been determined. The LOS is found by comparing the appropriate measures with the criteria of Exhibit 15-3. The measure(s) used must be appropriate to the class of the facility being studied:

- Class I: ATS and PTSF;
- Class II: PTSF; and
- Class III: PFFS.

For Class I highways, two service measures are applied. When Exhibit 15-3 is entered, therefore, two LOS designations can be obtained. The worse of the two is the prevailing LOS. For example, if ATS results in a LOS C designation and PTSF results in a LOS D designation, LOS D is assigned.

Capacity Determination

Capacity, which exists at the boundary between LOS E and F, is not determined by a measure of effectiveness. Under base conditions, the capacity of a two-lane highway (in one direction) is 1,700 pc/h. To determine the capacity under prevailing conditions, relevant adjustment factors must be applied to Equation 15-3 and Equation 15-7. In this case, however, the demand flow rate of 1,700 pc/h under base conditions is known, and the demand flow rate under prevailing conditions is sought.

First, capacity is defined as a flow rate, so the PHF in Equation 15-3 and Equation 15-7 is set at 1.00. Then, Equation 15-12 or Equation 15-13 (or both) are applied, as described below.

Equation 15-12

$$c_{dATS} = 1{,}700 f_{g,ATS} f_{HV,ATS}$$

Equation 15-13

$$c_{dPTSF} = 1{,}700 f_{g,PTSF} f_{HV,PTSF}$$

where

c_{dATS} = capacity in the analysis direction under prevailing conditions based on ATS (pc/h), and

c_{dPTSF} = capacity in the analysis direction under prevailing conditions based on PTSF (pc/h).

For Class I highways, both capacities must be computed. The lower value represents capacity. For Class II highways, only the PTSF-based capacity is computed. For Class III highways, only the ATS-based capacity is computed.

One complication is that the adjustment factors depend on the demand flow rate (in vehicles per hour). Thus, adjustment factors for a base flow rate of 1,700 pc/h must be used. Technically, this value should be adjusted to reflect grade and heavy vehicle adjustments. This would create an iterative process in which a result is guessed and then checked.

In practical terms, this is unnecessary, since the highest flow group in all adjustment exhibits is greater than 900 veh/h. It is highly unlikely that any adjustments would reduce 1,700 pc/h to less than 900 veh/h. Therefore, in capacity determinations, all adjustment factors should be based on a flow rate greater than 900 veh/h.

Capacity may be limited by the directional distribution of traffic and the total two-way base capacity of 3,200 pc/h.

Another characteristic of this methodology must be considered in evaluating capacity. When the directional distribution is other than 50/50 (in level and rolling terrain), the two-way capacity implied by each directional capacity may be different. Moreover, the implied two-way capacity from either or both directions may be more than the limit of 3,200 pc/h. In such cases, the directional capacities estimated are not achievable with the stated directional distribution. If this is the case, then base capacity is restricted to 1,700 pc/h in the direction with the heaviest flow, and capacity in the opposing direction is found by using the opposing proportion of flow, with an upper limit of 1,500 pc/h.

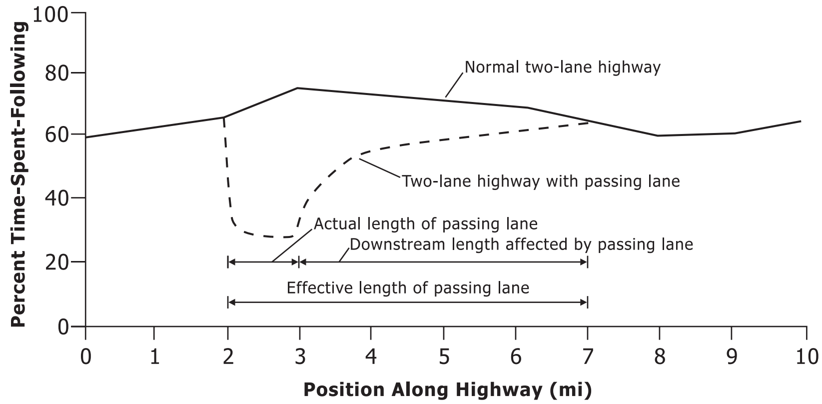
Directional Segments with Passing Lanes

Providing a passing lane on a two-lane highway in level or rolling terrain improves operational performance and therefore may improve LOS. A procedure to estimate this effect is described in this section.

This procedure should be applied only in level and rolling terrain. On specific grades, added lanes are considered to be *climbing lanes*, which are addressed in the next section.

The effective length of a passing lane is longer than its actual length.

Exhibit 15-22 illustrates the operational effect of a passing lane on PTSF. It shows that the passing lane provides operational benefits for some distance downstream before PTSF returns to its former level (without a passing lane). Thus, a passing lane's effective length is greater than its actual length.



Source: Harwood and Hoban (*6*).

Exhibit 15-22
Operational Effect of a Passing Lane on PTSF

Exhibit 15-23 gives the length of the downstream segment affected by the passing lane for both ATS and PTSF. In the case of ATS, the effect is limited to 1.7 mi in all cases. Where PTSF is concerned, however, the effect can be far longer than the passing lane itself—up to 13 mi for low demand flow rates.

Exhibit 15-23
Downstream Length of Roadway Affected by Passing Lanes on Directional Segments in Level and Rolling Terrain

Directional Demand Flow Rate, v_d (pc/h)	Downstream Length of Roadway Affected, L_{de} (mi) PTSF	ATS
≤200	13.0	1.7
300	11.6	1.7
400	8.1	1.7
500	7.3	1.7
600	6.5	1.7
700	5.7	1.7
800	5.0	1.7
900	4.3	1.7
≥1,000	3.6	1.7

Note: Interpolation to the nearest 0.1 is recommended.

The analysis segment should include the entire length of the passing lane's downstream effect.

The procedure here is intended for the analysis of directional segments in level or rolling terrain that encompass the entire passing lane. Segments of the highway upstream and downstream of the passing lane may be included in the analysis. It is recommended that the analysis segment include the full length of the passing lane's downstream effect.

Care should be taken in considering the effect of passing lanes on service flow rates; they are greatly affected by the length of the passing lane relative to the length of the analysis segment.

Because of the downstream effect on PTSF, the LOS on a two-lane highway segment that is determined by PTSF (Class I and Class II) may be significantly improved by the addition of a passing lane. Care must be taken, however, in considering the impact of a passing lane on service volumes or service flow rates. The result is highly dependent on the relative lengths of the analysis segment and the passing lane. If the analysis segment includes only the length of the passing lane and its downstream effective length (on PTSF), the passing lane may appear to increase service flow rates dramatically at LOS A–D (capacity, and therefore LOS E, would not be affected). However, if additional lengths are included in the analysis segment, this impact is reduced, sometimes considerably. Thus, apparent increases in service volumes or service flow rates must be carefully considered in the context of how they were obtained.

The steps in this special analysis procedure are as follows.

Step 1: Conduct an Analysis Without the Passing Lane

The first step in the operational analysis of the impact of a passing lane is to conduct the basic analysis steps described previously. The remainder of the procedure essentially predicts the improvement caused by the passing lane compared with a similar segment without a passing lane.

Step 2: Divide the Segment into Regions

The analysis segment can be divided into four regions, as follows:

1. Length upstream of the passing lane L_u,
2. Length of the passing lane L_{pl},
3. Length downstream of the passing lane within its effective length L_{de}, and
4. Length downstream of the passing lane beyond its effective length L_d.

Some of these regions may not be involved in a particular analysis. Region 2, the passing lane, must be included in every analysis. In addition, it is strongly recommended, but not absolutely necessary, that Region 3 be included. Regions 1 and 4 are optional, and inclusion is at the discretion of the analyst.

The four lengths must add up to the total length of the analysis segment. The analysis regions and their lengths will differ for estimations of ATS and PTSF, as the downstream effects indicated in Exhibit 15-23 differ for each.

The length of the passing lane L_{pl} is either the length of the passing lane as constructed or the planned length. It should include the length of the lane addition as well as the length of the entrance and exit tapers. The procedure is calibrated for passing lanes within the optimal lengths shown in Exhibit 15-24. Passing lanes that are substantially shorter or longer than the optimums shown may provide less operational benefit than predicted by this procedure.

Exhibit 15-24 Optimal Lengths of Passing Lanes on Two-Lane Highways

Directional Demand Flow Rate, v_d (pc/h)	Optimal Passing Lane Length (mi)
≤100	≤0.50
>100 ≤400	>0.50 ≤0.75
>400 ≤700	>0.75 ≤1.00
≥700	>1.00 ≤2.00

The length of the conventional two-lane highway segment upstream of the passing lane L_u is determined by the actual or planned placement of the passing lane within the analysis segment. The length of the downstream highway segment within the effective length of the passing lane L_{de} is determined from Exhibit 15-23. Any remaining length of the analysis segment downstream of the passing lane is included in L_d, which is computed from Equation 15-14:

Equation 15-14

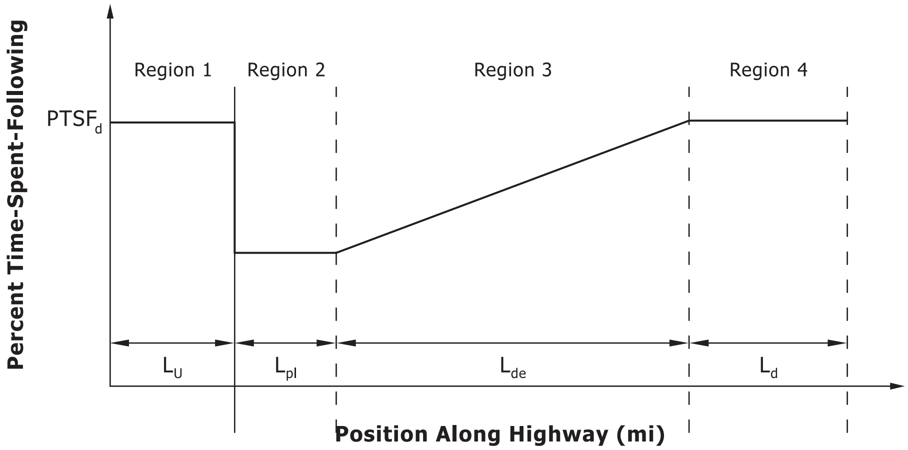
$$L_d = L_t - \left(L_u + L_{pl} + L_{de}\right)$$

where L_t is the total length of the analysis segment in miles and all other terms are as previously defined.

Step 3: Determine the PTSF

PTSF within lengths L_u and L_d is assumed to be equal to the $PTSF_d$ as predicted by the normal analysis procedure (without a passing lane). Within the segment with the passing lane L_{pl}, PTSF is generally equal to 58% to 62% of its upstream value. This effect is a function of the directional demand flow rate. Within L_{de}, the PTSF is assumed to increase linearly from the passing lane value to the normal upstream value. This distribution is illustrated in Exhibit 15-25.

Exhibit 15-25
Effect of a Passing Lane on PTSF



On the basis of this model, the PTSF for the entire analysis segment, as affected by the passing lane, is given by Equation 15-15:

Equation 15-15

$$PTSF_{pl} = \frac{PTSF_d \left[L_u + L_d + f_{pl,PTSF} L_{pl} + \left(\frac{1 + f_{pl,PTSF}}{2} \right) L_{de} \right]}{L_t}$$

where

$PTSF_{pl}$ = percent time-spent-following for segment as affected by the presence of a passing lane (decimal); and

$f_{pl,PTSF}$ = adjustment factor for the impact of a passing lane on percent time-spent-following, from Exhibit 15-26.

All other variables are as previously defined.

Exhibit 15-26
Adjustment Factor for the Impact of a Passing Lane on PTSF ($f_{pl,PTSF}$)

Directional Demand Flow Rate, v_d (pc/h)	$f_{pl,PTSF}$
≤100	0.58
200	0.59
300	0.60
400	0.61
500	0.61
600	0.61
700	0.62
800	0.62
≥900	0.62

Note: Interpolation is not recommended; use closest value.

If the analysis segment cannot encompass the entire length L_{de} because it is truncated by a town or major intersection within it, then distance L_d is not used. Therefore, the actual downstream length within the analysis segment L'_{de} is less than the value of L_{de} tabulated in Exhibit 15-23. In this case, Equation 15-16 should be used instead of Equation 15-15:

Equation 15-16

$$PTSF_{pl} = \frac{PTSF_d \left[L_u + f_{pl,PTSF} L_{pl} + f_{pl,PTSF} L'_{de} + \left(\frac{1 - f_{pl,PTSF}}{2} \right) \left(\frac{L'^{\,2}_{de}}{L_{de}} \right) \right]}{L_t}$$

where all terms are as previously defined.

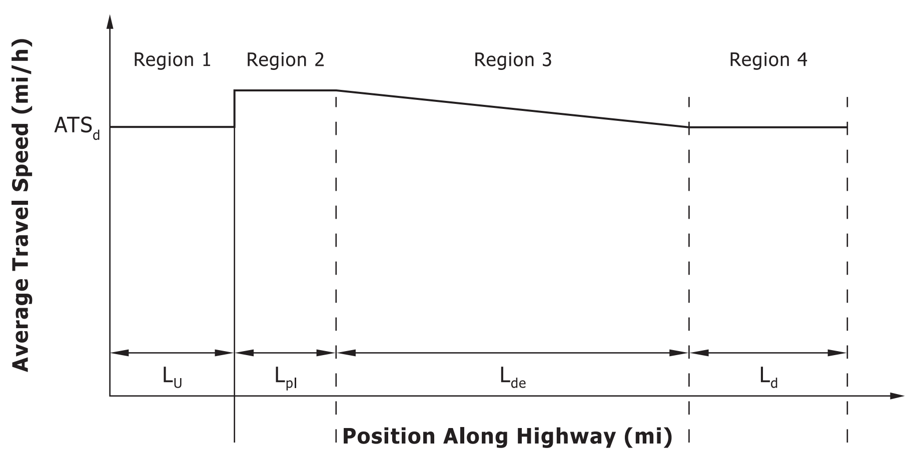
In general, the effective downstream distance of the passing lane should not be truncated. A downstream boundary short of the effective downstream distance should be considered at the point where any of the following occur:

- The environment of the highway radically changes, as in the case of entering a small town or developed area from a rural segment;
- A major unsignalized intersection is present, leading to a change in the demand flow rate;
- A proximate signalized intersection begins to affect the operation of the two-lane segment;
- The terrain changes significantly; and
- Lane or shoulder widths change significantly.

Step 4: Determine the ATS

The ATS within lengths L_u and L_d is assumed to be equal to ATS_d, the speed that would exist without the passing lane. Within the passing lane, the ATS is generally between 8% and 11% higher than its upstream value, depending on the directional demand flow rate. Within the effective downstream length, L_{de}, ATS is assumed to decrease linearly with the distance from the passing lane, from the passing lane value to the normal value. Exhibit 15-27 illustrates the impact of a passing lane on ATS.

Exhibit 15-27
Impact of a Passing Lane on ATS



The ATS is computed with Equation 15-17:

Equation 15-17

$$ATS_{pl} = \frac{ATS_d L_t}{L_u + L_d + \left(\frac{L_{pl}}{f_{pl,ATS}} \right) + \left(\frac{2L_{de}}{1 + f_{pl,ATS}} \right)}$$

where

ATS_{pl} = average travel speed in the analysis segment as affected by a passing lane (mi/h); and

$f_{pl,ATS}$ = adjustment factor for the effect of a passing lane on ATS, from Exhibit 15-28.

All other variables are as previously defined.

Exhibit 15-28
Adjustment Factor for Estimating the Impact of a Passing Lane on ATS ($f_{pl,ATS}$)

Directional Demand Flow Rate, v_d (pc/h)	$f_{pl,ATS}$
≤100	1.08
200	1.09
300	1.10
400	1.10
500	1.10
600	1.11
700	1.11
800	1.11
≥900	1.11

Note: Interpolation is not recommended; use closest value.

In the case where the analysis segment cannot include all of the effective downstream distance, L_{de}, because a town or major intersections cause the segment to be truncated, distance L'_{de} is less than the value of L_{de}. In this case, Equation 15-18 is used instead of Equation 15-17 to compute ATS.

Equation 15-18

$$ATS_{pl} = \frac{ATS_d L_t}{L_u + \frac{L_{pl}}{f_{pl,ATS}} + \frac{2L'_{de}}{\left[1 + f_{pl,ATS} + \left(f_{pl,ATS} - 1\right)\left(\frac{L_{de} - L'_{de}}{L_{de}}\right)\right]}}$$

where all terms are as previously defined.

Step 5: Determine the LOS

Determining the LOS for a segment with a passing lane is no different from determining the LOS for a normal segment, except that ATS_{pl} and $PTSF_{pl}$ are used as the service measures with the criteria of Exhibit 15-3.

As with a normal segment, LOS for Class I highways is based on both PTSF and ATS. LOS for Class II highways is based only on PTSF. Class III highways would not normally have passing lanes, but if such a situation arose, PFFS = ATS/FFS would be used to determine LOS.

Directional Segments with Climbing Lanes on Upgrades

A climbing lane is, in effect, a passing lane added on an upgrade to allow traffic to pass heavy vehicles whose speeds are reduced. Generally, a lane is added to the right, and all slow-moving vehicles should move to this lane, allowing faster vehicles to pass in the normal lane.

The American Association of State Highway and Transportation Officials (*7*) indicates that climbing lanes on two-lane highways are warranted when

- The directional flow rate on the upgrade exceeds 200 veh/h;
- The directional flow rate for trucks on the upgrade exceeds 20 veh/h; and

- Any of the following conditions apply:
  - A speed reduction of 10 mi/h or more exists for a typical truck;
  - LOS E or F exists on the upgrade without a climbing lane; or
  - Without a climbing lane, the LOS is two or more levels lower on the upgrade than on the approach segment to the grade.

An operational analysis of the impact of a climbing lane on a two-lane highway is performed with the same procedures as passing lanes in level or rolling terrain, with three major differences:

1. Adjustment factors for the existence of the climbing lane are taken from Exhibit 15-29,
2. The analysis without a climbing lane is conducted by using the specific grade procedures, and
3. Distances L_u and L_d are set to zero.

The effective downstream distance L_{de} is also generally set to zero unless the climbing lane ends before the grade does. In this case, a value less than the values typically used should be considered.

Exhibit 15-29
Adjustment Factors (f_{pl}) for Estimating ATS and PTSF Within a Climbing Lane

Directional Demand Flow Rate, v_d (pc/h)	f_{pl} ATS	f_{pl} PTSF
0–300	1.02	0.20
>300–600	1.07	0.21
>600	1.14	0.23

LOS Assessment for Directional Two-Lane Facilities

Two-lane highway segments have uniform characteristics that provide a basis for their analysis. Several contiguous two-lane highway segments (in the same directions) may be combined to look at a longer section (with varying characteristics) as a facility. A separate operational analysis would have to be done for each uniform segment within the facility.

Weighted-average values of PTSF and ATS may be estimated for the facility. The weighting is on the basis of total travel time within the 15-min analysis period. The total travel time of all vehicles within the 15-min analysis period is estimated with Equation 15-19 and Equation 15-20:

Equation 15-19

$$VMT_{i15} = 0.25\left(\frac{V_i}{PHF}\right)L_t$$

Equation 15-20

$$TT_{i15} = \frac{VMT_{i15}}{ATS_i}$$

where

VMT_{i15} = total vehicle miles traveled by all vehicles in directional segment *i* during the 15-min analysis period (veh-mi),

V_i = demand volume in directional segment *i* (veh/h),

PHF = peak hour factor,

L_t = total length of directional segment *i* (mi),

TT_{i15} = total travel time consumed by all vehicles traversing directional segment i during the 15-min analysis period (veh-h), and

ATS_i = average travel speed for directional segment i (mi/h).

Once the total travel time for all vehicles in each segment is computed, weighted-average values of PTSF and ATS can be obtained with Equation 15-21 and Equation 15-22:

$$ATS_F = \frac{VMT_1 + VMT_2 + VMT_3 + \ldots + VMT_i}{TT_1 + TT_2 + TT_3 + \ldots + TT_i}$$

Equation 15-21

$$PTSF_F = \frac{(TT_1 \times PTSF_1) + (TT_2 \times PTSF_2) + (TT_3 \times PTSF_3) + \ldots + (TT_i \times PTSF_i)}{TT_1 + TT_2 + TT_3 + \ldots + TT_i}$$

Equation 15-22

where

ATS_F = average travel speed for the facility (mi/h),

$PTSF_F$ = percent time-spent-following for the facility (decimal),

$PTSF_i$ = percent time-spent-following for segment i (decimal),

VMT_i = vehicle miles traveled for segment i (veh-mi), and

TT_i = total travel time of all vehicles in segment i (veh-h).

When a facility is put together, two-lane highway segments of different classes should not be combined. Levels of service for the facility are still based on the criteria of Exhibit 15-3. Class III two-lane highways generally only exist in short segments and would not be expected to cover a distance long enough to form a facility.

Other Performance Measures

This chapter provides detailed methodologies for estimating three measures of effectiveness that are used (depending on the highway class) to determine LOS:

- ATS (mi/h, Class I and Class III highways),
- PTSF (decimal, Class I and Class II highways), and
- PFFS (decimal, Class III highways).

In the previous section, two additional measures were introduced that can be considered as performance measures, even though they are not used to determine LOS. Equation 15-19 and Equation 15-20 can be used to estimate

- Total vehicle miles traveled by all vehicles in the analysis segment during the 15-min analysis period VMT_{i15} (veh-mi), and
- Total travel time consumed by all vehicles traversing the analysis segment during the 15-min analysis period TT_{i15} (veh-h).

These values may also be of interest in fully understanding the operational quality of the study segment.

A volume-to-capacity (v/c) ratio is also a common performance measure of interest in LOS and capacity analysis. It is most easily computed for two-lane highways with Equation 15-23:

Equation 15-23

$$v / c = \frac{v_d}{1{,}700}$$

where v_d is the directional demand flow rate, converted to equivalent base conditions.

The difficulty in this is that there may be two values of v_d: one for estimating ATS and another for estimating PTSF (depending on the class of highway). For Class I highways, where both measures are used, the result yielding the highest *v/c* ratio would be used. For Class II highways, only PTSF is used, and only one value would exist. For Class III highways, only ATS is used, and only one value would exist.

BICYCLE MODE

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, indicating the need for only one model.

The bicycle LOS model for two-lane and multilane highways uses a traveler-perception model calibrated by using a linear regression (*4*). The model fits independent variables associated with roadway characteristics to the results of a 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 15-4.

Step 1: Gather Input Data

The methodology requires gathering the following input data for the facility in question:

1. Lane width (ft),
2. Shoulder width (ft),
3. Hourly directional motorized vehicle volume (veh/h),
4. Number of directional through lanes (needed for multilane highways),
5. Percentage of heavy vehicles (decimal),
6. Posted speed limit (mi/h),
7. Percentage of segment with occupied on-highway parking (decimal), and
8. Pavement rating.

Pavement rating is determined by using FHWA's 5-point present serviceability rating scale (*8*): 1 (very poor), 2 (poor), 3 (fair), 4 (good), and 5 (very good). Where data for specific variables are not available, default values may be used as shown in Exhibit 15-5.

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 basic two-lane highways, two or more for passing lanes or multilane highways), calculate the directional demand flow rate of motorized traffic in the outside lane with Equation 15-24:

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

Equation 15-24

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 in 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 (Class III highways) and near entrances to recreational areas (Class II and Class III highways) 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 15-25 through Equation 15-29 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:

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

Equation 15-25

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

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

Equation 15-26

If W_s is less than 4 ft:

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

Equation 15-27

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

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

Equation 15-28

Otherwise,

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

Equation 15-29

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 (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 instance, 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 15-30 shows the calculation of the effective speed factor that accounts for this diminishing effect.

Equation 15-30

$$S_t = 1.1199 \ln(S_p - 20) + 0.8103$$

where

S_t = effective speed factor, and

S_p = 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 15-31:

Equation 15-31

$$BLOS = 0.507 \ln(v_{OL}) + 0.1999 S_t (1 + 10.38 HV)^2 + 7.066(1/P)^2 - 0.005(W_e)^2 + 0.057$$

where

$BLOS$ = bicycle level of service score;

v_{OL} = directional demand flow rate in the outside lane (veh/h);

HV = percentage of heavy vehicles (decimal); if $V < 200$ veh/h, then HV should be limited to a maximum of 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 15-4 to determine the bicycle LOS for the segment.

3. APPLICATIONS

This chapter provides methodologies for the analysis of two-lane highway uninterrupted-flow segments that serve a wide variety of travel purposes. The procedures are most easily applied in the operational analysis mode to determine the capacity and LOS of a two-lane highway segment with known characteristics. Other applications are also possible.

DEFAULT VALUES

A detailed report on the use of default values in uninterrupted-flow analysis, including the analysis of two-lane highways, is given elsewhere (*4*). Specific default values for use with the methodology of this chapter were given in Exhibit 15-5. Default values may also be based on local estimates developed from past observations of a specific site or similar sites in a given jurisdiction.

For operational analysis and design analysis, the use of default values should be minimized whenever possible. Every default value used to replace a field-measured or other site-specific value introduces additional uncertainty into the estimation process and into the accuracy of results. Nevertheless, where no site-specific values are available, default values allow at least an approximate analysis of the situation. For planning and preliminary design analysis, use of default values is generally required, since few details are available at this stage of consideration.

TYPES OF ANALYSIS

Operational Analysis

All geometric, development, and traffic-demand characteristics are provided. The LOS that is expected to exist during the analysis period is estimated. A number of alternative performance measures may also be estimated. The methodology of this chapter is most easily used in this mode.

Design Analysis

In design analysis, demand characteristics are generally known. The analysis is intended to give insights into design parameters needed to provide a target LOS for the demand characteristics as stated. For two-lane highways, design decisions are relatively limited. Lane and shoulder widths have a moderate impact on operations but generally do not result in a markedly different LOS.

Typical design projects include horizontal or vertical curve realignments, which may affect percent no-passing zones and free-flow speeds.

The special procedures outlined in this chapter to consider the impacts of passing lanes and climbing lanes can be used to provide critical design insight. However, the computations are performed in the operational analysis mode, leading to a comparison of operations with or without the passing or climbing lane.

This chapter's appendix deals with some special design issues related to two-lane highways. However, there is no methodology at this point for estimating the impact of these design treatments on operating quality.

Given the relatively few design parameters involved in a two-lane highway, most design analysis is conducted as an iterative series of operational analyses.

Planning and Preliminary Engineering Analysis

Planning and preliminary engineering analysis has the same objectives as design analysis, except that it occurs early in the process when few details of demand and other characteristics are known. Thus, design analysis is augmented by the use of default values for many inputs.

The other principal characteristic of planning and preliminary engineering analysis is that demands are generally described in terms of two-way AADT.

This chapter includes generalized daily service volume tables covering a specific range of default values. They can be used for a coarse and general evaluation of the likely LOS for a two-lane highway in various settings under an expected AADT demand. These tables are useful only for the most preliminary of analyses. For example, all two-lane highway segments in a particular region can be considered by using these criteria. Any segments that appear to be operating at an undesirable LOS should be subjected to site-specific study with a more detailed operational analysis before any major design, reconstruction, or investment decisions are made.

SERVICE FLOW RATES, SERVICE VOLUMES, AND DAILY SERVICE VOLUMES

Service flow rates, service volumes, and daily service volumes are useful concepts that can be used in the analysis of many types of facilities, including two-lane highways. The three terms must be clearly understood, because they are very different.

1. Service flow rates SF_i represent the maximum directional rate of flow that can be accommodated by a segment while maintaining the designated LOS *i*.
2. Service volumes SV_i represent the maximum directional hourly volume that can be accommodated by a segment while maintaining the designated LOS *i* during the worst 15-min period of the hour.
3. Daily service volumes DSV_i represent the maximum AADT that can be accommodated by a segment while maintaining the designated LOS *i* during the worst 15 min of the peak hour of the day, in the highest-flow direction.

In general, service flow rates and service volumes are directional values, while the daily service volume is usually stated as total traffic in both directions (since that is how AADT is stated).

The service flow rate for a particular LOS is estimated by using the methodology for the segment type under study (two-lane highways in this chapter). Equation 15-32 is then used to estimate service volume for a segment, and Equation 15-33 is used to estimate daily service volume for a segment.

$$SV_i = SF_i \times PHF$$

Equation 15-32

$$DSV_i = \frac{SV_i}{K \times D}$$

Equation 15-33

where *K* is the proportion of traffic occurring in the peak hour for the study segment and *D* is the proportion of traffic occurring in the peak direction for the study segment.

For two-lane highways, several complications arise. While all analyses of two-lane highways are for one direction, the two directions interact. Thus, if a two-way daily service volume is estimated by using the service flow rate in one direction, and then again in the other direction, different results could easily be obtained.

As with all uninterrupted-flow segments, capacity is synonymous with the service flow rate for LOS E. Thus, Equation 15-12 and Equation 15-13, presented earlier, may be used to estimate service flow rates for LOS E. Even in this case, there are two equations, since the value will depend on whether ATS or PTSF is the determining LOS parameter.

For other levels of service, the process of determining a service flow rate is more complicated. It would be beneficial if the methodology of this chapter could be used in reverse—that is, start with a value of ATS or PTSF and work backwards to the demand flow rate that would create that value. Unfortunately, virtually all of the adjustment factors used in this process depend on the demand flow rate, which is what the analyst would be trying to find. Such computations would therefore be iterative. Finding appropriate service flow rates for each LOS requires an iterative process in which different flow rates are incrementally used until the threshold for a particular LOS is found.

Once service flow rates are found, Equation 15-32 and Equation 15-33 can be used to infer service volumes and daily service volumes.

GENERALIZED DAILY SERVICE VOLUMES

Exhibit 15-30 shows generalized daily service volumes for use in planning and preliminary design. The exhibit provides daily service volume values for three types of segments: (*a*) a Class I highway in level terrain, (*b*) a Class I highway in rolling terrain, and (*c*) a Class II highway in rolling terrain.

Typical conditions assumed for each are given below the table. Various values of *K*- and *D*-factors are given. Since these values vary greatly from region to region, the analyst must select the values most appropriate to the particular application. Interpolation may be used, if desired, to obtain intermediate values.

Exhibit 15-30
Generalized Daily Service Volumes for Two-Lane Highways

The Class I—level example assumes higher speeds, with significant passing opportunities.

The Class I—rolling example assumes more moderate speeds and reduced passing opportunities because of the terrain.

The Class II—rolling example is similar to a scenic or recreational highway with lower speeds and limited passing opportunities.

K-Factor	D-Factor	Class I—Level				Class I—Rolling				Class II—Rolling			
		LOS B	LOS C	LOS D	LOS E	LOS B	LOS C	LOS D	LOS E	LOS B	LOS C	LOS D	LOS E
0.09	50%	5.5	9.3	16.5	31.2	4.2	8.4	15.7	30.3	5.0	9.8	18.2	31.2
	55%	4.9	8.7	14.9	30.2	3.7	7.9	14.0	29.2	4.1	8.7	16.0	30.2
	60%	4.4	8.1	13.9	27.6	3.7	6.2	12.8	26.8	3.7	7.9	14.6	27.6
	65%	4.1	7.9	12.9	25.5	3.4	5.9	11.4	24.7	3.3	5.9	13.2	25.5
0.10	50%	5.0	8.4	14.8	28.0	3.8	7.6	14.2	27.2	4.4	8.8	16.3	28.0
	55%	4.4	7.9	13.4	27.1	3.3	7.1	12.6	26.3	3.7	7.9	14.4	27.1
	60%	4.0	7.3	12.5	24.9	3.3	5.6	11.5	24.1	3.3	7.1	13.1	24.9
	65%	3.7	7.1	11.6	23.0	3.0	5.3	10.3	22.3	3.0	5.3	11.9	23.0
0.12	50%	4.1	7.0	12.4	23.4	3.1	6.3	11.8	22.7	3.7	7.4	13.6	23.4
	55%	3.7	6.5	11.2	22.6	2.8	5.9	10.5	21.9	3.1	6.5	12.0	22.6
	60%	3.3	6.1	10.4	20.7	2.7	4.7	9.6	20.1	2.7	5.9	10.9	20.7
	65%	3.1	5.9	9.6	19.1	2.5	4.4	8.5	18.5	2.4	4.4	9.9	19.1
0.14	50%	3.5	6.0	10.6	20.0	2.7	5.4	10.1	19.4	3.2	6.3	11.7	20.0
	55%	3.1	5.6	9.6	19.4	2.4	5.1	9.0	18.8	2.6	5.6	10.3	19.4
	60%	2.8	5.2	8.9	17.7	2.3	4.0	8.2	17.2	2.3	5.1	9.4	17.7
	65%	2.6	5.1	8.2	16.4	2.1	3.8	7.3	15.9	2.1	3.8	8.5	16.4

Notes: Volumes are thousands of vehicles per day.
Assumed values for all entries: 10% trucks, PHF = 0.88, 12-ft lanes, 6-ft shoulders, 10 access points/mi.
Assumed values for Class I—level: BFFS = 65 mi/h, 20% no-passing zones.
Assumed values for Class I—rolling: BFFS = 60 mi/h, 40% no-passing zones.
Assumed values for Class II—rolling: BFFS = 50 mi/h, 60% no-passing zones.

A number of interesting characteristics are displayed in Exhibit 15-30:

1. LOS A is not shown. Even in level terrain, it is possible to achieve this level only at very low demand flow rates (almost always lower than 50 veh/h, directional).
2. The range of demand flows falling within LOS E is broad compared with other levels of service. This is because the quality of service on two-lane highways tends to become unacceptable at relatively low v/c ratios. Few two-lane highways are observed operating at or near capacity (except for short segments), because most will have been expanded before capacity demand flows develop.

Exhibit 15-30 should be used only in generalized planning and preliminary engineering analysis. It is best used to examine a number of two-lane highways within a given jurisdiction to determine which need closer scrutiny. If anticipated AADTs on a given segment or facility appear to put the segment or facility into an undesirable LOS, then more site-specific data should be obtained (or forecast) and a full operational analysis conducted before any firm commitments to reconstruct or improve the highway are made.

USE OF ALTERNATIVE TOOLS

No alternative deterministic tools are in common use for two-lane highway analysis. Two-lane highway simulation tools are in various stages of development, but user experience with these tools is insufficient to support the formulation of useful guidance for their application to extend the scope of the procedures described in this chapter.

One of the potentially useful features of two-lane highway simulation is the ability to model specific configurations of a series of no-passing zones, exclusive passing lanes, and access points, all of which are now described in general terms (e.g., percent no-passing zones) in this chapter. Network simulation tools can also include traffic control devices at specific points.

It is possible to obtain additional performance measures from simulation results. One example is *follower density*, which is defined in terms of the number of followers per mile per lane. This concept, which is discussed in more detail in Chapter 24, Concepts: Supplemental, has attracted increasing international interest. Some examples that illustrate potential uses of two-lane highway simulation are presented elsewhere (*9*).

4. EXAMPLE PROBLEMS

Exhibit 15-31
List of Example Problems

Problem Number	Description	Type of Analysis
1	Find the LOS of a Class I highway in rolling terrain	Operational analysis
2	Find the LOS of a Class II highway in rolling terrain	Operational analysis
3	Find the LOS of a Class III highway in level terrain	Operational analysis
4	Find the LOS of a Class I highway with a passing lane	Operational analysis
5	Find the future bicycle LOS of a two-lane highway	Planning analysis

EXAMPLE PROBLEM 1: CLASS I HIGHWAY LOS

The Facts

A segment of Class I two-lane highway has the following known characteristics:

- Demand volume = 1,600 pc/h (total in both directions)
- Directional split (during analysis period) = 50/50
- PHF = 0.95
- 50% no-passing zones in the analysis segment (both directions)
- Rolling terrain
- 14% trucks; 4% RVs
- 11-ft lane widths
- 4-ft usable shoulders
- 20 access points/mi
- 60-mi/h BFFS
- 10-mi segment length

Find the expected LOS in each direction on the two-lane highway segment as described.

Comments

The problem statement calls for finding the LOS in each direction on a segment in rolling terrain. Because the directional split is 50/50, the solution in one direction will be the same as the solution in the other direction, so only one operational analysis needs to be conducted. The result will apply equally to each direction.

Because this is a Class I highway, both ATS and PTSF must be estimated to determine the expected LOS.

Step 1: Input Data

All input data were specified above.

Step 2: Estimate the FFS

FFS is estimated with Equation 15-2 and adjustment factors found in Exhibit 15-7 (for lane and shoulder width) and Exhibit 15-8 (for access points in both directions). For 11-ft lane widths and 4-ft usable shoulders, the adjustment factor for these features f_{LS} is 1.7 mi/h; for 20 access points/mi, the adjustment factor f_A is 5.0 mi/h. Then

$$FFS = BFFS - f_{LS} - f_A$$

$$FFS = 60.0 - 1.7 - 5.0 = 53.3 \text{ mi/h}$$

Step 3: Demand Adjustment for ATS

The demand volume must be adjusted to a flow rate in passenger cars per hour under equivalent base conditions. This is accomplished with Equation 15-3:

$$v_{i,ATS} = \frac{V_i}{PHF \times f_{g,ATS} \times f_{HV,ATS}}$$

Since the demand split is 50/50, both the analysis direction and opposing demand volumes are 1,600/2 = 800 veh/h.

The grade adjustment factor $f_{g,ATS}$ is selected from Exhibit 15-9 for rolling terrain. The table is entered with a demand flow rate v_{vph} in vehicles per hour, or 800/0.95 = 842 veh/h. By interpolation in Exhibit 15-9 between 800 and 900 veh/h, the factor is 0.99 to the nearest 0.01.

The passenger car equivalent for trucks and RVs is obtained from Exhibit 15-11, again for a demand flow rate of 842 veh/h. Again, by interpolation between 800 and 900 veh/h, the values obtained are E_T = 1.4 and E_R = 1.1. The heavy vehicle adjustment is then computed with Equation 15-4:

$$f_{HV,ATS} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

$$f_{HV,ATS} = \frac{1}{1 + 0.14(1.4 - 1) + 0.04(1.1 - 1)}$$

$$f_{HV,ATS} = 0.943$$

Then

$$v_{d,ATS} = v_{o,ATS} = \frac{800}{0.95 \times 0.99 \times 0.943} = 902 \text{ pc/h}$$

Step 4: Estimate ATS

The ATS is estimated with Equation 15-6. The adjustment factor $f_{np,ATS}$ is found in Exhibit 15-15 for an FFS of 53.3 mi/h, 50% no-passing zones, and an opposing demand flow of 902 veh/h. This selection must use interpolation on all three scales. Note that interpolation is only to the nearest 0.1 for this adjustment factor. Exhibit 15-32 illustrates the interpolation.

Exhibit 15-32
Interpolation for ATS Adjustment Factor

v_o (veh/h)	Factor for FFS = 55 mi/h			Factor for FFS = 50 mi/h		
	40% NPZ	50% NPZ	60% NPZ	40% NPZ	50% NPZ	60% NPZ
800	0.7	*0.9*	1.1	0.6	*0.75*	0.9
902		**0.8**			**0.65**	
1,000	0.6	*0.7*	0.8	0.4	*0.55*	0.7

Notes: $f_{np,ATS}$ = 0.65 + (0.8 - 0.65) (3.3 / 5.0) = 0.749 = **0.7**.
NPZ = no-passing zones.

Then, Equation 15-6 gives the following:

$$ATS = FFS - 0.00776(v_d + v_o) - f_{np,ATS}$$

$$ATS = 53.3 - 0.00776(902 + 902) - 0.7$$

$$ATS = 53.3 - 14.0 - 0.7 = 38.6 \text{ mi/h}$$

Step 5: Demand Adjustment for PTSF

The adjusted demand used to estimate PTSF is found with Equation 15-7 and Equation 15-8. The grade adjustment factor is taken from Exhibit 15-16 for rolling terrain and a demand flow rate of 800/0.95 = 842 pc/h. Passenger car equivalents for trucks and RVs are taken from Exhibit 15-18. In both exhibits, the demand flow rate of 842 pc/h is interpolated between 800 pc/h and 900 pc/h to obtain the correct values. The following values are obtained:

$f_{g,PTSF}$ = 1.00

E_T = 1.0

E_R = 1.0

Then, use of Equation 15-8 gives the following:

$$f_{HV,PTSF} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

$$f_{HV,PTSF} = \frac{1}{1 + 0.14(1.0 - 1) + 0.04(1.0 - 1)} = 1.00$$

Equation 15-7 gives

$$v_{i,PTSF} = \frac{V_i}{PHF \times f_{g,PTSF} \times f_{HV.PTSF}}$$

$$v_{d,PTSF} = v_{o,PTSF} = \frac{800}{0.95 \times 1.00 \times 1.00} = 842 \text{ pc/h}$$

Step 6: Estimate PTSF

PTSF is estimated with Equation 15-9 and Equation 15-10. Exhibit 15-20 is used to obtain exponents *a* and *b* for Equation 15-10, and Exhibit 15-21 is used to obtain the no-passing-zone adjustment for Equation 15-9. All three require interpolation.

Exponents *a* and *b* are based on the opposing flow rate of 842 pc/h, which is interpolated between tabulated values of 800 pc/h and 1,000 pc/h. This is illustrated in Exhibit 15-33.

Exhibit 15-33
Interpolation for Exponents *a* and *b* for Equation 15-10

Opposing Flow Rate (pc/h)	*a*	*b*
800	-0.0045	0.833
842	**-0.0046**	**0.832**
1,000	-0.0049	0.829

Then, use of Equation 15-10 gives

$$BPTSF = 100\left[1-\exp\left(av_d^b\right)\right]$$

$$BPTSF = 100\left[1-\exp\left(-0.0046\times 842^{0.832}\right)\right]$$

$$BPTSF = 71.3\%$$

The adjustment factor for no-passing zones must also be interpolated in two variables. Exhibit 15-21 is entered with 50% no-passing zones, a 50/50 directional split of traffic, and a total two-way demand flow rate of 842 + 842 = 1,684 pc/h. The interpolation is illustrated in Exhibit 15-34.

Exhibit 15-34
Interpolation for $f_{np,PTSF}$ for Equation 15-9

Total Flow Rate (pc/h)	Adjustment Factor for 40% NPZ	Adjustment Factor for 50% NPZ	Adjustment Factor for 60% NPZ
1,400	23.8	*25.0*	26.2
1,684		16.6 + (25.0 - 16.6) (316 / 600) = **21.0**	
2,000	15.8	*16.6*	17.4

Note: NPZ = no-passing zones.

Then, use of Equation 15-9 gives

$$PTSF = BPTSF + f_{np,PTSF}\left(\frac{v_{d,PTSF}}{v_{d,PTSF}+v_{o,PTSF}}\right)$$

$$PTSF = 71.3 + 21.0\left(\frac{842}{842+842}\right) = 81.8\%$$

Step 7: Estimate PFFS

This step is only used for Class III highways.

Step 8: Determine LOS and Capacity

LOS is determined by comparing the estimated values of ATS and PTSF with the criteria of Exhibit 15-3. An ATS of 38.6 mi/h suggests that LOS E will exist. A PTSF of 81.8% suggests that LOS E will exist. Thus, both criteria lead to the conclusion that the segment will operate at LOS E.

Capacity is determined by either Equation 15-12 or Equation 15-13, whichever produces the lower estimate. Note, however, that all adjustment factors for use in these equations are based on a directional flow rate greater than 900 pc/h. Thus, the grade factor will be 1.00 for both ATS and PTSF. The passenger car equivalent for trucks is 1.3 for ATS and 1.00 for PTSF; the passenger car equivalent for RVs is 1.1 for ATS and 1.00 for PTSF.

The adjustment factors for heavy vehicles are as follows:

$$f_{HV,ATS} = \frac{1}{1+0.14\,(1.3-1)+0.04\,(1.1-1)} = 0.96$$

$$f_{HV,PTSF} = \frac{1}{1 + 0.14\,(1.0 - 1) + 0.04\,(1.0 - 1)} = 1.00$$

and

$$c_{dATS} = 1700 \times f_{g,ATS} \times f_{HV,ATS} = 1{,}700 \times 1.00 \times 0.960 = 1{,}632 \text{ veh/h}$$

$$c_{dPTSF} = 1700 \times f_{g,PTSF} \times f_{HV,PTSF} = 1{,}700 \times 1.00 \times 1.00 = 1{,}700 \text{ veh/h}$$

Obviously, the first value holds, and the directional capacity of this facility is 1,632 veh/h. Given the 50/50 directional distribution, the two-way capacity of the segment is 1,632 + 1,632 = 3,264 veh/h. Because this exceeds the limiting capacity of 3,200 pc/h, the directional capacity cannot be achieved with a 50/50 directional distribution. A total two-way capacity of 3,200 pc/h would prevail. In terms of prevailing conditions, the capacity would be 3,200 × 1.00 × 0.960 = 3,072 veh/h. With a 50/50 directional split, this implies a directional capacity of 3,072/2 = 1,536 veh/h.

Discussion

The two-lane highway segment as described is expected to operate poorly, within LOS E. The operation is poor despite the fact that demand is only 842/1,536 = 0.55 of capacity. Both ATS and PTSF are at unacceptable levels (38.6 mi/h and 81.8%, respectively). This solution again highlights the characteristic of two-lane highways of having poor operations at relatively low v/c ratios. This segment should clearly be examined for potential improvements.

Given the 50/50 directional split of traffic, results for the second direction would be identical.

EXAMPLE PROBLEM 2: CLASS II HIGHWAY LOS

The Facts

A segment of Class II highway is part of a scenic and recreational route and has the following known characteristics:

- Class II highway
- 1,050 veh/h (both directions)
- 70/30 directional split
- 5% trucks; 7% RVs
- PHF = 0.85
- 10-ft lanes; 2-ft shoulders
- BFFS = 55.0 mi/h
- Rolling terrain
- 10 access points/mi
- 60% no-passing zones

Comments

Computational Steps 3 and 4, which relate to the estimation of average highway speed, will not be included. LOS for Class II highways depends solely on PTSF. The analysis will be conducted for both the 70% direction of flow and the 30% direction of flow. This is accomplished by merely reversing the analysis direction and opposing flows.

Step 1: Input Data

All input data have been summarized above.

Step 2: Estimate the FFS

FFS is estimated with Equation 15-2. Adjustment factors for lane and shoulder width (Exhibit 15-7) and access points per mile (Exhibit 15-8) are used.

Exhibit 15-7 is entered with 10-ft lanes and 2-ft shoulders. The resulting adjustment is 3.7 mi/h. Exhibit 15-8 is entered with 10 access points/mi. The resulting adjustment is 2.5 mi/h. The FFS is then estimated as follows:

$$FFS = 55.0 - 3.7 - 2.5 = 48.8 \text{ mi/h}$$

Steps 3 and 4

Steps 3 and 4 are not required for Class II highways.

Step 5: Demand Adjustment for PTSF

Equation 15-7 and Equation 15-8 are used to adjust analysis direction and opposing demands to flow rates under equivalent base conditions. With a 70/30 split of traffic, the two demands are as follows:

$$V_{70\%} = V_1 = 1{,}050 \times 0.70 = 735 \text{ veh/h}$$

$$V_{30\%} = V_2 = 1{,}050 \times 0.30 = 315 \text{ veh/h}$$

In this solution, directions will be referred to as 1 and 2. Since both directions are to be analyzed, their position as "analysis direction" and "opposing" will depend on which direction is under study.

Adjustment factors both for grades (Exhibit 15-16) and for heavy vehicles (Exhibit 15-18) are needed. Exhibit 15-16 and Exhibit 15-18 are entered with a directional flow rate of 735/0.85 = 865 veh/h (Direction 1) and 315/0.85 = 371 veh/h (Direction 2). Interpolation is required in both. The following values are obtained:

$f_{g,PTSF}$ = 1.00 (Direction 1); 0.89 (Direction 2)

E_T = 1.0 (Direction 1); 1.6 (Direction 2)

E_R = 1.0 (Direction 1); 1.0 (Direction 2)

The heavy vehicle adjustment factor for both directions is computed with Equation 15-8:

$$f_{HV,PTSF1} = \frac{1}{1 + 0.05(1.00 - 1) + 0.07(1.00 - 1)} = 1.00$$

$$f_{HV,PTSF2} = \frac{1}{1+0.05(1.6-1)+0.07(1.00-1)} = 0.97$$

The adjusted demand flow rates are computed with Equation 15-7:

$$v_{1,PTSF} = \frac{735}{0.85\times1.00\times1.00} = 865 \text{ pc/h}$$

$$v_{2,PTSF} = \frac{315}{0.85\times0.89\times0.97} = 429 \text{ pc/h}$$

Step 6: Estimate PTSF

PTSF is estimated with Equation 15-9 and Equation 15-10 with values a and b taken from Exhibit 15-20 and $f_{np,PTSF}$ taken from Exhibit 15-21.

Exhibit 15-20 is entered with opposing flow rates of 429 pc/h (for Direction 1) and 865 pc/h (for Direction 2). Both values must be interpolated. The resulting values are as follows:

Direction 1: $a = -0.0024$; $b = 0.915$

Direction 2: $a = -0.0046$; $b = 0.832$

Exhibit 15-21 is entered with the total demand flow rate of 865 + 429 = 1,294 pc/h, a directional split of 70/30, and 60% no-passing zones. Interpolation is required. The factor is the same for both Directions 1 and 2:

$$f_{np,PTSF} = 23.0\%$$

BPTSF is computed with Equation 15-10:

$$BPTSF_1 = 100\left[1-\exp(-0.0024\times865^{0.915})\right] = 68.9\%$$

$$BPTSF_2 = 100\left[1-\exp(-0.0046\times429^{0.832})\right] = 51.0\%$$

The PTSF for each direction is computed with Equation 15-9:

$$PTSF_1 = 68.9 + 23.0\left(\frac{865}{865+429}\right) = 84.3\%$$

$$PTSF_2 = 51.0 + 23.0\left(\frac{429}{429+865}\right) = 58.6\%$$

Step 7

Step 7 is only used for Class III highways.

Step 8: Determine LOS and Capacity

The LOS is determined by comparing the PTSF values obtained with the criteria of Exhibit 15-3. Applying these criteria reveals that Direction 1 operates at LOS D, while Direction 2 operates at LOS C.

By using the adjustment selected for ≥900 veh/h, capacity is computed with Equation 15-13:

$$c_{1,PTSF} = 1{,}700\times1.00\times1.00 = 1{,}700 \text{ veh/h}$$

$$c_{2,PTSF} = 1{,}700 \times 1.00 \times 1.00 = 1{,}700 \text{ veh/h}$$

Discussion

The LOS is, at best, somewhat marginal on this two-lane highway segment, based solely on the PTSF.

The value of capacity must be carefully considered. If the directional capacities were expanded to two-way capacities based on the given demand split, the capacity in the 30% direction would imply a two-way capacity well in excess of the 3,200 pc/h limitation for both directions. Therefore, even though a capacity of 1,700 veh/h is possible in the 30% direction, it could not occur with a 70/30 demand split. In this case, the two-way capacity would be limited by the capacity in the 70% direction and would be 1,700/0.70 = 2,429 veh/h. The practical capacity for the 30% direction of flow is actually best estimated as 2,429 – 1,700 or 729 veh/h. Given that the 70/30 directional split holds, when the 30% direction reaches a demand flow rate of 729 veh/h, the opposing direction (the 70% side) would be at its capacity.

EXAMPLE PROBLEM 3: CLASS III HIGHWAY LOS

The Facts

A Class III two-lane highway runs through a rural community in level terrain. It has the following known characteristics:

- Class III highway
- Demand volume = 900 veh/h (both directions)
- 10% trucks; no RVs
- Measured FFS = 40 mi/h
- 12-ft lanes; 6-ft shoulders
- PHF = 0.88
- 80% no-passing zones
- 60/40 directional split
- 40 access points/mi
- Level terrain

Comments

Because this is a Class III highway, LOS will be based on PFFS. Thus, Steps 5 and 6, which relate to the estimation of PTSF, will not be used.

Step 1: Input Data

All input data are specified above.

Step 2: Estimate FFS

A measured FFS is specified: 40 mi/h.

Step 3: Demand Adjustment for ATS

The total demand volume of 900 veh/h must be separated into two directional flows. Since both directions will be evaluated, directions are labeled 1 and 2.

$$V_1 = 900 \times 0.60 = 540 \text{ veh/h}$$

$$V_2 = 900 \times 0.40 = 360 \text{ veh/h}$$

The adjusted demand flow rate in passenger cars per hour under equivalent base conditions is estimated with Equation 15-3. A grade adjustment factor is selected from Exhibit 15-9, and passenger car equivalents for trucks are selected from Exhibit 15-11. Both exhibits are entered with a demand flow rate in vehicles per hour:

$$v_1 = 540 / 0.88 = 614 \text{ veh/h}$$

$$v_2 = 360 / 0.88 = 409 \text{ veh/h}$$

The following values are selected from Exhibit 15-9 and Exhibit 15-11. In all cases, interpolation is required:

Value	Direction 1	Direction 2
$f_{g,ATS}$	1.00	1.00
E_T	1.1	1.3

Then, use of Equation 15-4 gives

$$f_{HV,ATS(1)} = \frac{1}{1 + 0.10(1.1 - 1)} = 0.99$$

$$f_{HV,ATS(2)} = \frac{1}{1 + 0.10(1.3 - 1)} = 0.97$$

Use of Equation 15-3 gives

$$v_{1ATS} = \frac{540}{0.88 \times 1.00 \times 0.99} = 620 \text{ pc/h}$$

$$v_{2ATS} = \frac{360}{0.88 \times 1.00 \times 0.97} = 422 \text{ pc/h}$$

Step 4: Estimate ATS

ATS is estimated with Equation 15-6 with an adjustment factor for no-passing zones taken from Exhibit 15-15. The adjustment factor is based on a 40-mi/h FFS and 80% no-passing zones. Interpolating for an opposing demand flow rate of 422 pc/h (Direction 1) and 620 pc/h (Direction 2) gives the following:

$$f_{np,ATS(1)} = 2.4 \text{ mi/h}$$

$$f_{np,ATS(2)} = 1.6 \text{ mi/h}$$

Then, use of Equation 15-6 gives

$$ATS_1 = 40.0 - 0.00776(620 + 422) - 2.4 = 29.5 \text{ mi/h}$$

$$ATS_2 = 40.0 - 0.00776(422 + 620) - 1.6 = 30.3 \text{ mi/h}$$

Steps 5 and 6

Steps 5 and 6 are not used for Class III highways.

Step 7: Estimate PFFS

The LOS for Class III facilities is based on PFFS achieved, or ATS/FFS. For this segment PFFS is as follows:

$$PFFS_1 = 29.5 / 40.0 = 73.8\%$$

$$PFFS_2 = 30.3 / 40.0 = 75.8\%$$

Step 8: Determine LOS and Capacity

From Exhibit 15-3, the LOS for Direction 1 is D, while the LOS for Direction 2 is C. The two values of PFFS are close, but the boundary condition between LOS C and D is 0.75. To be LOS C, PFFS must exceed 0.75, and it is just below the threshold in Direction 1 and just above the threshold in Direction 2.

Capacity is evaluated with adjustment factors for ≥900 pc/h in level terrain. This makes all adjustment factors 1.00 (for ATS). Thus, the capacity in either direction is as follows:

$$c_{1,ATS} = c_{2,ATS} = 1{,}700 \times 1.00 \times 1.00 = 1{,}700 \text{ veh/h}$$

The two-way capacity values implied are 1,700/0.60 = 2,833 veh/h (Direction 1) and 1,700/0.40 = 4,250 veh/h (Direction 2). Obviously, the implied two-way capacity is the 2,833 veh/h. Moreover, this suggests that the directional capacity in Direction 2 cannot be achieved with a 60/40 demand split. Rather, the directional capacity in Direction 2 occurs when the capacity in Direction 1 occurs, or 2,833 × 0.40 = 1,133 veh/h.

Discussion

This segment of Class III two-lane highway operates just at the LOS C–D boundary. Depending on the length of the segment and local expectations, this may or may not be acceptable.

EXAMPLE PROBLEM 4: CLASS I HIGHWAY LOS WITH A PASSING LANE

The Facts

The 10-mi segment of the two-lane highway analyzed in Example Problem 1 will be improved with 2-mi passing lanes (one in each direction), both installed at 1.00 mi from the segment's beginning. The segment without a passing lane has already been analyzed, and the results of that analysis are listed below:

- Demand volume = 800 veh/h in each direction
- Demand flow rate (ATS) = 902 pc/h in each direction
- Demand flow rate (PTSF) = 842 pc/h in each directions

- FFS = 53.3 mi/h
- ATS = 38.6 mi/h
- PTSF = 81.8%
- Rolling terrain
- PHF = 0.95

Comments

Both directions will involve the same computations, since the directional distribution is 50/50, and in both cases, the passing lane will start 1.00 mi after the beginning of the segment (of 10 mi) and will end 3.00 mi after the beginning of the segment.

Step 1: Conduct an Analysis Without the Passing Lane

Completed as Example Problem 1.

Step 2: Divide the Segment into Regions

Exhibit 15-35 shows the division of the 6-mi segment into regions. The effective downstream length of the passing lane is selected from Exhibit 15-23 (value is different for ATS and PTSF) for a demand flow rate of 800/0.95 = 842 veh/h.

Exhibit 15-35
Region Lengths for Use in Example Problem 4

To Determine	L_u (mi)	L_{pl} (mi)	L_{de} (mi) Exhibit 15-23	L_d (mi) Equation 15-14
ATS	1.00	2.00	1.7	5.3
PTSF	1.00	2.00	4.7	2.3

Step 3: Determine the PTSF

The PTSF, as affected by the presence of a passing lane, is estimated with Equation 15-15 and an adjustment factor selected from Exhibit 15-26. The adjustment factor $f_{pl,PTSF}$ is 0.62. Then

$$PTSF_{pl} = \frac{PTSF\left[L_u + L_d + f_{pl,PTSF} L_{pl} + \left(\frac{1 + f_{pl,PTSF}}{2}\right) L_{de}\right]}{L_t}$$

$$PTSF_{pl} = \frac{81.8\left[1.0 + 2.3 + (0.62 \times 2.00) + \left(\frac{1 + 0.62}{2}\right) 4.7\right]}{10}$$

$$PTSF_{pl} = \frac{81.8(3.3 + 1.24 + 3.81)}{10} = \frac{81.8 \times 8.35}{10} = 68.3\%$$

Step 4: Determine the ATS

The ATS as affected by the presence of a passing lane is found with Equation 15-17 and an adjustment factor selected from Exhibit 15-28. The adjustment factor selected is 1.11. Then

$$ATS_{pl} = \frac{ATSL_t}{L_u + L_d + \left(\dfrac{L_{pl}}{f_{pl,ATS}}\right) + \left(\dfrac{2L_{de}}{1 + f_{pl,ATS}}\right)}$$

$$ATS_{pl} = \frac{38.6 \times 10}{1.00 + 5.3 + \left(\dfrac{2.00}{1.11}\right) + \left(\dfrac{2 \times 11.7}{1 + 1.11}\right)}$$

$$ATS_{pl} = \frac{38.6 \times 110}{6.30 + 1.80 + 1.61} = \frac{38.6 \times 110}{9.71} = 39.7 \text{ mi/h}$$

Step 5: Determine the LOS

Exhibit 15-3 shows that the LOS, as determined by PTSF, has improved to D. The LOS determined by ATS remains E. Thus, while PTSF has improved significantly, the ATS has not improved enough to improve the overall LOS, which remains E.

Discussion

Adding a 2-mi passing lane to a 10-mi segment of Class I highway operating at LOS E was insufficient to improve the overall LOS, although the PTSF did improve from 81.8% to 68.3%. It is likely that a longer (or a second) passing lane would be needed to improve the ATS sufficiently to result in LOS C or LOS D.

EXAMPLE PROBLEM 5: TWO-LANE HIGHWAY BICYCLE LOS

A segment of two-lane highway (without passing lanes) is being evaluated for potential widening, realigning, and repaving. Analyze the impacts of the proposed project on the bicycle LOS in the peak direction.

The Facts

The roadway currently has the following characteristics:

- Lane width = 12 ft
- Shoulder width = 2 ft
- Pavement rating = 3 (fair)
- Posted speed limit = 50 mi/h
- Hourly directional volume = 500 veh/h (no growth is expected)
- Percentage of heavy vehicles = 5%
- PHF = 0.90
- No on-highway parking

The proposed roadway design has the following characteristics:

- Lane width = 12 ft
- Shoulder width = 6 ft
- Pavement rating = 5 (very good)
- Posted speed limit = 55 mi/h
- No on-highway parking

Step 1: Gather Input Data

All data needed to perform the analysis are listed above.

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

By using the hourly directional volume and the PHF, calculate the directional demand flow rate with Equation 15-24. Because this is a two-lane highway segment without a passing lane, the number of directional lanes N is 1. Because traffic volumes are not expected to grow over the period of the analysis, v_{OL} is the same for both current and future conditions.

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

$$v_{OL} = \frac{500}{0.90 \times 1} = 556 \text{ veh/h}$$

Step 3: Calculate the Effective Width

For current conditions, the hourly directional demand V is greater than 160 veh/h and the paved shoulder width is 2 ft; therefore, Equation 15-27 and Equation 15-28 are used to determine the effective width of the outside lane. Under future conditions, the paved shoulder width will increase to 6 ft; therefore, Equation 15-26 and Equation 15-28 are used.

For current conditions:

$$W_v = W_{OL} + W_s = 12 \text{ ft} + 2 \text{ ft} = 14 \text{ ft}$$

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

$$W_e = 14 \text{ ft} + (0 \times (2 \text{ ft} + 2 \text{ ft})) = 14 \text{ ft}$$

Under the proposed design:

$$W_v = W_{OL} + W_s = 12 \text{ ft} + 6 \text{ ft} = 18 \text{ ft}$$

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

$$W_e = 18 \text{ ft} + 6 \text{ ft} - 2 \times (0 \times (2 \text{ ft} + 6 \text{ ft})) = 24 \text{ ft}$$

Step 4: Calculate the Effective Speed Factor

Equation 15-30 is used to calculate the effective speed factor. Under current conditions:

$$S_t = 1.1199 \ln(S_p - 20) + 0.8103$$

$$S_t = 1.1199\ln(50-20) + 0.8103 = 4.62$$

Under the proposed design:

$$S_t = 1.1199\ln(55-20) + 0.8103 = 4.79$$

Step 5: Determine the LOS

Equation 15-31 is used to calculate the bicycle LOS score, which is then used in Exhibit 15-4 to determine the LOS. Under existing conditions:

$$BLOS = 0.507\ln(v_{OL}) + 0.1999 S_t (1 + 10.38 HV)^2$$
$$+ 7.066(1/P)^2 - 0.005(W_e)^2 + 0.057$$

$$BLOS = 0.507\ln(556) + 0.1999(4.62)(1 + 10.38 \times 0.05)^2$$
$$+ 7.066(1/3)^2 - 0.005(14)^2 + 0.057$$

$$BLOS = 3.205 + 2.131 + 0.785 - 0.980 + 0.057 = 5.20$$

Therefore, the bicycle LOS for existing conditions is LOS E. Use of the same process for the proposed design results in the following:

$$BLOS = 0.507\ln(556) + 0.1999(4.79)(1 + 10.38 \times 0.05)^2$$
$$+ 7.066(1/5)^2 - 0.005(24)^2 + 0.057$$

$$BLOS = 3.205 + 2.209 + 0.283 - 2.880 + 0.057 = 2.87$$

The corresponding LOS for the proposed design is LOS C.

Discussion

Although the posted speed would increase as a result of the proposed design, this negative impact on bicyclists would be more than offset by the proposed shoulder widening, as indicated by the improvement from LOS E to LOS C.

5. REFERENCES

Many of these references can be found in the Technical Reference Library in Volume 4.

1. Harwood, D. W., A. D. May, Jr., I. B. Anderson, and A. R. Archilla. *Capacity and Quality of Service of Two-Lane Highways*. Final report, NCHRP Project 3-55(3). Midwest Research Institute, Kansas City, Mo., 1999.
2. Harwood, D. W., I. B. Potts, K. M. Bauer, J. A. Bonneson, and L. Elefteriadou. *Two-Lane Road Analysis Methodology in the Highway Capacity Manual*. Final report, NCHRP Project 20-7(160). Midwest Research Institute, Kansas City, Mo., Sept. 2003.
3. Washburn, S. S., D. S. McLeod, and K. G. Courage. Adaptation of *Highway Capacity Manual* 2000 for Planning-Level Analysis of Two-Lane and Multilane Highways in Florida. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1802*, Transportation Research Board of the National Academies, Washington D.C., 2002, pp. 62–68.
4. Zegeer, J. D., M. A. Vandehey, M. Blogg, K. Nguyen, and M. Ereti. *NCHRP Report 599: Default Values for Highway Capacity and Level of Service Analyses.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
5. 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.
6. Harwood, D. W., and C. J. Hoban. *Low Cost Methods for Improving Traffic Conditions on Two-Lane Roads—Informational Guide.* Report FHWA-IF-87/2. U.S. Department of Transportation, Washington, D.C., Jan. 1987.
7. *A Policy on Geometric Design of Streets and Highways.* American Association of State Highway and Transportation Officials, Washington, D.C., 2004.
8. *Highway Performance Monitoring System Field Manual*, Chapter 4. Federal Highway Administration, Washington, D.C., May 2005.
9. Courage, K. G., S. Washburn, L. Elefteriadou, and D. Nam. *Guidance for the Use of Alternative Traffic Analysis Tools in Highway Capacity Analyses.* National Cooperative Highway Research Program Project 3-85 Final Report. University of Florida, Gainesville, 2010.

APPENDIX A: DESIGN AND OPERATIONAL TREATMENTS

Two-lane highways make up approximately 80% of all paved rural highways in the United States but carry only about 30% of all traffic. For the most part, two-lane highways carry light volumes and experience few operational problems. Some two-lane highways, however, periodically experience significant operational and safety problems brought about by a variety of traffic, geometric, and environmental causes. Such highways may require design or operational improvements to alleviate congestion.

When traffic operational problems occur on two-lane highways, many agencies consider widening to four lanes. Another effective method for alleviating operational problems is to provide passing lanes at intervals in each direction of travel or to provide climbing lanes on steep upgrades. Passing and climbing lanes cannot increase the capacity of a two-lane highway, but they can improve its LOS. Short sections of four-lane highway can function as a pair of passing lanes in opposite directions of travel. Operational analysis procedures for passing and climbing lanes are included in this chapter.

A number of other design and operational treatments are effective in alleviating operational congestion on two-lane highways, including

- Turnouts,
- Shoulder use,
- Wide cross sections,
- Intersection turn lanes, and
- Two-way left-turn lanes.

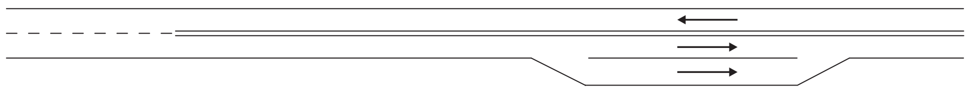
No calculation methodologies are provided in this chapter for these treatments; however, the treatments are discussed below to indicate their potential for improving traffic operations on two-lane highways.

TURNOUTS

A turnout is a widened, unobstructed shoulder area on a two-lane highway that allows slow-moving vehicles to pull out of the through lane so that vehicles following may pass. Turnouts are relatively short, generally less than 625 ft. At a turnout, the driver of a slow-moving vehicle that is delaying one or more following vehicles is expected to pull out of the through lane, allowing the vehicles to pass. The driver of the slow-moving vehicle is expected to remain in the turnout only long enough to allow the following vehicle to pass before returning to the travel lane. When there are only one or two following vehicles, this maneuver can usually be completed smoothly, with no need for the vehicle to stop in the turnout. When there are three or more following vehicles, however, the vehicle in the turnout will generally have to stop to allow all vehicles to pass. In this case, the driver of the slower vehicle is expected to stop before the end of the turnout, so that the vehicle will develop some speed before reentering the lane. Signs inform drivers of the turnout's location and reinforce the legal requirements concerning turnout use.

Turnouts have been used in several countries to provide additional passing opportunities on two-lane highways. In the United States, turnouts have been used extensively in western states. Exhibit 15-A1 illustrates a typical turnout.

Exhibit 15-A1
Typical Turnout Illustrated



Turnouts may be used on nearly any type of two-lane highway that offers limited passing opportunities. To avoid confusing drivers, turnouts and passing lanes should not be intermixed on the same highway.

A single well-designed and well-located turnout can be expected to accommodate 20% to 50% of the number of passes that would occur in a 1.0-mi passing lane in level terrain (*A1, A2*). Turnouts have been found to operate safely, with experts (*A2–A4*) noting that turnout accidents occur at a rate of only 1 per 80,000 to 400,000 users.

SHOULDER USE

The primary purpose of the shoulder on two-lane highways is to provide a stopping and recovery area for disabled or errant vehicles. However, paved shoulders also may be used to increase passing opportunities on two-lane highways.

In some parts of the United States and Canada, if the paved shoulders are adequate, there is a long-standing custom for slower vehicles to move to the shoulder when a vehicle approaches from the rear. The slower vehicle then returns to the travel lane once the passing vehicles has cleared. The custom is regarded as a courtesy and requires little or no sacrifice in speed by either motorist. A few highway agencies encourage drivers of slow-moving vehicles to use the shoulder in this way because it improves the LOS of two-lane highways without the expense of adding passing lanes or widening the highway. On the other hand, there are agencies that discourage this practice because their shoulders are not designed for frequent use by heavy vehicles.

One highway agency in the western United States generally does not permit shoulder use by slow-moving vehicles but designates specific sections on which the shoulder may be used for this purpose. These shoulder segments range in length from 0.2 to 3.0 mi and are identified by traffic signs.

Research (*A1, A2*) has shown that a shoulder-use segment is about 20% as effective in reducing platoons as a passing lane of comparable length.

WIDE CROSS SECTIONS

Two-lane highways with lanes about 50% wider than normal have been used in several European countries as a less expensive alternative to passing lanes. Sweden, for example, built approximately 500 mi of roadways with two 18-ft travel lanes and relatively narrow (3.3-ft) shoulders. The wider lane permits faster vehicles to pass slower vehicles while encroaching only slightly on the opposing lane of traffic. Opposing vehicles must move toward the shoulder to permit such maneuvers. Roadway segments with wider lanes can be provided at intervals, like passing lanes, to increase passing opportunities on two-lane highways.

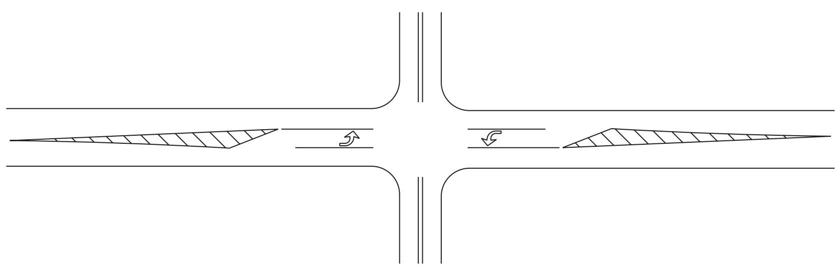
Research has shown that speeds at low traffic volumes tend to increase on wider lanes, but the effect on speeds at higher volumes varies (*A5*). More than 70% of drivers indicated that they appreciate the increased passing opportunities available on the wider lanes. No safety problems have been associated with the wider lanes.

Formal procedures have not yet been developed for evaluating the traffic operational effectiveness of wider lanes in increasing the passing opportunities on a two-lane highway. It is reasonable to estimate the traffic operational performance on a directional two-lane highway segment containing wider lanes as midway between the segment with and without a passing lane of comparable length.

INTERSECTION TURN LANES

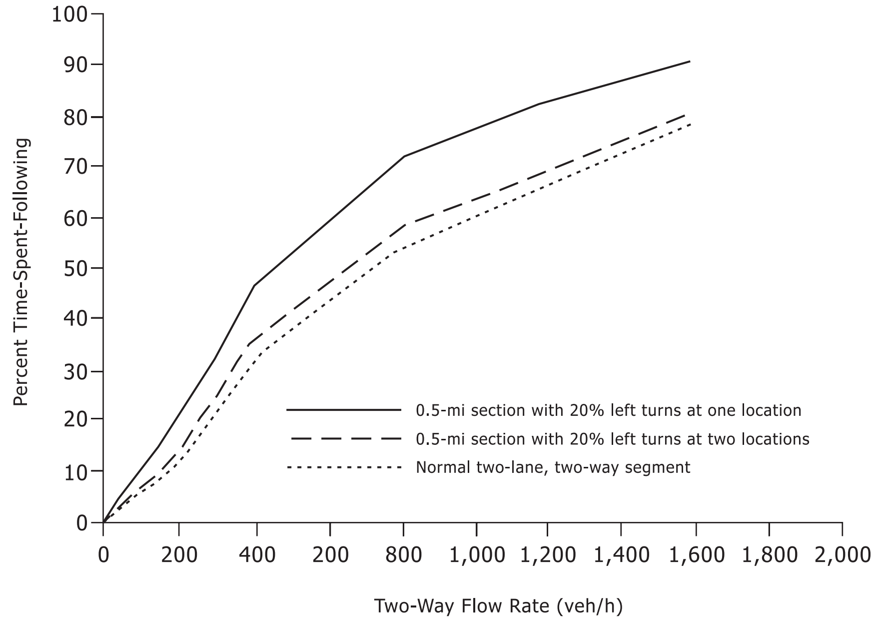
Intersection turn lanes are desirable at selected locations on two-lane highways to reduce delays to through vehicles cased by turning vehicles and to reduce turning accidents. Separate right- and left-turn lanes may be provided, as appropriate, to remove turning vehicles from the through travel lanes. Left-turn lanes, in particular, provide a protected location for turning vehicles to wait for an acceptable gap in the opposing traffic stream. This reduces the potential for collisions from the rear and may encourage drivers of left-turning vehicles to wait for an adequate gap in opposing traffic before turning. Exhibit 15-A2 shows a typical two-lane highway with left-turn lanes at an intersection.

Exhibit 15-A2
Typical Two-Lane Highway Intersection with Left-Turn Lane



Research recommends specific operational warrants for left-turn lanes at intersections on two-lane highways based on the directional volumes and the percentage of left turns (*A6*). The HCM's intersection analysis methodologies can be used to quantify the effects of intersection turn lanes on signalized and unsignalized intersections. There is no methodology, however, for estimating the effect of turn lanes on average highway speed. Modeling of intersection delays shows the relative magnitude of likely effects of turning delays on PTSF (*A7*); the results are shown in Exhibit 15-A3. The top line in the exhibit shows that turning vehicles can increase PTSF substantially over a short road segment. However, when these effects are averaged over a longer road segment, the increase in PTSF is greatly reduced, as indicated by the dashed line in the exhibit. The provision of intersection turn lanes has the potential to minimize these effects.

Exhibit 15-A3
Effect of Turning Delays at Intersections on PTSF

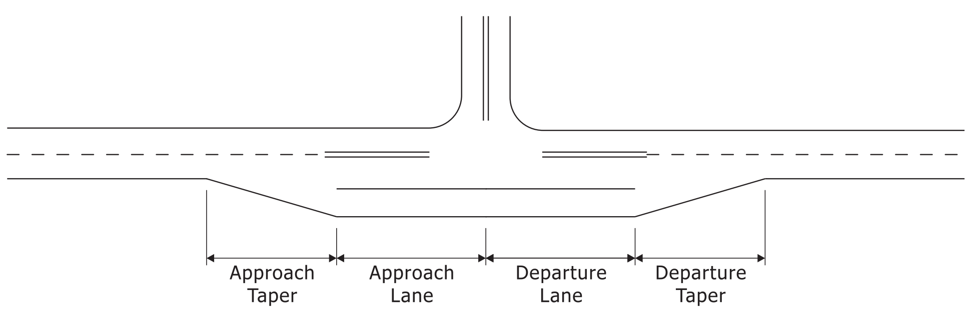


Source: Hoban (*A7*).

Several agencies in the United States provide shoulder bypass lanes at three-leg intersections as a low-cost alternative to a left-turn lane. As shown in Exhibit 15-A4, a portion of the paved shoulder may be marked as a lane for through traffic to bypass vehicles that are slowing or stopped to make a left turn. Bypass lanes may be appropriate for intersections that do not have volumes high enough to warrant a left-turn lane.

The delay benefits of shoulder bypass lanes have not been quantified, but field studies have indicated that 97% of drivers who need to avoid delay will make use of an available shoulder bypass lane. One state has reported a marked decrease in rear-end collisions at intersections where shoulder bypass lanes were provided (*A8*).

Exhibit 15-A4
Typical Shoulder Bypass Lane at a Three-Leg Intersection on a Two-Lane Highway

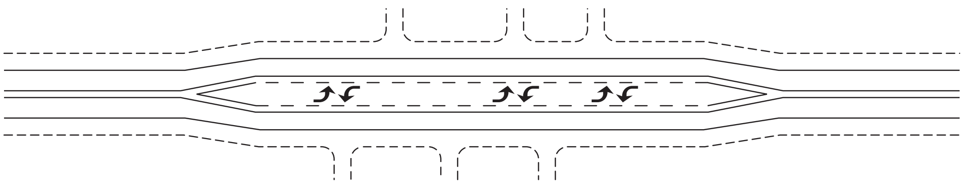


TWO-WAY LEFT-TURN LANES

A two-way left-turn lane (TWLTL) is a paved area in the highway median that extends continuously along a roadway segment and is marked to provide a deceleration and storage area for vehicles traveling in either direction that are making left turns at intersections and driveways.

TWLTLs have been used for many years on urban and suburban streets with high driveway densities and turning demands to improve safety and reduce delays to through vehicles. TWLTLs can be used on two-lane highways in rural and urban fringe areas to obtain the same types of operational and safety benefits—particularly on Class III two-lane highways. Exhibit 15-A5 illustrates a typical TWLTL.

Exhibit 15-A5
Typical TWLTL on a Two-Lane Highway

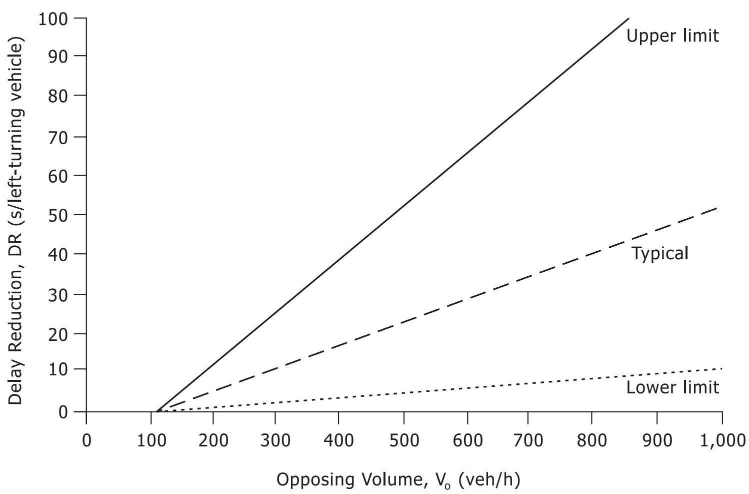


There is no formal methodology for evaluating the traffic operational effectiveness of a TWLTL on a two-lane highway. Research has found that delay reduction provided by a TWLTL depends on both the left-turn demand and the opposing traffic volume (*A2*). Without a TWLTL or other left-turn treatment, vehicles that are slowing or stopped to make a left turn may create delays for following through vehicles. A TWLTL minimizes these delays and makes the roadway segment operate more like two-way and directional segments with 100% no-passing zones. These research results apply to sites that do not have paved shoulders available for following vehicles to bypass turning vehicles. Paved shoulders may alleviate as much of the delay as a TWLTL.

Research has found little delay reduction at rural TWLTL segments with traffic volumes below 300 veh/h in one direction (*A2*). At several low-volume sites, no reduction was observed. The highest delay reduction observed was 3.4 s per left-turning vehicle. Therefore, at low-volume rural sites, TWLTLs should be considered for reducing accidents but should not be expected to improve the operational performance of the highway.

At higher-volume urban fringe sites, greater delay reduction was found with TWLTLs on a two-lane highway. Exhibit 15-A6 shows the expected delay reduction per left-turning vehicle as a function of opposing volume. As the delay reduction increases, a TWLTL can be justified for improving both safety and operations.

Exhibit 15-A6
Estimated Delay Reduction with a TWLTL on a Two-Lane Highway Without Paved Shoulders



Source: Harwood and St. John (*A2*).

REFERENCES

Some of these references can be found in the Technical Reference Library in Volume 4.

A1. Harwood, D. W., and C. J. Hoban. *Low-Cost Methods for Improving Traffic Operations on Two-Lane Roads*. Report FHWA-IP-87/2. U.S. Department of Transportation, Washington, D.C., Jan. 1987.

A2. Harwood, D. W., and A. D. St. John. *Passing Lanes and Other Operational Improvements on Two-Lane Highways*. Report FHWA/RD-85/028. U.S. Department of Transportation, Washington, D.C., July 1984.

A3. Rooney, F. D. *Turnouts—Summary Report: Traffic Operational Report No. 1*. California Department of Transportation, Sacramento, Nov. 1976.

A4. Rooney, F. D. *Turnouts: Traffic Operational Report No. 2*. California Department of Transportation, Sacramento, Nov. 1976.

A5. Bergh, T. 2+1 Roads with Cable Barrier for Improved Traffic Safety. *Proc., Third International Symposium on Highway Capacity*, Danish Road Directorate, Copenhagen, June 1998.

A6. Harmelink, M. D. Volume Warrants for Left-Turn Storage Lanes at Unsignalized Grade Intersections. In *Highway Research Record 211*, Highway Research Board, National Research Council, Washington, D.C., 1967, pp. 1–18.

A7. Hoban, C. J. *A Model for Predicting Turning and Platooning Delays.* Internal Report AIR 359-16. Australian Road Research Board, 1986.

A8. Sebastian, O. L., and R. S. Pusey. *Paved-Shoulder Left-Turn By-Pass Lanes: A Report on the Delaware Experience.* Delaware Department of Transportation, Oct. 1982.