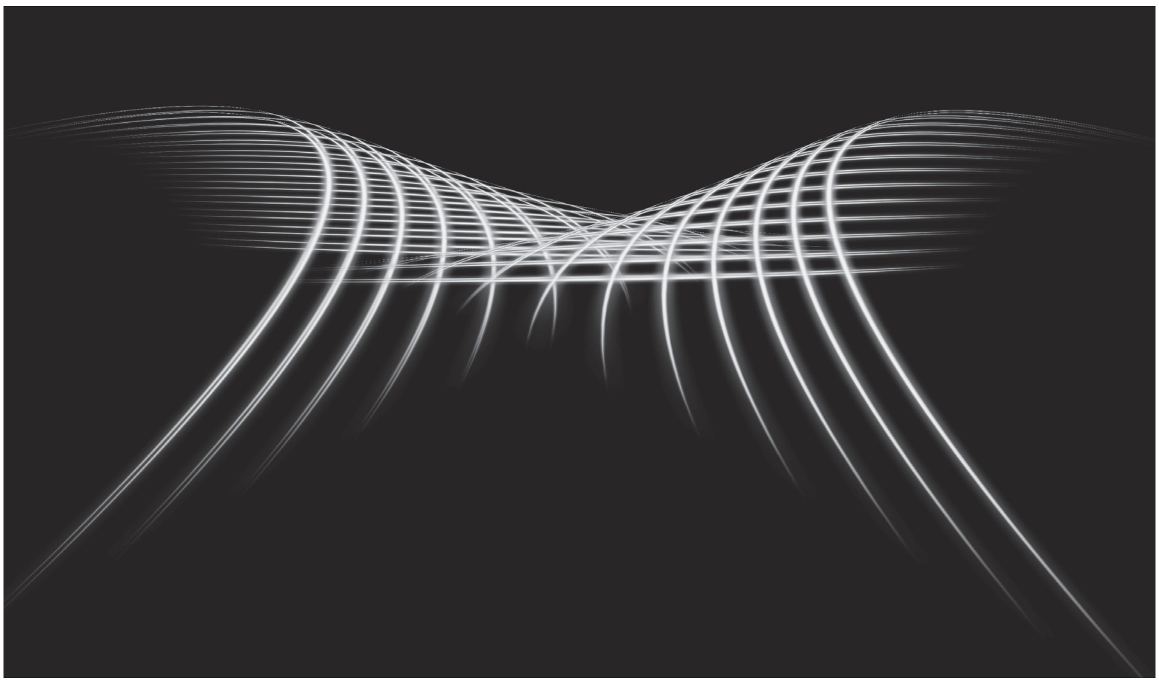
HCM2010

HIGHWAY CAPACITY MANUAL



VOLUME 4: APPLICATIONS GUIDE

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CHAPTER 38
MANAGED LANE FACILITIES

CONTENTS

1. INTRODUCTION..38-1
Segments and Influence Areas.. 38-1
Lane Group Concept 38-5
Basic ML Segment Speed–Flow Relationships 38-6
Basic ML Segment Characteristics... 38-9

2. BASIC ML SEGMENT SPEED–FLOW RELATIONSHIPS 38-12
Continuous Access Segments 38-13
Buffer 1 Segments 38-14
Buffer 2 Segments 38-15
Barrier 1 Segments...38-16
Barrier 2 Segments...38-17

3. ADJUSTMENTS FOR CROSS-WEAVE EFFECTS.......................................38-18

4. METHODOLOGY 38-20
Limitations of the Methodology 38-20
Overview of the Methodology..38-20
Computational Steps..38-21

5. EXAMPLE PROBLEMS..38-24
Example Problem 1: Barrier-Separated Reversible ML Facility 38-24
Example Problem 2: Buffer-Separated ML Facility......................................38-32

6. REFERENCES 38-43

LIST OF EXHIBITS

Exhibit 38-1 Comparison of GP and ML Segment Types 38-2
Exhibit 38-2 Typology of ML Access Point Designs 38-3
Exhibit 38-3 Defining Dimensions of APIA Through Minimum and Maximum Cross-Weave Lengths 38-5
Exhibit 38-4 Example of Continuous Access Basic ML Segment 38-7
Exhibit 38-5 Example of Buffer 1 Basic ML Segment 38-7
Exhibit 38-6 Example of Buffer 2 Basic ML Segment 38-8
Exhibit 38-7 Example of Barrier 1 Basic ML Segment...38-8
Exhibit 38-8 Example of Barrier 2 Basic ML Segment...38-9
Exhibit 38-9 Speed–Flow Curves for Different ML Basic Segment Types 38-10
Exhibit 38-10 Illustrative Impact of GP Lane Congestion on ML Speeds 38-11
Exhibit 38-11 Equations Describing Speed–Flow Curves for Continuous Access Segments (mi/h) 38-13
Exhibit 38-12 Speed–Flow Curves for Continuous Access Segments................38-13
Exhibit 38-13 Speed–Flow Curves for Buffer 1 Segments 38-14
Exhibit 38-14 Equations Describing Speed–Flow Curves for Buffer 1 Segments (mi/h) 38-14
Exhibit 38-15 Speed–Flow Curves for Buffer 2 Segments 38-15
Exhibit 38-16 Equations Describing Speed–Flow Curves for Buffer 2 Segments (mi/h) 38-15
Exhibit 38-17 Speed–Flow Curves for Barrier 1 Segments 38-16
Exhibit 38-18 Equations Describing Speed–Flow Curves for Barrier 1 Segments (mi/h) 38-16
Exhibit 38-19 Speed–Flow Curves for Barrier 2 Segments 38-17
Exhibit 38-20 Equations Describing Speed–Flow Curves for Barrier 2 Segments (mi/h) 38-17
Exhibit 38-21 CRF Estimates by Configuration Scenario....................................38-19
Exhibit 38-22 Methodological Flowchart for ML Facility Analysis....................38-21
Exhibit 38-23 Graphical Illustration of ML Segmentation Method 38-22
Exhibit 38-24 List of Example Problems 38-24
Exhibit 38-25 Example Problem 1: Lane Group Segmentation 38-24
Exhibit 38-26 Example Problem 1: GP Lane Group Demand Inputs 38-26
Exhibit 38-27 Example Problem 1: ML Lane Group Demand Inputs 38-26
Exhibit 38-28 Example Problem 1: GP Segment Capacities 38-27
Exhibit 38-29 Example Problem 1: ML Segment Capacities...............................38-27
Exhibit 38-30 Example Problem 1: GP Segment Demand-to-Capacity Ratios 38-27

Exhibit 38-31 Example Problem 1: ML Segment Demand-to-Capacity Ratios....38-28
Exhibit 38-32 Example Problem 1: GP Segment Volume-to-Capacity Ratios....38-28
Exhibit 38-33 Example Problem 1: GP Segment Space Mean Speeds....38-29
Exhibit 38-34 Example Problem 1: ML Segment Space Mean Speeds....38-29
Exhibit 38-35 Example Problem 1: GP Segment Densities....38-29
Exhibit 38-36 Example Problem 1: ML Segment Densities....38-29
Exhibit 38-37 Example Problem 1: GP Segment LOS....38-30
Exhibit 38-38 Example Problem 1: ML Segment LOS....38-30
Exhibit 38-39 Example Problem 1: Cumulative Speed and Travel Time Comparison for ML and GP Lanes....38-31
Exhibit 38-40 Example Problem 2: Lane Group Segmentation....38-32
Exhibit 38-41 Example Problem 2: GP Lane Group Demand Inputs....38-33
Exhibit 38-42 Example Problem 2: ML Lane Group Demand Inputs....38-34
Exhibit 38-43 Example Problem 2: GP Segment Capacities....38-34
Exhibit 38-44 Example Problem 2: ML Segment Capacities....38-35
Exhibit 38-45 Example Problem 2: Summary of Estimated Cross-Weave CRFs....38-35
Exhibit 38-46 Example Problem 2: GP Segment Demand-to-Capacity Ratios....38-36
Exhibit 38-47 Example Problem 2: ML Segment Demand-to-Capacity Ratios....38-36
Exhibit 38-48 Example Problem 2: GP Segment Volume-to-Capacity Ratios....38-37
Exhibit 38-49 Example Problem 2: ML Segment Volume-to-Capacity Ratios....38-37
Exhibit 38-50 Example Problem 2: GP Segment Space Mean Speeds....38-38
Exhibit 38-51 Example Problem 2: ML Segment Space Mean Speeds....38-38
Exhibit 38-52 Example Problem 2: GP Segment Densities....38-39
Exhibit 38-53 Example Problem 2: ML Segment Densities....38-39
Exhibit 38-54 Example Problem 2: GP Segment LOS....38-40
Exhibit 38-55 Example Problem 2: ML Segment LOS....38-40
Exhibit 38-56 Example Problem 2: Cumulative Speed and Travel Time Comparison for ML and GP Lanes....38-41

1. INTRODUCTION

This chapter serves as an extension of Chapter 10, Freeway Facilities. It provides methods for analyzing freeway facilities with a managed lane (ML) component. The methodology described in this chapter is largely based on results of NCHRP Project 3-96 (*1*). MLs (as defined in this chapter) may include high-occupancy vehicle (HOV) lanes, high-occupancy/toll (HOT) lanes, or express toll lanes. Freeways, as defined in the *Highway Capacity Manual* (HCM), are classified into a variety of segment types that may be analyzed to determine the capacity and level of service (LOS) at the segment or facility level. Three types of freeway segments are defined in Chapter 10, including *freeway merge and diverge segments*, *freeway weaving segments*, and *basic freeway segments*.

The procedures for general purpose (GP) lanes that are adjacent to the MLs build on this classification. In addition, a lane group concept is introduced to allow analysts to ascribe separate attributes to MLs and GP lanes while retaining a degree of interaction between the two facilities. The adjacent lane groups (one GP and one ML segment) are required to have the same segment length, but their segment types or separations do not have to be the same. For the ML group, five new segment types are defined in this chapter, including *ML basic*, *ML on-ramp*, *ML off-ramp*, *ML weave*, and *ML access segment*.

The NCHRP 3-96 research leading to this chapter found that the composition, driver type, free-flow speed (FFS), capacity, and behavior characteristics of ML traffic streams are different from those of GP lanes. In addition, interaction between the two facilities was evident, especially for ML facilities that do not have physical barrier separation from the GP lanes either en route or at access points. Therefore, certain features have been added to the newly defined ML segment types.

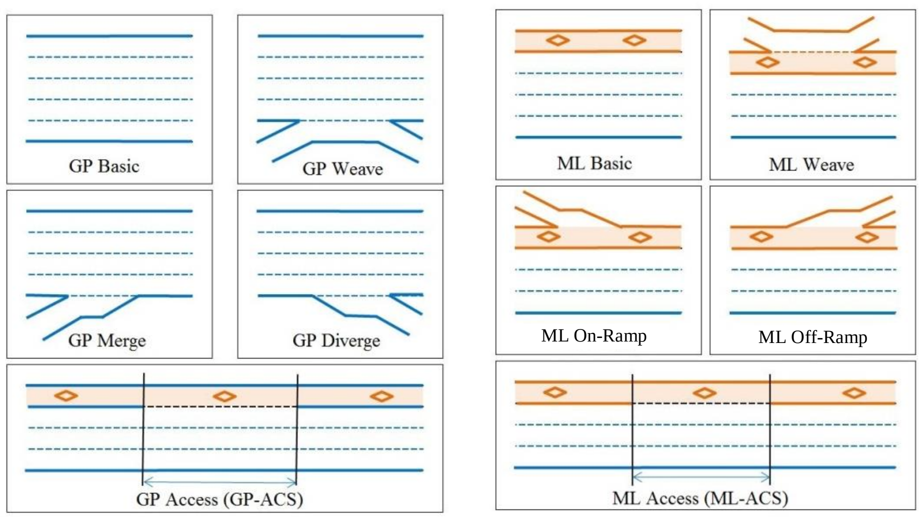
SEGMENTS AND INFLUENCE AREAS

The five ML segment types are presented in Exhibit 38-1 and are discussed below:

- *ML basic*: This segment type is analogous to the GP basic freeway segment but serves ML traffic demands. Five ML basic segment types are defined on the basis of the number of MLs and the type of separation between the two lane groups. New speed–flow models for these basic segments are developed in the NCHRP 3-96 research report and are presented in Section 2. Note that the continuous access ML segment type, where access between the managed and GP lanes is allowed at any point, is classified as one of the five ML basic types. It is distinguished from the ML access segment introduced later in this section.
- *ML on-ramp* and *ML off-ramp*: These segments are analogous to GP merge and diverge segments, but with ML traffic demands. ML on-ramp and off-ramp segments apply the GP ramp procedures from Chapter 13, with some necessary assumptions, as will be discussed later.

- *ML weave*: This segment is analogous to the GP weaving segment, but with ML weaving traffic demands. The operational characteristics of an ML weave segment are reasonably close to those of a GP weaving segment, and hence the Chapter 12 procedure for weaving segments can be applied.
- *ML access*: This is a new segment type that is unique to ML facilities with intermittent access. Lane changing between GP lanes and MLs can occur throughout the segment but is prohibited in the segments just before and after it. It is treated as a weaving segment, and the Chapter 12 weaving methodology is applied to compute its impact. By definition, an ML access segment is always parallel to a GP access segment, which is also shown in Exhibit 38-1. In the methodology, the operational performance of the concurrent ML and GP access segments is assumed to be estimated together for the entire cross section, and the results are applied to both ML and GP lane groups.

Exhibit 38-1
Comparison of GP and ML Segment Types



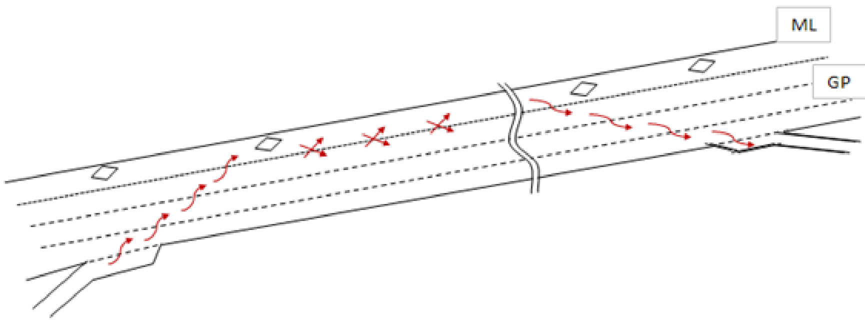
(a) GP segment types

(b) ML segment types

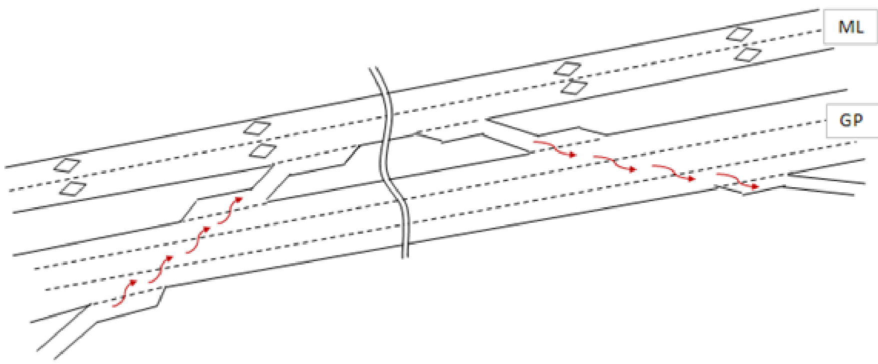
ML access segments are potential bottlenecks for an ML facility due to the interaction between ML and GP access segments. ML access point design plays an important role in the operational performance of ML facilities, in addition to the level of interactions between the managed and GP lanes. As illustrated in Exhibit 38-2, there are three principal types of ML access configurations:

A. **At-grade lane-change access (Type A)** occurs where ML traffic enters the GP lanes through a conventional on-ramp roadway (from the right), weaves across multiple GP lanes, and then enters the ML facility. ML traffic exits in the same segment, so this configuration is also a form of weaving movement. This access strategy is common for concurrent ML facilities. Access between ML and GP lanes is sometimes constrained to specific locations or openings, which affects the weaving intensity at these access points as well as the intensity of the two-sided weaving maneuver across the GP lanes. The Type A access configuration requires a *cross-weaving* movement across GP lanes for drivers to position themselves prior to the access point and a *lane-change movement* to get from the GP lanes into the MLs.

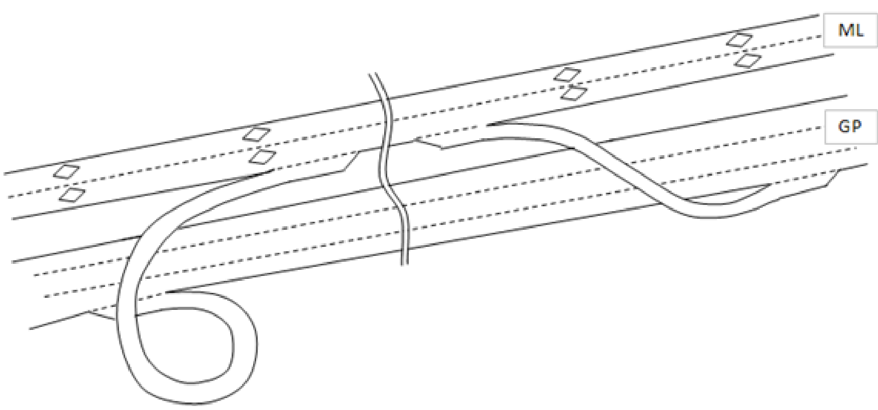
Exhibit 38-2
Typology of ML Access Point Designs



(a) At-Grade Lane Change Access



(b) At-Grade Ramp Access



(c) Grade-Separated Ramp Access

B. **At-grade ramp access (Type B)** occurs where ML traffic enters the GP lanes through a conventional on-ramp roadway (from the right). Entering and exiting traffic may weave across multiple GP lanes (similar to Case A), but the entrance to (or exit from) the ML facility is confined to an *at-grade* on-ramp or off-ramp. Operationally, the GP lanes may be affected by the cross-weaving flow as well as by the friction caused by the on- and off-ramps. The ML operations, in turn, are affected by the cross-weaving maneuvers to and from the access points at the ramps. The Type B access configuration requires a *cross-weaving* movement across GP lanes for drivers to position themselves prior to the access point and a *ramp movement* to get from the GP lanes into the ML.

C. **Grade-separated ramp access (Type C)** occurs where access to the MLs occurs on a grade-separated structure (i.e., flyover, bridge, or underpass). The operational impact on the GP lanes is minimal in this case, since the cross-weaving movement is eliminated. The MLs are affected by friction from the entering or exiting ramp flows in the same fashion as GP lanes. The Type C access configuration does not require any cross-weaving across GP lanes because of a grade-separated ramp, and the ML access is handled by a *ramp movement*.

The spatial extent of the *access-point influence area* (APIA) for Type C access is already defined in the HCM's ramp merge and diverge methodology. The ramp influence area for GP facilities is defined to be 1,500 ft from the ramp gore for both on-ramps (measured downstream) and off-ramps (measured upstream). The APIA for Type C ML access points follows the same convention.

For Type A and B accesses, the intensity and impact of the *cross-weaving flows* between a GP ramp and the access region between the GP and MLs need to be analyzed. The minimum cross-weave length ($L_{CW\text{-}Min}$) is defined as the distance between the closest upstream GP on-ramp gore and the start of the ML access opening. The maximum cross-weave length ($L_{CW\text{-}Max}$) is defined as the distance from the ramp gore to the end of the access opening.

Exhibit 38-3 illustrates this concept for a concurrent single ML next to three GP lanes with stripe separation. In this case, on-ramp vehicles desiring to enter the ML must complete all three lane-change maneuvers (not counting the merge from the acceleration lane); this results in cross-weave friction for the GP lane traffic. The NCHRP 3-96 research (*1*) indicates that most drivers attempt to complete the lane change maneuver as early as possible; this results in a lower operating speed and capacity on the GP lanes prior to the ML access point. The overall cross-weave intensity can be estimated on the basis of the number of lane change maneuvers, minimum and maximum available distances to complete all lane changes ($L_{CW\text{-}Min}$ and $L_{CW\text{-}Max}$), and the cross-weave demand. Beyond the effect of cross-weaves, intermittent-access MLs are analyzed as regular weaving segments by using the Chapter 12 procedures.

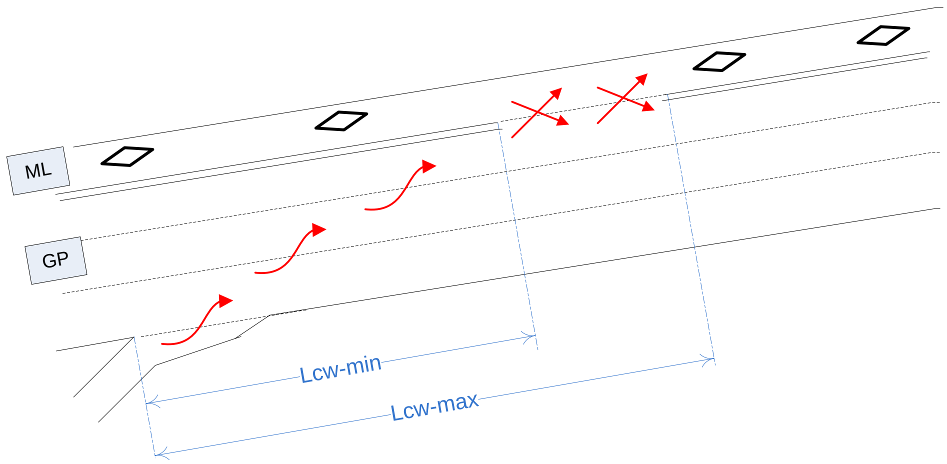


Exhibit 38-3
Defining Dimensions of APIA Through Minimum and Maximum Cross-Weave Lengths

LANE GROUP CONCEPT

To capture the interaction effects between ML and GP lanes while allowing for the varying demand, capacity, and speed inputs, the concept of *lane groups* is introduced for freeway MLs. The lane group concept is well established in the signalized intersection methodology in Chapter 18, where exclusive left-turn lanes are recognized to have geometric and driver behavior characteristics different from those of the adjacent through lanes or shared lanes. By adopting the lane group concept in the ML context, the analyst is able to ascribe separate attributes to parallel ML and GP facilities while retaining the ability to model a degree of interaction between the two.

Each segment of a freeway facility is represented as having either one or two lane groups, depending on whether a concurrent ML segment is present. Input variables such as geometric characteristics (e.g., number of lanes), traffic performance attributes (e.g., FFS, capacity), and traffic demands must be entered separately for each lane group. The methodology is then applied to assess the operational performance of each lane group, with consideration given to the empirically derived interaction effects between the two lane groups. If a portion of the facility has no ML, it is simply coded as a single GP lane group that serves all traffic demand.

The following principles apply:

- A freeway GP segment with a parallel ML segment is considered as two adjacent lane groups.
- Adjacent lane groups (one GP and one ML segment) must share the same segment lengths.
- Adjacent lane groups can be of different segment types. For example, a basic ML segment may be concurrent with an on-ramp GP segment.
- A lane group may have different geometric characteristics, including number of lanes, lane widths, shoulder clearance, and so on.
- A lane group may have unique attributes, including FFS, segment capacity, or various capacity- or speed-reducing friction factors. The attributes representing the GP speed–flow relationships are those

provided in the Chapter 10 freeway facility methodology. Many ML-specific relationships have been derived empirically in NCHRP 3-96 (*1*).

- A lane group may have unique traffic demand parameters, which are entered by the user and obtained through an external process. This chapter's operational methodology does not predict the split in demand between the managed and GP lanes.
- The operational performance of adjacent ML and GP lane groups is interdependent in that congestion in one lane group may have a frictional effect on operations in the adjacent lane group. This frictional effect was empirically derived, can be user-calibrated, and is sensitive to the type of physical separation between lane groups (e.g., striping, buffer, barrier).

The method assumes that all ML segments operate at a demand-to-capacity ratio less than 1 (i.e., $d/c < 1$), which means that no queuing or oversaturation would occur on ML segments. Oversaturated ML facilities are relatively rare in practice, since one of the underlying principles for ML operations (especially for HOT lanes) is to ensure that ML traffic density is below the critical density even in peak periods, which in turn guarantees satisfactory service to ML customers. Congestion on GP lanes can and should be considered by the method, since many facilities operate during peak periods with congested GP lanes and below-capacity ML volumes.

BASIC ML SEGMENT SPEED–FLOW RELATIONSHIPS

For basic ML segments, the separation type and number of lanes are the key factors affecting traffic flow behavior. A basic ML segment can be categorized into one of five segment types: continuous access, Buffer 1, Buffer 2, Barrier 1, and Barrier 2. Each of the five segment types is described below.

Continuous Access Separation

Under continuous access separation, which applies to single-lane, concurrent ML facilities, access between the ML and GP lanes is allowed at any point (e.g., with skip striping or a solid single line). ML entrances and exits are unrestricted. These facilities are typically located on the leftmost lane on freeways, parallel to the GP lanes, as illustrated in Exhibit 38-4 with a schematic and an aerial view of I-5 in Seattle, Washington. Although these types of facilities are common, they are more favorable to HOV than HOT lane operations, since continuous access is more difficult to manage for most tolling schemes.

Exhibit 38-4
Example of Continuous Access Basic ML Segment

Source: ©2014 Google.
Note: I-5, Seattle, Washington.

Buffer 1 Separation

Buffer 1 separation applies to a single-lane, concurrent ML facility with intermittent access. Similar to continuous access, these facilities are located in the leftmost lane of the freeway cross section. They are separated from the GP lane with a striped buffer. The striping techniques for Buffer 1 vary by location and can feature a double white line, a double yellow line, or two yellow stripes and one white stripe (as is typical in California). Access to and from the ML is limited to occasional buffer opening areas designated by dashed line separation. This geometry is commonly used for both HOV and HOT facilities. Exhibit 38-5 shows the basic schematic of a Buffer 1 facility along with an example from I-394 in Minneapolis, Minnesota. Note that the buffer opening itself is analyzed as a different ML segment type.

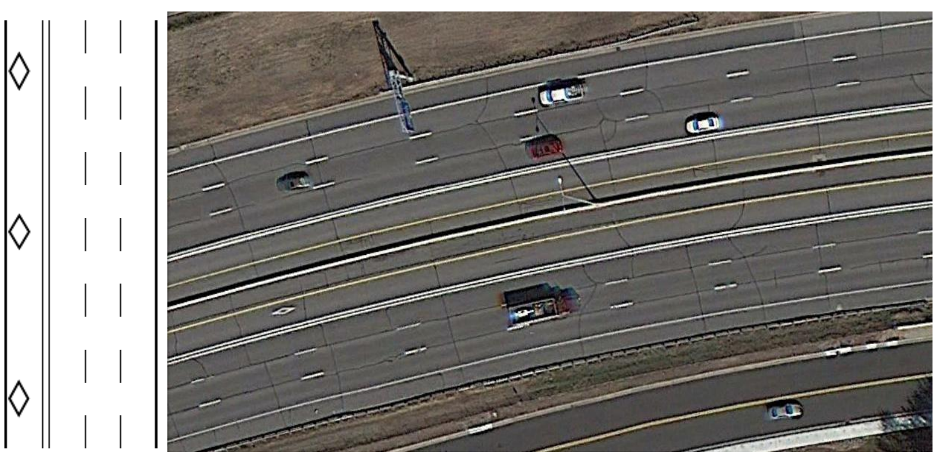


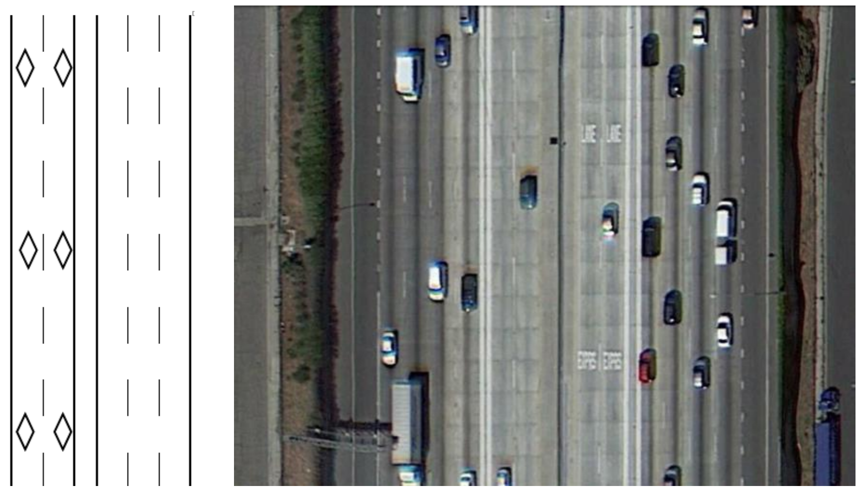
Exhibit 38-5
Example of Buffer 1 Basic ML Segment

Source: ©2014 Google.
Note: I-394, Minneapolis, Minnesota.

Buffer 2 Separation

Buffer 2 separation is similar to Buffer 1 separation but provides multiple MLs. Separation from the GP lanes is generally by means of a painted buffer; various painting schemes are used for the buffer. This type of facility was the rarest of the five facility types studied by NCHRP 3-96 (*1*), although it may become more common. Exhibit 38-6 shows a schematic of this facility type and an aerial view of I-110 in Los Angeles, California.

Exhibit 38-6
Example of Buffer 2 Basic ML Segment

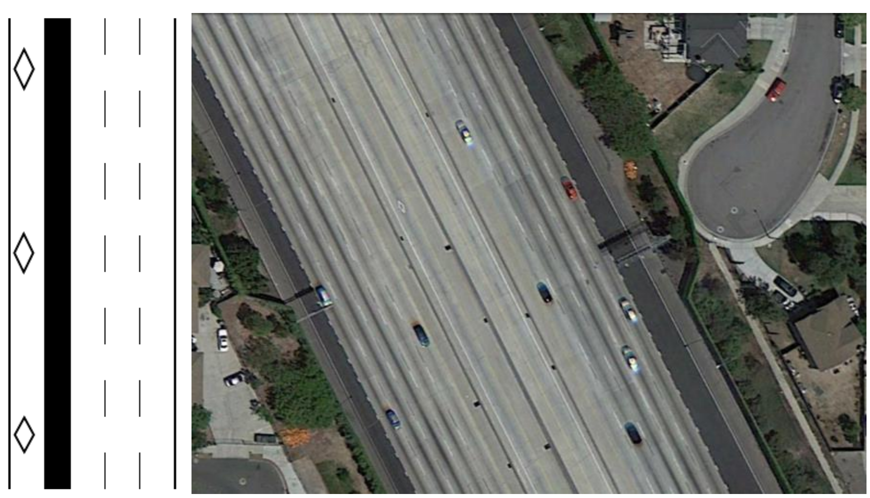


Source: ©2014 Google.
Note: I-110, Los Angeles, California.

Barrier 1 Separation

Under Barrier 1 separation, a single ML is separated from the GP lanes by a concrete barrier or other method of physically separating traffic, such as raised delineators or landscaping. This facility type is suitable for HOV, HOT, and express lanes. Exhibit 38-7 shows a schematic of Barrier 1 separation, along with an aerial view of I-5 in Orange County, California.

Exhibit 38-7
Example of Barrier 1 Basic ML Segment

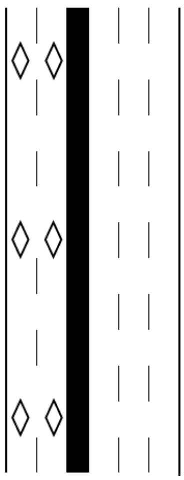


Source: ©2014 Google.
Note: I-5, Orange County, California.

Barrier 2 Separation

Under Barrier 2 separation, multiple MLs are separated from the GP lanes by a concrete barrier or other method of physically separating traffic, such as raised delineators or landscaping. Access between the MLs and GP lanes is limited and can be in the form of a weave access or a direct ramp access. This type of facility is commonly used for HOV, HOT, and express lanes. Exhibit 38-8 shows a schematic of the Barrier 2 configuration and an image of I-5 in Seattle, Washington, as an example of a Barrier 2 facility.

Exhibit 38-8
Example of Barrier 2 Basic ML Segment



Source: ©2014 Google.
Note: I-5, Seattle, Washington.

BASIC ML SEGMENT CHARACTERISTICS

The following three traffic performance characteristics of ML facilities are different from those of GP lanes and are discussed in detail in the subsections below:

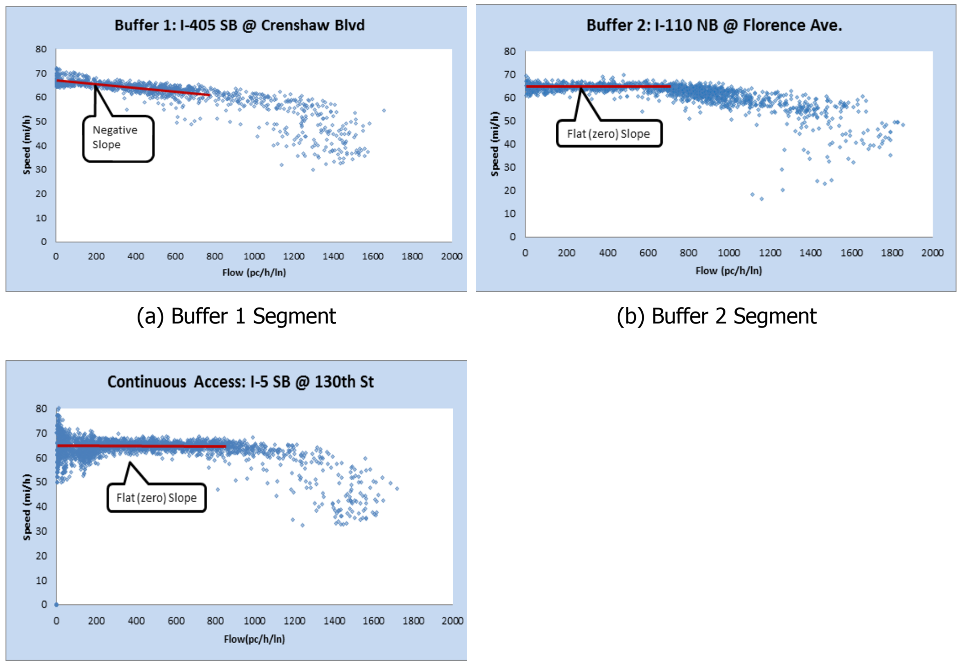
1. No opportunity for passing in single-lane ML facilities,
2. ML sensitivity to GP-lane congestion under certain separation conditions, and
3. Lower ML capacity.

Impact of Single-Lane ML Facilities on Travel Speeds

Single-lane ML operations are affected by the inability of faster-moving vehicles to pass slower-moving vehicles. This condition can result in ML facility speeds lower than those of GP lanes serving the same per lane traffic demands.

The slow-car-following effect for ML facilities is defined as the degradation in speed in a single-lane ML facility due to the inability of faster vehicles to pass slower vehicles. Exhibit 38-9(a) provides an example of the speed–flow plot for a Buffer 1–separated facility. Exhibit 38-9(b) provides an example of a speed–flow plot for a Buffer 2–separated facility. The major difference between the shapes of the two curves can be seen on the left sides of the data plots under low-flow conditions. The Buffer 1 facility shows a negative slope in the low-flow section of the curve, while the Buffer 2 facility shows virtually a horizontal line in the same flow range. Under low-flow demand, the Buffer 2 separation type maintains its relatively constant FFS while the Buffer 1 speed decreases with an increase in flow.

Exhibit 38-9
Speed–Flow Curves for Different ML Basic Segment Types



(a) Buffer 1 Segment

(b) Buffer 2 Segment

(c) Continuous Access Segment

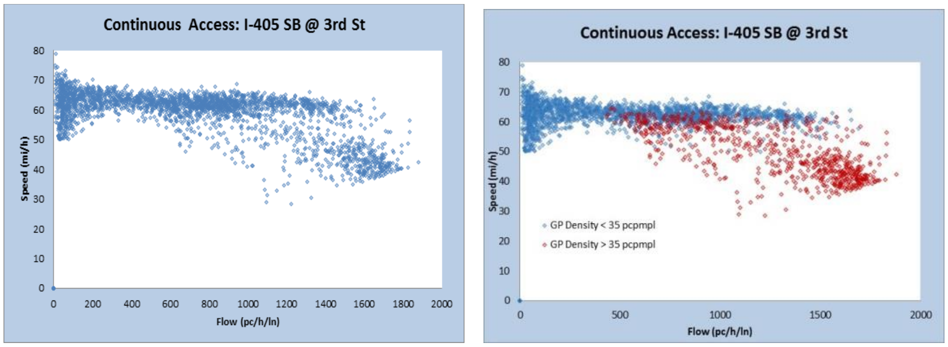
Exhibit 38-9(c) shows an example plot of speed–flow data from a continuous access facility. Although the continuous access facility consists of only one lane, passing can occur via the adjacent GP lane under low-flow conditions. As long as there is an acceptable gap in the adjacent GP lane and speeds in the GP lane are not below that of the vehicle in the ML, a passing maneuver can be completed through the GP lane. Therefore, for continuous access facilities, the speed is constant (i.e., equals FFS) and does not decline with increasing flow up until the break point normally experienced with freeway facilities.

Sensitivity of ML Operations to GP Lane Congestion

ML operations are sensitive to congestion in GP lanes under certain separation conditions. Vehicles in the ML(s) will tend to slow down to reduce the discomfort associated with high-speed differentials with adjacent traffic, possibly in anticipation of a vehicle making a sudden lane change from the slow GP lane to the faster ML. This phenomenon typically occurs when traffic density in the GP lanes equals or exceeds 35 pc/mi/ln.

The frictional effect is stronger on facilities with minimal physical separation, such as the continuous access and Buffer 1 types (2). Exhibit 38-10 illustrates this effect for a continuous access facility. In Exhibit 38-10(a), all of the speed–flow data are shown. There is a wide spread in the data from a flow of 600 pc/h/ln to 1,700 pc/h/ln. This trend is atypical for what is usually seen in GP lane speed–flow curves, which normally show little speed variance between conditions of equal flows.

Exhibit 38-10
Illustrative Impact of GP Lane Congestion on ML Speeds



(a) All ML data points

(b) Paired ML data points by GP lane density

When the data are segregated on the basis of the quality of operations in the GP lanes, as shown in Exhibit 38-10(b), the reason for the dispersion of speed can be ascertained. A density of 35 pc/mi/ln is used as a threshold for the drop in GP facility performance. This density threshold is selected since it serves as the transition point from LOS D to LOS E for freeway facilities. When the GP lane has a density greater than 35 pc/mi/ln, lower speeds can be observed on the ML. The lack of continuity of the curve can be seen as breakdown appears to occur at different levels of flow, depending on the GP lane's performance.

Reduced ML Capacity

Given the more restrictive speed–flow relationship of MLs shown in Exhibit 38-10, predicted ML capacity will be lower than that of GP lanes under the same conditions. However, no recurrent breakdown conditions were observed in the MLs during the course of the NCHRP 3-96 field observations (*1*), so further studies are needed to quantify ML capacities under different traffic and geometric conditions.

2. BASIC ML SEGMENT SPEED–FLOW RELATIONSHIPS

Speed–flow curves have been developed for the five basic ML segment types. Five curves are provided for each segment type, one for each of the following FFSs: 75 mi/h, 70 mi/h, 65 mi/h, 60 mi/h, and 55 mi/h. There are two clear ranges in the shape of the curves:

- At flow rates from 0 pc/h/ln to the break point, the slope is linear. For Buffer 1 and Barrier 1 segments, speed decreases linearly with increasing flow because of the slow-moving-vehicle effect. For all other segment types, FFS prevails up to the break point.
- At flow rates between the break point and the maximum observed flows, speeds decline along a curvilinear trend.

For continuous access and Buffer 1 segment types, as the frictional effect takes hold, a second set of curves is adopted to show the speed–flow relationship under the frictional effect during GP lane congestion. When the adjacent GP lane is congested (GP density ≥ 35 pc/mi/ln), the frictional curve comes into play. It is a function of both the nonfrictional curve and the flow rate. FFS should be rounded to the nearest 5 mi/h as follows:

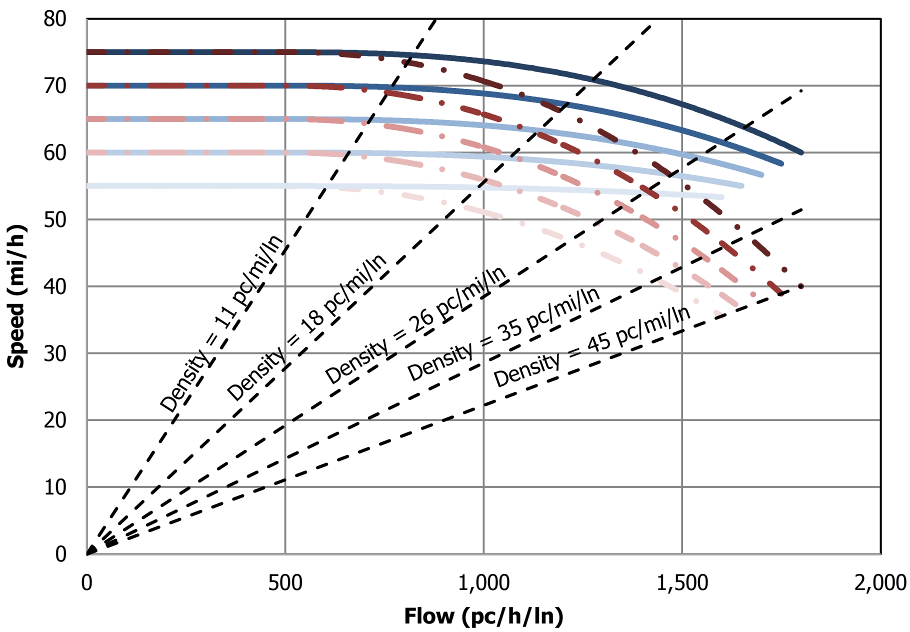
- For 72.5 mi/h ≤ FFS < 77.5 mi/h, use FFS = 75 mi/h.
- For 67.5 mi/h ≤ FFS < 72.5 mi/h, use FFS = 70 mi/h.
- For 62.5 mi/h ≤ FFS < 67.5 mi/h, use FFS = 65 mi/h.
- For 57.5 mi/h ≤ FFS < 62.5 mi/h, use FFS = 60 mi/h.
- For 52.5 mi/h ≤ FFS < 57.5 mi/h, use FFS = 55 mi/h.

No attempt should be made to interpolate between basic curves.

CONTINUOUS ACCESS SEGMENTS

Exhibit 38-11 shows the speed–flow relationships at each FFS for the continuous access segment type. Nonfrictional curves are shown as solid lines, while the corresponding frictional curves are shown as dashed lines. Exhibit 38-12 shows the models defining each of the curves in Exhibit 38-11.

Exhibit 38-11
Equations Describing Speed–Flow Curves for Continuous Access Segments (mi/h)



Note: Solid lines indicate nonfrictional curves; dashed lines indicate frictional curves.

Exhibit 38-12
Speed–Flow Curves for Continuous Access Segments

FFS (mi/h)	GP Friction?	Flow ≤ 500 pc/h/ln	Flow > 500 pc/h/ln	Capacity (pc/h/ln)
75	No	75	$75 - 2.46\times10^{-7}(v_p - 500)^{2.5}$	1,800
	Yes	75	$75 - 2.46\times10^{-7}(v_p - 500)^{2.5} - 1.18\times10^{-5}(v_p - 500)^2$	
70	No	70	$70 - 2.12\times10^{-7}(v_p - 500)^{2.5}$	1,750
	Yes	70	$70 - 2.12\times10^{-7}(v_p - 500)^{2.5} - 1.24\times10^{-5}(v_p - 500)^2$	
65	No	65	$65 - 1.67\times10^{-7}(v_p - 500)^{2.5}$	1,700
	Yes	65	$65 - 1.67\times10^{-7}(v_p - 500)^{2.5} - 1.31\times10^{-5}(v_p - 500)^2$	
60	No	60	$60 - 1.12\times10^{-7}(v_p - 500)^{2.5}$	1,650
	Yes	60	$60 - 1.12\times10^{-7}(v_p - 500)^{2.5} - 1.39\times10^{-5}(v_p - 500)^2$	
55	No	55	$55 - 4.15\times10^{-8}(v_p - 500)^{2.5}$	1,600
	Yes	55	$55 - 4.15\times10^{-8}(v_p - 500)^{2.5} - 1.47\times10^{-5}(v_p - 500)^2$	

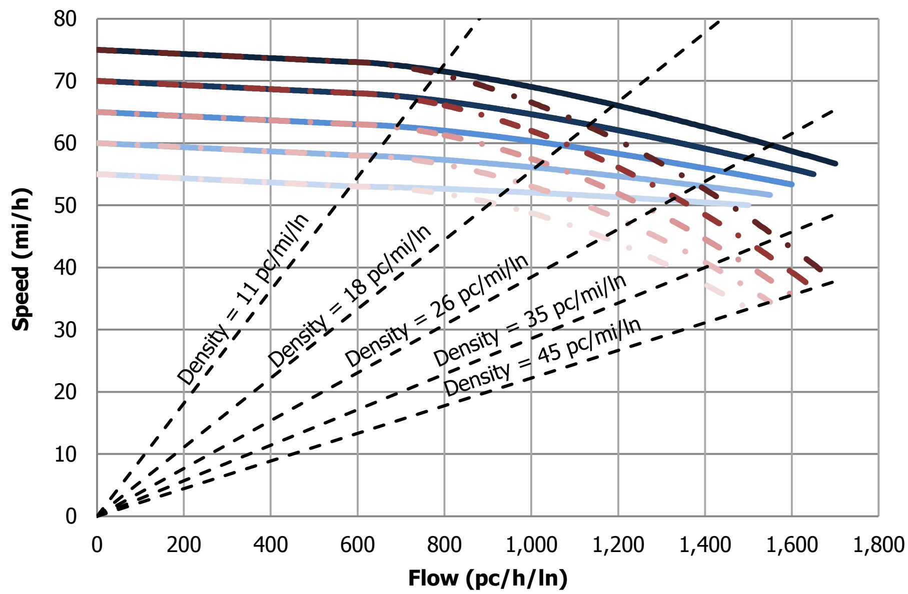
Notes: FFS = free-flow speed; v_p = demand flow rate (pc/h/ln) under equivalent base conditions.

Note that the frictional curves terminate at a density of 45 pc/mi/ln, which is consistent with Chapter 11, Basic Freeway Segments. However, the range of observed data for the nonfrictional curves never reached a density level this high (*1*). This result is probably attributable to a low likelihood of observing nonfrictional cases in combination with high flow rates. As a result, the terminal density of the nonfrictional curves is 30 pc/mi/ln.

BUFFER 1 SEGMENTS

Exhibit 38-13 shows the speed–flow relationships for each FFS for the Buffer 1 segment type. Nonfrictional curves are shown as solid lines, while the corresponding frictional curves are shown as dashed lines. The speed–flow equations are provided in Exhibit 38-14.

Exhibit 38-13
Speed–Flow Curves for Buffer 1 Segments



Note: Solid lines indicate nonfrictional curves; dashed lines indicate frictional curves.

Exhibit 38-14
Equations Describing Speed–Flow Curves for Buffer 1 Segments (mi/h)

FFS (mi/h)	GP Friction?	Flow ≤ 600 pc/h/ln	Flow > 600 pc/h/ln	Capacity (pc/h/ln)
75	No	$75 - 0.00333v_p$	$73 - 0.00090(v_p - 600)^{1.4}$	1,700
	Yes	$75 - 0.00333v_p$	$73 - 0.00090(v_p - 600)^{1.4} - 1.38\times10^{-5}(v_p - 600)^2$	
70	No	$70 - 0.00333v_p$	$68 - 0.00077(v_p - 600)^{1.4}$	1,650
	Yes	$70 - 0.00333v_p$	$68 - 0.00077(v_p - 600)^{1.4} - 1.46\times10^{-5}(v_p - 600)^2$	
65	No	$65 - 0.00333v_p$	$63 - 0.00061(v_p - 600)^{1.4}$	1,600
	Yes	$65 - 0.00333v_p$	$63 - 0.00061(v_p - 600)^{1.4} - 1.56\times10^{-5}(v_p - 600)^2$	
60	No	$60 - 0.00333v_p$	$58 - 0.00043(v_p - 600)^{1.4}$	1,550
	Yes	$60 - 0.00333v_p$	$58 - 0.00043(v_p - 600)^{1.4} - 1.66\times10^{-5}(v_p - 600)^2$	
55	No	$55 - 0.00333v_p$	$53 - 0.00022(v_p - 600)^{1.4}$	1,500
	Yes	$55 - 0.00333v_p$	$53 - 0.00022(v_p - 600)^{1.4} - 1.65\times10^{-5}(v_p - 600)^2$	

Notes: FFS = free-flow speed; v_p = demand flow rate (pc/h/ln) under equivalent base conditions.

As with the continuous access curves, the nonfrictional curves terminate at a density of 30 pc/mi/ln, since higher densities were not observed when the GP lanes were not congested (*1*). The frictional curves terminate at a density of 45 pc/mi/ln.

BUFFER 2 SEGMENTS

Exhibit 38-15 shows the speed–flow relationships for each FFS for the Buffer 2 segment type. There is only one set of curves because no frictional effect is observed for this type of segment. The equations describing speed–flow relationships are provided in Exhibit 38-16.

Exhibit 38-15
Speed–Flow Curves for Buffer 2 Segments

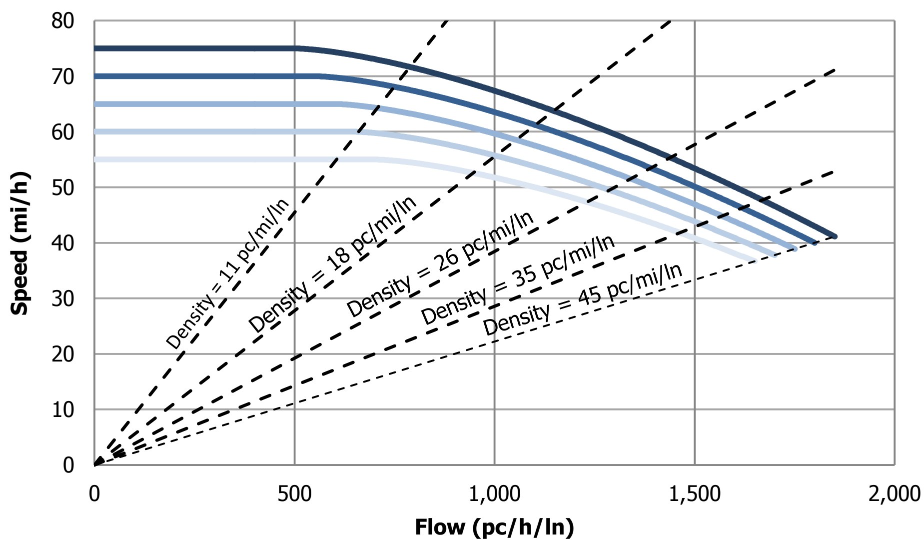


Exhibit 38-16
Equations Describing Speed–Flow Curves for Buffer 2 Segments (mi/h)

FFS (mi/h)	Break Point Flow (pc/h/ln)	Flow ≤ Break Point	Flow > Break Point	Capacity (pc/h/ln)
75	500	75	$75 - 0.000683(v_p - 500)^{1.5}$	1,850
70	550	70	$70 - 0.000679(v_p - 550)^{1.5}$	1,800
65	600	65	$65 - 0.000670(v_p - 600)^{1.5}$	1,750
60	650	60	$60 - 0.000653(v_p - 650)^{1.5}$	1,700
55	700	55	$55 - 0.000626(v_p - 700)^{1.5}$	1,650

Notes: FFS = free-flow speed; v_p = demand flow rate (pc/h/ln) under equivalent base conditions.

BARRIER 1 SEGMENTS

Exhibit 38-17 shows the speed–flow relationships at each FFS level for the Barrier 1 segment type. The linear portion of the curve is sloped from the flow range of 0 to the break point because of the slow-car-following effect. The equations showing speed–flow relationships are provided in Exhibit 38-18.

Exhibit 38-17
Speed–Flow Curves for Barrier 1 Segments

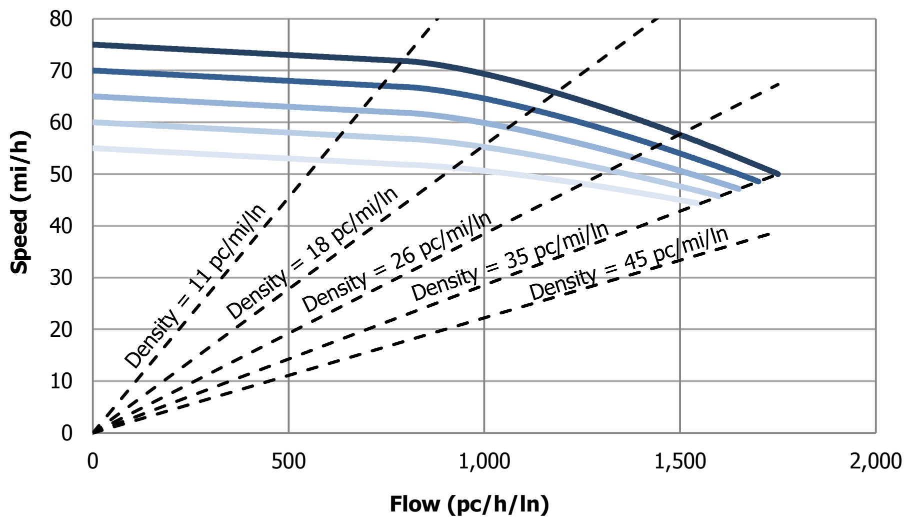


Exhibit 38-18
Equations Describing Speed–Flow Curves for Barrier 1 Segments (mi/h)

FFS (mi/h)	Flow ≤ 800 pc/h/ln	Flow > 800 pc/h/ln	Capacity (pc/h/ln)
75	$75 - (0.004 v_p)$	$71.8 - 0.00148(v_p - 800)^{1.4}$	1,750
70	$70 - (0.004 v_p)$	$66.8 - 0.00133(v_p - 800)^{1.4}$	1,700
65	$65 - (0.004 v_p)$	$61.8 - 0.00116(v_p - 800)^{1.4}$	1,650
60	$60 - (0.004 v_p)$	$56.8 - 0.00096(v_p - 800)^{1.4}$	1,600
55	$55 - (0.004 v_p)$	$51.8 - 0.00071(v_p - 800)^{1.4}$	1,550

Notes: FFS = free-flow speed; v_p = demand flow rate (pc/h/ln) under equivalent base conditions.

While the curves for many of the other facility types terminate at a density of 45 pc/mi/ln, the breakdown for Barrier 1 facilities was observed to occur at a lower density (*1*). The termination point for the Barrier 1 speed–flow curves was determined to be 35 pc/mi/ln. This lower density of break point could be attributable to driver behavior in this type of facility. Drivers may not feel as comfortable traveling at shorter headways. Since barriers are present on both sides of the facility, there is little room to maneuver. Should a vehicle stop, the trailing vehicle does not have the option of swerving to the right or left if the driver cannot brake in time, because of the presence of the barriers. The increase in the acceptable car-following headway would cause breakdown at a lower density.

BARRIER 2 SEGMENTS

The Barrier 2 speed–flow curve is similar to that of a basic freeway segment. A Barrier 2 segment can essentially be thought of as its own independent facility, since there is no slow-car-following or frictional effect. Exhibit 38-19 shows the speed–flow relationships for each FFS for the Barrier 2 type. The corresponding equations defining the curves are provided in Exhibit 38-20.

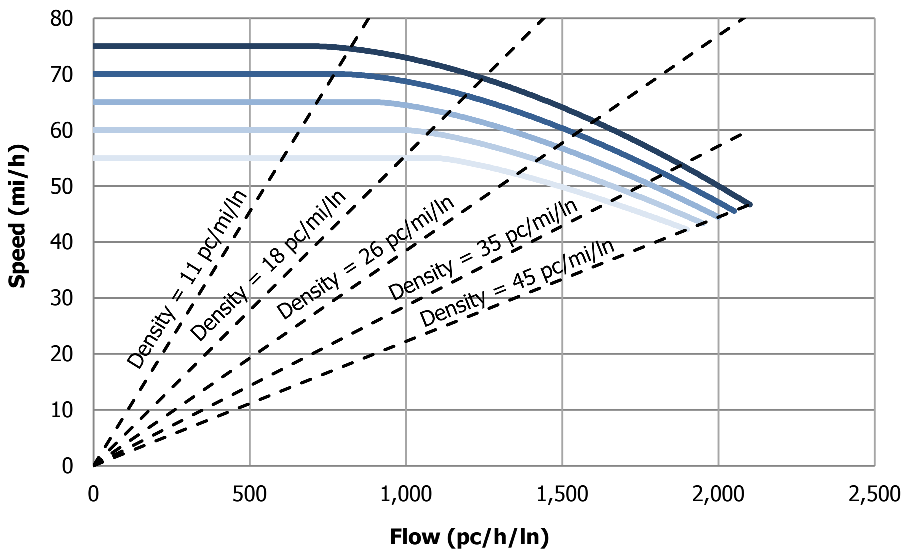


Exhibit 38-19
Speed–Flow Curves for Barrier 2 Segments

Exhibit 38-20
Equations Describing Speed–Flow Curves for Barrier 2 Segments (mi/h)

FFS (mi/h)	Break Point Flow (pc/h/ln)	Flow ≤ Break Point	Flow > Break Point	Capacity (pc/h/ln)
75	700	75	$75 - 0.000127(v_p - 700)^{1.7}$	2,100
70	800	70	$70 - 0.000271(v_p - 800)^{1.6}$	2,050
65	900	65	$65 - 0.000563(v_p - 900)^{1.5}$	2,000
60	1,000	60	$60 - 0.00113(v_p - 1{,}000)^{1.4}$	1,950
55	1,100	55	$55 - 0.00215(v_p - 1{,}100)^{1.3}$	1,900

Notes: FFS = free-flow speed; v_p = demand flow rate (pc/h/ln) under equivalent base conditions.

3. ADJUSTMENTS FOR CROSS-WEAVE EFFECTS

In estimating the GP segment capacity, the cross-weave adjustment should be taken into account to quantify the reduction in GP segment capacity from ML cross-weave flows. The adjustment should be applied where there is intermittent access to the ML over an access segment. If the upstream end of the access segment is relatively close to a GP on-ramp, the resulting weaving maneuvers by vehicles attempting to access the ML will have a capacity-reducing impact on GP traffic operations.

Research indicated that the impact of cross-weaving on GP capacity reduction is positively correlated with the level of cross-weave demand entering at the on-ramp and the number of lanes to be crossed (*1*). The impact of the cross weave is negatively correlated with the distance between the on-ramp gore and the ML access point. This effect is akin to a two-sided weaving segment in Chapter 12, Freeway Weaving Segments. Because of the difficulties in observing these relationships in the field, microscopic simulation models were developed and calibrated to quantify the cross-weave effects.

This capacity-reducing effect is reflected through a set of capacity reduction factors (CRFs), or, conversely, capacity adjustment factors (CAFs), as described in Chapter 25, Freeway Facilities: Supplemental. A CRF is expressed as a function of the base capacity C_{base} (pc/h/ln) and the cross-weave capacity C_{cw} (pc/h/ln). The CRF and CAF can be estimated as follows:

Equation 38-1

$$CRF = \frac{C_{base} - C_{cw}}{C_{base}}$$

Equation 38-2

$$CAF = 1 - CRF$$

The CRF is estimated as a function of the number of GP lanes, cross-weave flows, and the distance from the ramp gore to the beginning of intermittent access (shown previously in Exhibit 38-3):

Equation 38-3

$$CRF = \frac{-8.957 + 2.52 \times \ln(CW) - 0.001453 L_{CW\text{-}Min} + 0.2967 N_{GP}}{100}$$

where

CRF = capacity reduction factor (decimal),

CW = cross-weave flow (pc/h),

$L_{CW\text{-}Min}$ = distance from the ramp gore to the beginning of intermittent access (ft), and

N_{GP} = number of GP lanes (2–4).

Exhibit 38-21 shows sample CRF results for several common combinations of roadway geometries and cross-weave flow conditions.

Exhibit 38-21
CRF Estimates by Configuration Scenario

N_{GP}	L_{CW-Min} (ft)	Cross-Weave Flow (veh/h) 100	200	300	450	600
4	1,500	0.016	0.033	0.045	0.057	0.065
	2,000	0.010	0.022	0.037	0.047	0.053
	2,500	0.002	0.016	0.033	0.041	0.047
3	1,500	0.012	0.031	0.039	0.055	0.061
	2,000	0.008	0.020	0.035	0.043	0.047
	2,500	0.002	0.014	0.026	0.041	0.043
2	1,500	0.010	0.027	0.037	0.051	0.053
	2,000	0.006	0.020	0.031	0.043	0.049
	2,500	0.000	0.012	0.022	0.033	0.041

Notes: N_{GP} = number of GP lanes.
L_{CW-Min} = distance from the ramp gore to the beginning of intermittent access.

The cross-weave effect is only applied to ML facilities where intermittent access is present. For a continuous access ML facility, the cross-weave effect occurs across the entire facility, and the behavior is treated as vehicles moving to or departing from a faster lane in the basic freeway methodology.

4. METHODOLOGY

This chapter's methodology can be used to analyze the capacity and LOS of ML freeway segments and the effects of design features on their performance. The methodology is based on the results of NCHRP Project 3-96 (*1*) and is implemented in the FREEVAL-ML 2011 computational engine. This chapter discusses the basic principles of the methodology.

LIMITATIONS OF THE METHODOLOGY

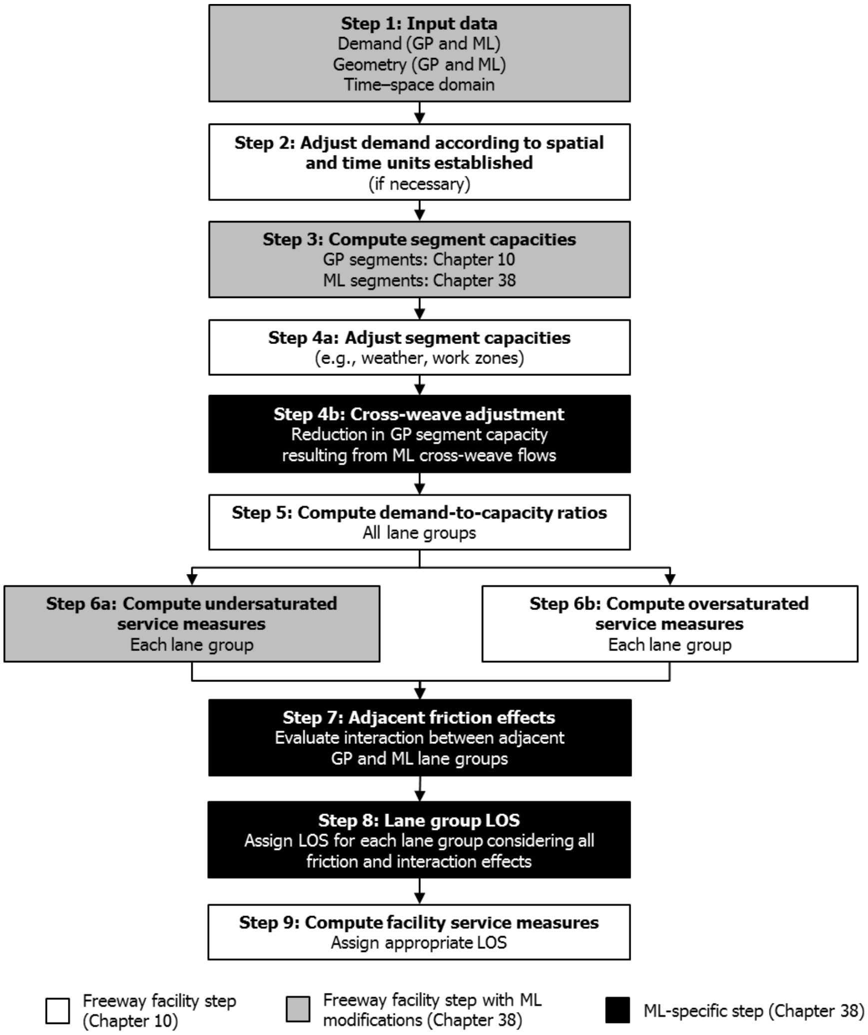
The methodology of this chapter does not apply to or take into account (without modification by the analyst) the following:

- Operational effects of oversaturated conditions in the MLs;
- Variations in the design of the start and end access points of ML facilities, as well as the operational impact from variations in the design of the termini;
- Demand estimation for both ML and GP facilities, especially demand dynamics due to a pricing component that may be in effect on the ML;
- Facilities with FFS below 55 mi/h or above 75 mi/h; and
- Spillback in the ML due to a downstream queue in the GP lanes.

In most of the cases cited above, to incorporate the effects of any of the above conditions, an analyst would have to (*a*) apply alternative tools or (*b*) draw on other research information or apply customized modifications of this methodology.

OVERVIEW OF THE METHODOLOGY

The methodological flowchart that incorporates ML facilities is shown in Exhibit 38-22. While both undersaturated and oversaturated scenarios are shown, the ML method is limited to undersaturated conditions in the MLs. By design, the majority of ML facilities operate below capacity, especially when they include a pricing component (i.e., HOT lanes). Thus, obtaining ML performance data at breakdown is difficult, which makes the development of an empirical relationship impractical. Therefore, the operations of congested ML facilities are considered to be beyond the scope of the HCM method; they may be appropriate for analysis with a simulation-based approach if necessary.



Notes: GP = general purpose lanes; ML = managed lanes.

Exhibit 38-22
Methodological Flowchart for ML Facility Analysis

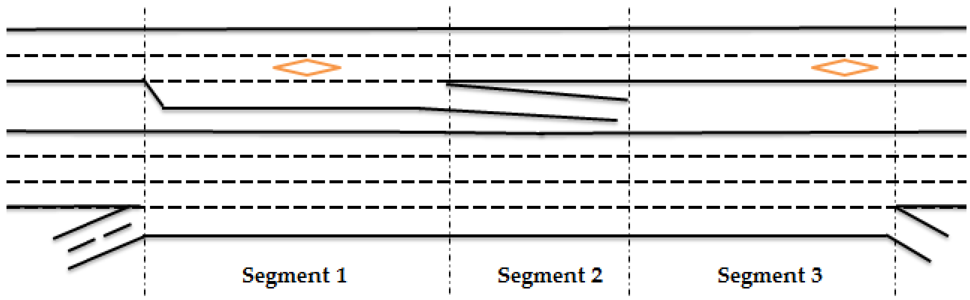
COMPUTATIONAL STEPS

Step 1: Input Data

For a typical operational analysis, the analyst must specify demand volume, roadway geometric information (including number of lanes, lane width, right-side lateral clearance, and total ramp density), percentage of heavy vehicles, peak hour factors, terrain, and driver population factor, similar to what is required for a Chapter 10 freeway facility analysis. The only difference is that this information must be specified separately for the ML and GP lane groups.

In addition, the time–space domain for the analysis must be established. To preserve the lane group concept, the segmentation is performed slightly differently from that for a freeway facility consisting only of GP lanes. (See Exhibit 38-23 for an example.) In the absence of a parallel ML facility, the GP lanes would be treated as one weaving segment according to the Chapter 10 method. However, since an ML facility exists, the segmentation also needs to consider the ML segment types. Therefore, the GP lane group is divided into three segments: merge, basic, and diverge.

Exhibit 38-23
Graphical Illustration of ML Segmentation Method



Step 2: Adjust Demand According to Spatial and Time Units Established

Step 2 is identical to that of the Chapter 10 method. The sum of the input demands must equal the sum of the output demands in every time interval. The demand estimation model provided in Chapter 10 is valid for freeway segments with an ML component.

Step 3: Compute Segment Capacities

The capacity estimation for GP segments is not initially affected by the presence of MLs. The GP segment capacity estimates are determined by using the methodologies of Chapter 11 for basic freeway segments, Chapter 12 for weaving segments, and Chapter 13 for merge and diverge segments. For the ML segments, capacity estimates are determined by using the speed–flow models in Section 2 of this chapter for ML basic segments, Chapter 13 for ML on-ramp and off-ramp segments, and Chapter 12 for ML weave segments.

Steps 4a and 4b: Adjust Segment Capacities (4a) and Incorporate Cross-Weave Adjustments (4b)

Segment capacities are adjusted in Step 4a for the presence of work zones, weather effects, incidents, and so on, as desired by the analyst, in accordance with the methods outlined in Chapter 10.

When the segment capacities are adjusted, one particular segment type, ML access, needs to be treated with care. This segment often exists in ML facilities with intermittent access. The segment itself is treated as a weaving segment, and Chapter 12 is used to compute its impact. However, for the segments between a GP on-ramp and the ML access segment or between the ML access segment and a GP off-ramp, the cross-weave method must be used to estimate the GP lane capacity reduction effects (if any) due to the cross-weaving flows.

Step 5: Compute Demand-to-Capacity Ratios

Within each cell of the time–space unit, demand-to-capacity ratios need to be calculated for both lane groups. As explained in Chapter 10, there are two possible outcomes:

1. If all cells have d/c ratios of 1.00 or less, the entire time–space unit contains undersaturated flow.
2. If any cell has a d/c ratio greater than 1.00, the time−space unit will contain both undersaturated and oversaturated cells. Analysis of oversaturated conditions is much more complex because of the

interactions between freeway segments and the shifting of demand in both time and space. This condition may occur only for GP segments.

If Case 1 exists, the analysis moves to Step 6a. If Case 2 exists, the analysis moves to Step 6b. Note that for the ML group, the methodology is limited to undersaturated conditions. The operations of congested ML facilities are beyond the scope of the current method, and a simulation-based analysis can be considered if needed (*3*).

Steps 6a and 6b: Compute Undersaturated (6a) and Oversaturated (6b) Service Measures

Depending on the prevailing congestion levels in the GP lanes, either the undersaturated or the oversaturated performance module is invoked. The oversaturated methodology for GP lanes (Step 6b) is applied in the standard way by using Chapters 10 and 25. For undersaturated operations (Step 6a), performance measures are estimated for each segment; traffic demands and appropriate adjustments to segment capacities are considered.

Step 7: Adjacent Frictional Effects

The fact that ML performance is affected by GP lane traffic requires that the GP lane analysis be done before the ML analysis. When the GP lanes operate at densities above the specified threshold, the friction-based speed prediction model is used. When the GP lanes operate below the specified threshold, the non-friction-based speed prediction model is used. This concept is applied to both continuous access and Buffer 1 basic ML segments.

Step 8: Lane Group LOS

On the completion of the frictional effect adjustments, LOS is assigned to the segment for each 15-min time interval.

Step 9: Compute Facility Service Measures

Finally, facility service measures are estimated by using Chapter 10. Additional performance measures specific to MLs can also be estimated, and ML and GP operations can be compared. Aggregations of performance measures over the entire time–space domain of the analysis would be performed for each lane group separately. Cumulative travel time and average speed, weighted by both segment length and the number of lanes in a segment, can be calculated and compared for the two lane groups.

5. EXAMPLE PROBLEMS

Exhibit 38-24
List of Example Problems

Example Problem	Description	Application
1	Barrier-separated reversible ML facility	Operational analysis
2	Buffer-separated ML facility	Operational analysis

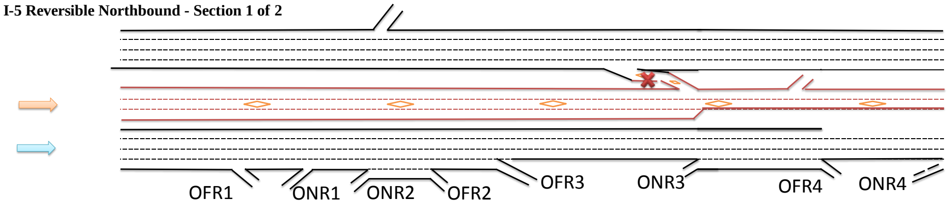
EXAMPLE PROBLEM 1: BARRIER-SEPARATED REVERSIBLE ML FACILITY

The Facility

The subject of this operational analysis is an urban freeway facility with a 4-mi-long reversible ML facility separated from the GP lanes by a concrete barrier. Therefore, no frictional effect is present in this example. The example is based on an actual ML facility in the United States to demonstrate the capability of the methodology in replicating the geometry of actual facilities. The reversible MLs are assumed to operate in the northbound direction during the study period. Sixteen individual analysis segments are identified on the basis of the methodology, as shown in Exhibit 38-25. Note that the segment length of parallel lane groups is identical in accordance with the assumptions discussed. Exhibit 38-25 also shows the geometric details of the facility.

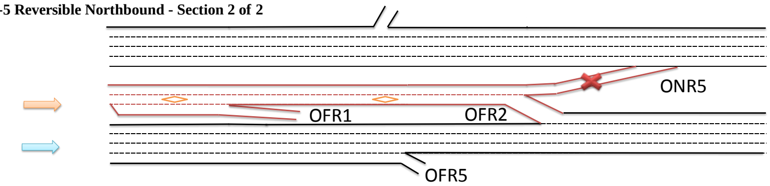
Exhibit 38-25
Example Problem 1: Lane Group Segmentation

I-5 Reversible Northbound - Section 1 of 2



Segment Number	1	2	3	4	5	6	7	8	9	10
GP Segment Type	B	OFR	B	ONR	W	B	OFR	B	W	B
ML Segment Type	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B
Length (ft)	1000	1500	2818	1457	682	1207	1500	2008	1311	2621

I-5 Reversible Northbound - Section 2 of 2



Segment Number	11	12	13	14	15	16
GP Segment Type	ONR	B	OFR	B	ONR	B
ML Segment Type	ML-OFR	ML-B	ML-B	ML-B	ML-OFR	ML-B
Length (ft)	1500	700	1500	1500	1500	1000

The following issue is important to take into account in this facility. For the GP lane group, Segments 11, 12, and 13 should be considered as one weave segment in accordance with Chapter 12 conventions, since the on- and off-ramps are connected by an auxiliary lane. However, on the parallel ML, an ML off-ramp is included in Segment 11. To preserve the lane group concept, the analyst needs to decide whether to (*a*) code Segments 11 to 13 individually (thereby ignoring the weaving functionality) or (*b*) code only one segment that captures the GP weave (but ignores the ML off-ramp). In view of the length of GP weave segment

(3,700 ft) and the presumed focus of the analysis on the ML portion, the first option is selected here.

Note that the MLs merge with the GP lanes in Segment 15. In this analysis, this merge is assumed to operate as an off-ramp segment on the MLs and as an on-ramp on the GP lanes. For facilities where this assumption is not valid or where significant turbulence or congestion is expected at the ML terminus, this chapter's methodology is not appropriate. In particular, the methodology does not capture off-ramp congestion and queuing and does not model spillback from the GP lanes onto the ML portion of the facility. In these cases, the analyst is referred to the use of alternative analysis tools, such as microsimulation.

The analysis question is the following: What are the operational performance and LOS of the ML freeway facility shown in Exhibit 38-25?

The Facts

In addition to the information contained in Exhibit 38-25, the following facility characteristics are known:

- GP lane group
  - FFS = 60 mi/h (all mainline segments)
  - Heavy vehicles = 0% (f_{HV} = 1)
  - PHF = 1
  - Commuter drivers (f_p = 1)
- ML lane group
  - FFS = 70 mi/h
  - Heavy vehicles = 0% (f_{HV} = 1)
  - PHF = 1
  - Commuter drivers (f_p = 1)

The study period is 60 min, divided into four 15-min analysis periods; 15-min demand flow rates are given in vehicles per hour under prevailing conditions. These demands must be converted to passenger cars per hour under equivalent ideal conditions for use in the parts of the methodology involving segment LOS estimation.

Step 1: Input Data

Traffic demand inputs for all 16 segments and four analysis periods are given in Exhibit 38-26 and Exhibit 38-27.

Exhibit 38-26
Example Problem 1: GP Lane Group Demand Inputs

Analysis Period	Entering Flow Rate (veh/h)	Ramp Flow Rate by Time Period (veh/h)										Exiting Flow Rate (veh/h)
		ONR1	ONR2	ONR3	ONR4	ONR5	OFR1	OFR2	OFR3	OFR4	OFR5	
1	4,000	1,000	1,000	250	250	1,299	250	250	250	250	350	6,449
2	5,500	500	500	2,000	50	1,549	350	50	500	500	2,100	6,645
3	5,000	1,300	1,300	1,200	200	1,499	450	450	450	500	2,100	6,549
4	4,000	500	500	400	258	1,199	250	400	350	358	264	5,235

Exhibit 38-27
Example Problem 1: ML Lane Group Demand Inputs

Analysis Period	Entering Flow Rate (veh/h)	Ramp Flow Rate by Time Period (veh/h)		Exiting Flow Rate (veh/h)[a]
		OFR1	OFR2	
1	1,650	350	1,299	1
2	1,650	100	1,549	1
3	1,650	150	1,499	1
4	1,450	250	1,199	1

Note: [a] Because of a limitation of the computational engine, a minimum flow of 1 veh/h is needed.

The volumes in Exhibit 38-26 and Exhibit 38-27 represent the 15-min demand flow rates on the facility. The actual volume served in each segment will be determined by the methodology. The demand flows are given for the extended time–space domain consistent with the Chapter 10 methodology. Peaking occurs in the second 15-min period. Since inputs are in the form of 15-min flow rates, no peak hour factor adjustment is necessary. Since the ML portion of the facility ends in Segment 15, the ML off-ramp (and corresponding GP on-ramp) demands are designed to empty out the ML facility. A flow rate of 1 veh/h is retained in the MLs related to the software implementation of the methodology in FREEVAL-ML.

Step 2: Demand Adjustments

The traffic flows in Exhibit 38-26 and Exhibit 38-27 are already given in the form of actual 15-min demand flow rates. Therefore, no additional demand adjustment is necessary, since the flows represent true demand. Note that the FREEVAL-ML computational engine assumes that the user inputs true demand flows.

Step 3: Compute Segment Capacities

Segment capacities are determined with the methodologies of Chapter 11 for basic GP segments, Chapter 12 for GP weaving segments, Chapter 13 for GP merge and diverge segments, and Section 2 of this chapter for ML basic segments. The resulting capacities are shown in Exhibit 38-28 and Exhibit 38-29.

With regard to the GP segment capacities shown in Exhibit 38-28, the capacity of a weaving segment (Segments 5 and 9) is dependent on traffic patterns (i.e., the weaving ratio), so it varies by time period. The remaining segment capacities are constant in all four time intervals. For the ML segment, the capacities for Segments 1 through 15 are the same, since the segments have the same cross section. Note that Segment 16 is a “virtual” segment, which is not designed to carry any traffic.

Exhibit 38-28
Example Problem 1: GP Segment Capacities

Analysis Period	Capacity (veh/h) by Segment							
	1	2	3	4	5	6	7	8
1	8,976	8,976	8,976	8,976	9,772	8,976	8,976	6,732
2	8,976	8,976	8,976	8,976	10,435	8,976	8,976	6,732
3	8,976	8,976	8,976	8,976	9,892	8,976	8,976	6,732
4	8,976	8,976	8,976	8,976	10,123	8,976	8,976	6,732
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	8,348	6,732	8,976	8,976	8,976	6,732	6,732	6,732
2	7,704	6,732	8,976	8,976	8,976	6,732	6,732	6,732
3	7,983	6,732	8,976	8,976	8,976	6,732	6,732	6,732
4	8,142	6,732	8,976	8,976	8,976	6,732	6,732	6,732

Exhibit 38-29
Example Problem 1: ML Segment Capacities

Analysis Period	Capacity (veh/h) by Segment							
	1	2	3	4	5	6	7	8
1	4,683	4,683	4,683	4,683	4,683	4,683	4,683	4,683
2	4,683	4,683	4,683	4,683	4,683	4,683	4,683	4,683
3	4,683	4,683	4,683	4,683	4,683	4,683	4,683	4,683
4	4,683	4,683	4,683	4,683	4,683	4,683	4,683	4,683
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	4,683	4,683	4,683	4,683	4,683	4,683	4,683	N/A
2	4,683	4,683	4,683	4,683	4,683	4,683	4,683	N/A
3	4,683	4,683	4,683	4,683	4,683	4,683	4,683	N/A
4	4,683	4,683	4,683	4,683	4,683	4,683	4,683	N/A

Note: N/A = not applicable.

Steps 4a and 4b: Adjust Segment Capacities and Incorporate Cross-Weave Adjustments

Step 4a allows the user to adjust capacities of specific segments or time periods to model the effects of work zones, inclement weather, incidents, and so forth. No additional capacity adjustment is performed for this example problem, since normal operating conditions are being analyzed.

Step 4b adjusts GP segment capacities to account for cross-weave effects between a GP on-ramp and ML access point or the ML access point and a GP off-ramp. No capacity adjustment is performed here, since the MLs are separated from the GP lanes by a barrier without intermediate access points.

Step 5: Compute Demand-to-Capacity Ratios

The demand-to-capacity ratios are calculated on the basis of the demand flows and segment capacities given in Exhibit 38-26 through Exhibit 38-29. The results for the GP and ML lane groups are shown in Exhibit 38-30 and Exhibit 38-31, respectively.

Exhibit 38-30
Example Problem 1: GP Segment Demand-to-Capacity Ratios

Analysis Period	Demand-to-Capacity Ratio by Segment							
	1	2	3	4	5	6	7	8
1	0.45	0.45	0.42	0.53	0.59	0.61	0.61	0.78
2	0.61	0.61	0.57	0.63	0.59	0.68	0.68	0.83
3	0.56	0.56	0.51	0.65	0.72	0.75	0.75	0.93
4	0.45	0.45	0.42	0.47	0.47	0.48	0.48	0.59
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0.66	0.78	0.61	0.61	0.61	0.77	0.96	0.96
2	0.99	1.05	0.80	0.80	0.80	0.75	0.98	0.98
3	0.93	1.03	0.80	0.80	0.80	0.75	0.97	0.97
4	0.54	0.60	0.48	0.48	0.48	0.60	0.78	0.78

Exhibit 38-31
Example Problem 1: ML Segment Demand-to-Capacity Ratios

Analysis Period	Demand-to-Capacity Ratio by Segment							
	1	2	3	4	5	6	7	8
1	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
2	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
3	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
4	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0.35	0.35	0.35	0.28	0.28	0.28	0.28	0.00
2	0.35	0.35	0.35	0.33	0.33	0.33	0.33	0.00
3	0.35	0.35	0.35	0.32	0.32	0.32	0.32	0.00
4	0.31	0.31	0.31	0.26	0.26	0.26	0.26	0.00

The computed demand-to-capacity ratio matrices for GP and ML segments show that the GP lane group has an active bottleneck in Segment 10 in Time Intervals 2 and 3 with a *d/c* ratio of 1.05 and 1.03, respectively. For the ML lane group, no segment has a *d/c* ratio greater than 1.0 in any time interval. Therefore, for the GP segments, the oversaturation module is invoked; for ML segments, the facility is categorized as globally undersaturated, and the analysis proceeds with computing the undersaturated service measures. Exhibit 38-32 shows the volume-to-capacity ratios by GP segment and time. Notice that the volume served at the active bottleneck in Segment 10 is limited to the segment capacity, which results in a v/c ratio of 1.0. Because all ML segments are undersaturated in all time periods, the ML volume-to-capacity ratios are the same as the ML demand-to-capacity ratios given in Exhibit 38-31.

Exhibit 38-32
Example Problem 1: GP Segment Volume-to-Capacity Ratios

Analysis Period	Volume-to-Capacity Ratio by Segment							
	1	2	3	4	5	6	7	8
1	0.45	0.45	0.42	0.53	0.59	0.61	0.61	0.78
2	0.61	0.61	0.57	0.63	0.59	0.68	0.68	0.83
3	0.56	0.56	0.51	0.65	0.72	0.75	0.75	0.93
4	0.45	0.45	0.42	0.47	0.47	0.48	0.48	0.59
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0.66	0.78	0.61	0.61	0.61	0.77	0.96	0.96
2	0.94	1.00	0.76	0.76	0.76	0.71	0.94	0.94
3	0.90	1.00	0.77	0.77	0.77	0.73	0.95	0.95
4	0.62	0.69	0.54	0.54	0.54	0.66	0.84	0.84

Step 6: Compute Segment Service Measures

The methodology proceeds to calculate service measures for each segment and each time period starting with the first segment in Time Step 1. The computational details for each segment type are exactly as described in Chapters 11 through 13 for GP segments and in this chapter for ML segments.

The basic performance measures computed for each segment and each time step are the segment speed (Exhibit 38-33 and Exhibit 38-34) and density (Exhibit 38-35 and Exhibit 38-36). Other performance measures for comparing the two facilities are available as well.

Exhibit 38-33
Example Problem 1: GP Segment Space Mean Speeds

Analysis Period	Space Mean Speed (mi/h) by Segment							
	1	2	3	4	5	6	7	8
1	60.00	59.65	59.99	55.56	46.16	57.00	59.67	59.32
2	60.00	58.85	59.97	55.00	49.93	57.82	59.76	55.26
3	60.00	58.90	59.97	54.69	41.83	56.07	59.56	51.36
4	60.00	59.65	59.99	55.95	49.31	57.69	59.74	59.98
Analysis Period	**Space Mean Speed (mi/h) by Segment**							
	9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	49.71	59.32	59.98	60.00	60.00	59.54	50.42	53.39
2	30.34	51.10	59.66	59.66	59.66	59.97	50.31	54.19
3	26.87	51.10	59.44	59.44	59.44	59.90	50.23	53.79
4	49.00	59.54	59.98	60.00	60.00	60.00	52.40	58.02

Exhibit 38-34
Example Problem 1: ML Segment Space Mean Speeds

Analysis Period	Space Mean Speed (mi/h) by Segment							
	1	2	3	4	5	6	7	8
1	56.81	56.81	56.81	56.81	56.81	56.81	56.81	56.81
2	56.81	56.81	56.81	56.81	56.81	56.81	56.81	56.81
3	56.81	56.81	56.81	56.81	56.81	56.81	56.81	56.81
4	61.42	61.42	61.42	61.42	61.42	61.42	61.42	61.42
Analysis Period	**Space Mean Speed (mi/h) by Segment**							
	9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	56.81	56.81	54.05	64.36	64.36	64.36	52.48	70.00
2	56.81	56.81	54.47	59.21	59.21	59.21	52.06	70.00
3	56.81	56.81	54.39	60.33	60.33	60.33	52.15	70.00
4	61.42	61.42	54.22	66.05	66.05	66.05	52.65	70.00

Exhibit 38-35
Example Problem 1: GP Segment Densities

Analysis Period	Density (pc/mi/ln) by Segment							
	1	2	3	4	5	6	7	8
1	16.67	16.76	15.63	21.37	24.91	24.12	23.05	29.50
2	22.92	23.36	21.47	25.68	24.63	26.37	25.52	33.78
3	20.83	21.22	18.97	26.74	34.18	29.88	28.12	40.50
4	16.67	16.76	15.63	18.99	19.26	18.85	18.20	22.27
Analysis Period	**Density (pc/mi/ln) by Segment**							
	9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	27.66	29.50	22.93	22.92	22.92	28.83	42.63	40.27
2	59.40	43.91	28.42	28.42	28.42	26.62	42.00	38.99
3	67.16	43.91	29.16	29.16	29.16	27.24	42.44	39.63
4	25.63	25.91	20.37	20.36	20.36	24.72	35.93	32.46

Exhibit 38-36
Example Problem 1: ML Segment Densities

Analysis Period	Density (pc/mi/ln) by Segment							
	1	2	3	4	5	6	7	8
1	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52
2	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52
3	14.52	14.52	14.52	14.52	14.52	14.52	14.52	14.52
4	11.80	11.80	11.80	11.80	11.80	11.80	11.80	11.80
Analysis Period	**Density (pc/mi/ln) by Segment**							
	9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	14.52	14.52	15.70	10.10	10.10	10.10	12.69	0.01
2	14.52	14.52	15.70	13.09	13.09	13.09	14.84	0.01
3	14.52	14.52	15.70	12.43	12.43	12.43	14.41	0.01
4	11.80	11.80	13.98	9.08	9.08	9.08	11.83	0.01

Step 7: Adjacent Frictional Effects

Since the two lane groups are separated by a concrete barrier in this sample problem, it is assumed that there are no frictional effects. Therefore, no adjustment for the frictional effect is performed.

Step 8: Lane Group LOS

After completion of the frictional effect adjustments, a LOS is assigned to each segment for each 15-min analysis period on the basis of the LOS table given in Exhibit 10-7 in Chapter 10. Exhibit 38-37 and Exhibit 38-38 show the distribution of LOS across all segments and time periods for the GP lanes and MLs, respectively. The GP lane group experienced congestion in Analysis Periods 2 and 3, while the ML group maintained free-flow travel during the same periods. This demonstrates the MLs' operational advantage.

Exhibit 38-37
Example Problem 1: GP Segment LOS

Analysis Period	LOS by Segment							
	1	2	3	4	5	6	7	8
1	B	B	B	C	C	C	C	D
2	C	C	C	C	C	D	D	D
3	C	C	C	D	D	D	D	E
4	B	B	B	C	C	C	C	C
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	D	D	C	C	C	D	E	E
2	F	E	D	D	D	D	E	E
3	F	E	D	D	D	D	E	E
4	C	C	C	C	C	C	E	D

Exhibit 38-38
Example Problem 1: ML Segment LOS

Analysis Period	LOS by Segment							
	1	2	3	4	5	6	7	8
1	B	B	B	B	B	B	B	B
2	B	B	B	B	B	B	B	B
3	B	B	B	B	B	B	B	B
4	B	B	B	B	B	B	B	B
Analysis Period	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	B	B	B	A	A	A	B	A
2	B	B	B	B	B	B	B	A
3	B	B	B	B	B	B	B	A
4	B	B	B	A	A	A	B	A

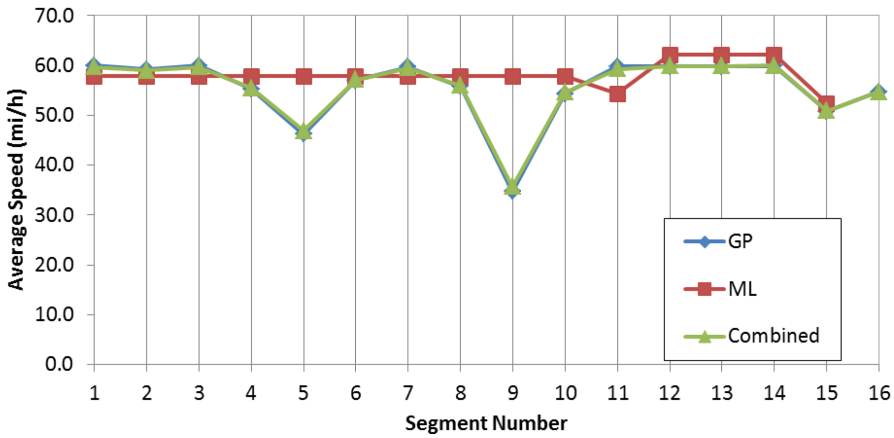
Step 9: Compute Facility Service Measures

Facility LOS for a given analysis period is based on the length- and lane-weighted average density of the facility (see Equation 10-2 in Chapter 10). However, if any component segment of the facility has a demand-to-capacity ratio exceeding 1.0, the facility LOS is automatically set to LOS F regardless of the average density. Since Segment 9 of the GP facility experiences LOS F during Analysis Periods 2 and 3, the GP facility LOS is automatically LOS F for those analysis periods. During Analysis Period 1, the average GP density is 24.56 pc/mi/ln, which corresponds to LOS C. During Analysis Period 4, the average GP density is 21.36 pc/mi/ln, which also corresponds to LOS C.

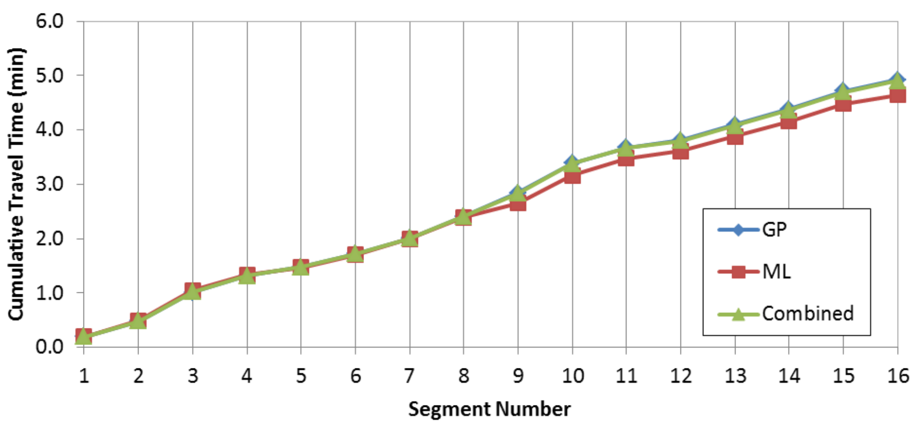
For the MLs, the average densities for Analysis Periods 1 through 4 are 13.18, 13.78, 13.65, and 11.05, respectively, all of which correspond to LOS B. Thus, the MLs experience better LOS than the GP lanes across all analysis periods.

Other performance measures can also be evaluated. For example, Exhibit 38-39 contrasts average speed profiles and the cumulative travel time difference for the two facilities. Exhibit 38-39(a) highlights the drop in speed due to congestion on the GP lanes (averaged across all analysis periods), while the separated ML facility operates almost at FFS during the same time. Accordingly, the cumulative travel time in the GP lanes is affected by the drop in speed, showing the advantage of the MLs over the length of the facility. The "combined" curve refers to the weighted average performance of ML and GP lanes.

Exhibit 38-39
Example Problem 1: Cumulative Speed and Travel Time Comparison for ML and GP Lanes



(a) Speed Comparison



(b) Cumulative Travel Time Comparison

Notes: GP = general purpose; ML = managed lane; combined = weighted average of GP and ML.

EXAMPLE PROBLEM 2: BUFFER-SEPARATED ML FACILITY

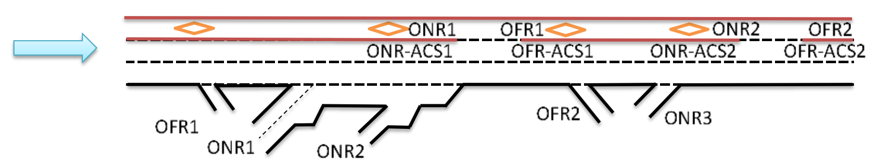
The Facility

The second sample facility is a northbound ML 11.3 mi long consisting of 38 segments. Like the first example problem, this example is based on an actual ML facility in the United States to demonstrate the methodology's capability of replicating the geometry of actual facilities. This facility uses buffer separation; therefore, the frictional effect will be modeled when the GP lane density exceeds 35 pc/mi/ln.

As shown in Exhibit 38-40, there are a total of five access segments between the ML and the GP lanes. Without the ML, the GP facility would have had only 29 segments. However, nine segments are added to preserve the parallel lane group assumption. For example, Segments 22, 23, and 24 would have been coded as one basic GP segment in the absence of the ML, but they are now modeled as basic, GP access, and basic. The GP access segment is coded in parallel to an ML access segment.

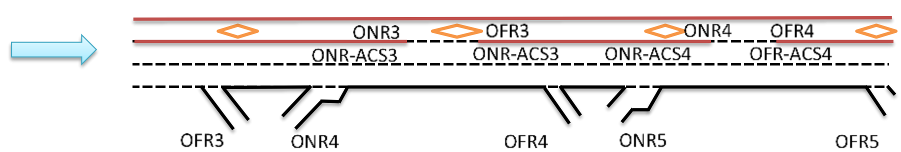
Exhibit 38-40
Example Problem 2: Lane Group Segmentation

SR-167 Northbound - Section 1 of 3



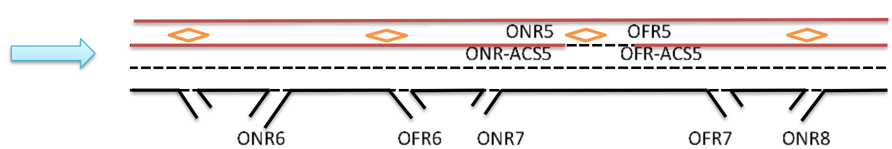
Segment Number	1	2	3	4	5	6	7	8	9	10	11	12
GP Segment Type	B	OFR	B	ONR	ONR	GP-ACS	OFR	B	ONR	B	GP-ACS	B
ML Segment Type	ML-B	ML-B	ML-B	ML-B	ML-B	ML-ACS	ML-B	ML-B	ML-B	ML-B	ML-ACS	ML-B
Length (ft)	10	740	3274	1450	1050	2300	720	2500	1500	700	1500	2900

SR-167 Northbound - Section 2 of 3



Segment Number	12	13	14	15	16	17	18	19	20	21	22	23	24	25
GP Segment Type	B	OFR	B	ONR	B	GP-ACS	B	OFR	B	ONR	B	GP-ACS	B	OFR
ML Segment Type	ML-B	ML-B	ML-B	ML-B	ML-B	ML-ACS	ML-B	ML-B	ML-B	ML-B	ML-B	ML-ACS	ML-B	ML-B
Length (ft)	2900	1500	2587	1500	802	1500	932	1500	2800	1500	750	1500	1300	1500

SR-167 Northbound - Section 3 of 3



Segment Number	25	26	27	28	29	30	31	32	33	34	35	36	37	38
GP Segment Type	OFR	B	ONR	R	OFR	B	ONR	B	GP-ACS	B	OFR	B	ONR	B
ML Segment Type	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-B	ML-ACS	ML-B	ML-B	ML-B	ML-B	ML-B
Length (ft)	1500	2640	982	518	982	1848	1500	974	1500	3314	1500	3300	1500	200

The Facts

In addition to the information contained in Exhibit 38-40, the following facility characteristics are known:

- GP lane group
  - FFS = 60 mi/h (all mainline segments)
  - Heavy vehicles = 0% ($f_{HV} = 1$)
  - $PHF = 1$
  - Commuter drivers ($f_p = 1$)
- ML lane group
  - FFS = 70 mi/h
  - Heavy vehicles = 0% ($f_{HV} = 1$)
  - $PHF = 1$
  - Commuter drivers ($f_p = 1$)

The study period is 60 min, divided into four 15-min analysis periods; 15-min demand flow rates are given in vehicles per hour under prevailing conditions. These demands must be converted to passenger cars per hour under equivalent ideal conditions for use in the parts of the methodology involving segment LOS estimation.

Step 1: Input Data

The demand input data for this facility are shown in Exhibit 38-41 for the GP lanes and Exhibit 38-42 for the ML.

Exhibit 38-41
Example Problem 2: GP Lane Group Demand Inputs

Analysis Period	Entering Flow Rate (veh/h)	Ramp Flow Rate by Time Period (veh/h)							
		ONR1	ONR2	ONR3	ONR4	ONR5	ONR6	ONR7	ONR8
1	2,000	325	400	300	1,000	200	1,400	10	250
2	2,900	325	400	300	1,000	200	1,400	10	250
3	2,800	325	400	300	1,000	200	1,400	10	250
4	2,700	325	400	300	1,000	200	1,400	10	250

Analysis Period	OFR1	OFR2	OFR3	OFR4	OFR5	OFR6	OFR7	ONR-ACS1	OFR-ACS1
1	326	400	1,000	350	10	1,600	240	300	250
2	326	400	1,000	350	10	1,600	240	350	250
3	326	400	1,000	350	10	1,600	240	164	258
4	326	400	1,000	350	10	1,600	240	358	320

Analysis Period	ONR-ACS2	OFR-ACS2	ONR-ACS3	OFR-ACS3	ONR-ACS4	OFR-ACS4	ONR-ACS5	OFR-ACS5	Exiting Flow Rate (veh/h)
1	400	300	700	350	350	400	400	350	2,459
2	387	250	358	478	329	324	258	500	2,859
3	369	258	168	145	358	147	300	450	2,759
4	247	258	180	138	358	145	258	350	2,659

Exhibit 38-42
Example Problem 2: ML Lane Group Demand Inputs

Analysis Period	Entering Flow Rate (veh/h)	Ramp Flow Rate by Time Period (veh/h)										Exiting Flow Rate (veh/h)
		ONR1	ONR2	ONR3	ONR4	ONR5	OFR1	OFR2	OFR3	OFR4	OFR5	
1	1,400	250	300	350	400	350	300	400	700	350	400	900
2	1,450	250	250	478	324	500	350	387	358	329	258	1,570
3	1,500	258	258	145	147	450	164	369	168	358	300	1,399
4	1,450	320	258	138	145	350	358	247	180	358	258	1,260

Step 2: Demand Adjustments

The traffic flows in Exhibit 38-41 and Exhibit 38-42 are already given in the form of actual demands. No additional demand adjustment is necessary, since the flows represent true demand. Note that the FREEVAL-ML computational engine assumes that the user inputs true demand flows.

Step 3: Compute Segment Capacities

Segment capacities are determined with the methodologies of Chapter 11 for basic GP segments, Chapter 12 for GP weaving segments, Chapter 13 for GP merge and diverge segments, and Section 2 of this chapter for ML basic segments. The resulting capacities are shown in Exhibit 38-43 and Exhibit 38-44.

The computed GP segment capacities are shown in Exhibit 38-43. Since there are no weaving segments (on-ramp followed by off-ramp connected by an auxiliary lane) on this facility, the capacity for each segment is constant over all time periods. Variation of capacity across segments is related to the presence of ramps and GP access segments. For the ML segment, the capacities for all segments are the same, since the segments have the same cross section.

Exhibit 38-43
Example Problem 2: GP Segment Capacities

Analysis Period	Capacity (veh/h) by Segment									
	1	2	3	4	5	6	7	8	9	10
1	4,488	4,488	4,488	6,732	6,669	4,488	4,369	4,488	4,382	4,382
2	4,488	4,488	4,488	6,732	6,669	4,488	4,369	4,488	4,382	4,382
3	4,488	4,488	4,488	6,732	6,669	4,488	4,369	4,488	4,382	4,382
4	4,488	4,488	4,488	6,732	6,669	4,488	4,369	4,488	4,382	4,382

Analysis Period	Capacity (veh/h) by Segment									
	11	12	13	14	15	16	17	18	19	20
1	4,488	4,488	4,488	4,488	4,368	4,368	4,488	4,382	4,382	4,488
2	4,488	4,488	4,488	4,488	4,368	4,368	4,488	4,382	4,382	4,488
3	4,488	4,488	4,488	4,488	4,368	4,368	4,488	4,382	4,382	4,488
4	4,488	4,488	4,488	4,488	4,368	4,368	4,488	4,382	4,382	4,488

Analysis Period	Capacity (veh/h) by Segment									
	21	22	23	24	25	26	27	28	29	30
1	4,419	4,419	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488
2	4,419	4,419	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488
3	4,419	4,419	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488
4	4,419	4,419	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488

Analysis Period	Capacity (veh/h) by Segment							
	31	32	33	34	35	36	37	38
1	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488
2	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488
3	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488
4	4,488	4,488	4,488	4,488	4,488	4,488	4,488	4,488

Exhibit 38-44
Example Problem 2: ML Segment Capacities

Analysis Period	Capacity (veh/h) by Segment									
	1	2	3	4	5	6	7	8	9	10
1	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
2	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
3	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
4	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
Analysis Period	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
2	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
3	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
4	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
Analysis Period	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
1	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
2	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
3	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
4	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341
Analysis Period	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**		
1	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341		
2	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341		
3	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341		
4	2,341	2,341	2,341	2,341	2,341	2,341	2,341	2,341		

Steps 4a and 4b: Adjust Segment Capacities and Incorporate Cross-Weave Adjustments

Step 4a allows the user to adjust capacities of specific segments or time periods to model the effects of work zones, inclement weather, incidents, and so forth. No additional capacity adjustment is performed for this example problem, since normal operating conditions are being analyzed.

Step 4b adjusts GP segment capacities to account for cross-weave effects between a GP on-ramp and ML access point or the ML access point and a GP off-ramp. Exhibit 38-45 summarizes the cross-weave effects for all (potentially applicable) GP segments along the facility. The values in the table correspond to the percentage reduction in segment capacity due to cross weave.

Exhibit 38-45
Example Problem 2: Summary of Estimated Cross-Weave CRFs

Analysis Period	Cross-Weave Capacity Reduction Factor by Segment									
	4	5	7	9	10	12	13	15	16	18
1	0.00	0.01	0.03	0.02	0.02	0.00	0.00	0.03	0.03	0.02
2	0.00	0.01	0.03	0.02	0.02	0.00	0.00	0.03	0.03	0.02
3	0.00	0.01	0.03	0.02	0.02	0.00	0.00	0.03	0.03	0.02
4	0.00	0.01	0.03	0.02	0.02	0.00	0.00	0.03	0.03	0.02
Analysis Period	**19**	**21**	**22**	**24**	**25**	**31**	**32**	**34**	**35**	
1	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	
2	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	
3	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	
4	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	

Step 5: Compute Demand-to-Capacity Ratios

The demand-to-capacity ratios are calculated on the basis of the demand flows and segment capacities in Exhibit 38-41 through Exhibit 38-44 for the GP and ML lane groups, separately, and with consideration of the cross-weave adjustments in Exhibit 38-45. The results for the GP and ML lane groups are shown in Exhibit 38-46 and Exhibit 38-47, respectively.

Exhibit 38-46
Example Problem 2: GP Segment Demand-to-Capacity Ratios

Analysis Period	Demand-to-Capacity Ratio by Segment									
	1	2	3	4	5	6	7	8	9	10
1	0.45	0.45	0.37	0.30	0.36	0.60	0.56	0.46	0.54	0.54
2	0.65	0.65	0.57	0.43	0.49	0.74	0.76	0.65	0.73	0.73
3	0.62	0.62	0.55	0.42	0.48	0.71	0.73	0.62	0.71	0.71
4	0.60	0.60	0.53	0.40	0.46	0.69	0.71	0.60	0.68	0.68
Analysis Period	11	12	13	14	15	16	17	18	19	20
1	0.61	0.55	0.55	0.32	0.56	0.56	0.70	0.64	0.64	0.55
2	0.71	0.71	0.71	0.49	0.73	0.73	0.71	0.73	0.73	0.63
3	0.69	0.69	0.69	0.47	0.71	0.71	0.69	0.71	0.71	0.61
4	0.67	0.67	0.67	0.45	0.69	0.69	0.67	0.68	0.68	0.59
Analysis Period	21	22	23	24	25	26	27	28	29	30
1	0.60	0.60	0.67	0.58	0.58	0.58	0.89	0.89	0.89	0.53
2	0.69	0.69	0.68	0.68	0.68	0.68	0.99	0.99	0.99	0.63
3	0.67	0.67	0.66	0.66	0.66	0.65	0.97	0.97	0.97	0.61
4	0.64	0.64	0.63	0.63	0.63	0.63	0.94	0.94	0.94	0.59
Analysis Period	31	32	33	34	35	36	37	38		
1	0.53	0.53	0.62	0.55	0.55	0.49	0.55	0.55		
2	0.63	0.63	0.63	0.63	0.63	0.58	0.64	0.64		
3	0.61	0.61	0.61	0.61	0.61	0.56	0.61	0.61		
4	0.59	0.59	0.59	0.59	0.59	0.54	0.59	0.59		

Exhibit 38-47
Example Problem 2: ML Segment Demand-to-Capacity Ratios

Analysis Period	Demand-to-Capacity Ratio by Segment									
	1	2	3	4	5	6	7	8	9	10
1	0.60	0.60	0.60	0.60	0.60	0.70	0.58	0.58	0.58	0.58
2	0.62	0.62	0.62	0.62	0.62	0.73	0.58	0.58	0.58	0.58
3	0.64	0.64	0.64	0.64	0.64	0.75	0.68	0.68	0.68	0.68
4	0.62	0.62	0.62	0.62	0.62	0.76	0.60	0.60	0.60	0.60
Analysis Period	11	12	13	14	15	16	17	18	19	20
1	0.70	0.53	0.53	0.53	0.53	0.53	0.68	0.38	0.38	0.38
2	0.68	0.52	0.52	0.52	0.52	0.52	0.72	0.57	0.57	0.57
3	0.79	0.63	0.63	0.63	0.63	0.63	0.70	0.62	0.62	0.62
4	0.71	0.61	0.61	0.61	0.61	0.61	0.67	0.59	0.59	0.59
Analysis Period	21	22	23	24	25	26	27	28	29	30
1	0.38	0.38	0.56	0.41	0.41	0.41	0.41	0.41	0.41	0.41
2	0.57	0.57	0.71	0.57	0.57	0.57	0.57	0.57	0.57	0.57
3	0.62	0.62	0.69	0.53	0.53	0.53	0.53	0.53	0.53	0.53
4	0.59	0.59	0.65	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Analysis Period	31	32	33	34	35	36	37	38		
1	0.41	0.41	0.56	0.38	0.38	0.38	0.38	0.38		
2	0.57	0.57	0.78	0.67	0.67	0.67	0.67	0.67		
3	0.53	0.53	0.73	0.60	0.60	0.60	0.60	0.60		
4	0.50	0.50	0.65	0.54	0.54	0.54	0.54	0.54		

The computed demand-to-capacity ratio matrices for GP and ML segments show that the GP lane group operates at a demand level very close to capacity, with *d/c* ratios of 0.99 in Segments 27 through 29. However, since no segment has a *d/c* ratio of more than 1.0, the facility is considered to be globally undersaturated. Similarly, for the ML lane group, no segment has a *d/c* ratio greater than 1.0 in any analysis period. Exhibit 38-48 and Exhibit 38-49 show the volume-to-capacity ratios by segment and time interval for the two lane groups, respectively. Without any queuing impacts, the resulting *v/c* ratios are identical to the *d/c* ratios of the same segment and time period presented earlier.

Exhibit 38-48
Example Problem 2: GP Segment Volume-to-Capacity Ratios

Analysis Period	Volume-to-Capacity Ratio by Segment									
	1	2	3	4	5	6	7	8	9	10
1	0.45	0.45	0.37	0.30	0.36	0.60	0.56	0.46	0.54	0.54
2	0.65	0.65	0.57	0.43	0.49	0.74	0.76	0.65	0.73	0.73
3	0.62	0.62	0.55	0.42	0.48	0.71	0.73	0.62	0.71	0.71
4	0.60	0.60	0.53	0.40	0.46	0.69	0.71	0.60	0.68	0.68
Analysis Period	11	12	13	14	15	16	17	18	19	20
1	0.61	0.55	0.55	0.32	0.56	0.56	0.70	0.64	0.64	0.55
2	0.71	0.71	0.71	0.49	0.73	0.73	0.71	0.73	0.73	0.63
3	0.69	0.69	0.69	0.47	0.71	0.71	0.69	0.71	0.71	0.61
4	0.67	0.67	0.67	0.45	0.69	0.69	0.67	0.68	0.68	0.59
Analysis Period	21	22	23	24	25	26	27	28	29	30
1	0.60	0.60	0.67	0.58	0.58	0.58	0.89	0.89	0.89	0.53
2	0.69	0.69	0.68	0.68	0.68	0.68	0.99	0.99	0.99	0.63
3	0.67	0.67	0.66	0.66	0.66	0.65	0.97	0.97	0.97	0.61
4	0.64	0.64	0.63	0.63	0.63	0.63	0.94	0.94	0.94	0.59
Analysis Period	31	32	33	34	35	36	37	38		
1	0.53	0.53	0.62	0.55	0.55	0.49	0.55	0.55		
2	0.63	0.63	0.63	0.63	0.63	0.58	0.64	0.64		
3	0.61	0.61	0.61	0.61	0.61	0.56	0.61	0.61		
4	0.59	0.59	0.59	0.59	0.59	0.54	0.59	0.59		

Exhibit 38-49
Example Problem 2: ML Segment Volume-to-Capacity Ratios

Analysis Period	Volume-to-Capacity Ratio by Segment									
	1	2	3	4	5	6	7	8	9	10
1	0.60	0.60	0.60	0.60	0.60	0.70	0.58	0.58	0.58	0.58
2	0.62	0.62	0.62	0.62	0.62	0.73	0.58	0.58	0.58	0.58
3	0.64	0.64	0.64	0.64	0.64	0.75	0.68	0.68	0.68	0.68
4	0.62	0.62	0.62	0.62	0.62	0.76	0.60	0.60	0.60	0.60
Analysis Period	11	12	13	14	15	16	17	18	19	20
1	0.70	0.53	0.53	0.53	0.53	0.53	0.68	0.38	0.38	0.38
2	0.68	0.52	0.52	0.52	0.52	0.52	0.72	0.57	0.57	0.57
3	0.79	0.63	0.63	0.63	0.63	0.63	0.70	0.62	0.62	0.62
4	0.71	0.61	0.61	0.61	0.61	0.61	0.67	0.59	0.59	0.59
Analysis Period	21	22	23	24	25	26	27	28	29	30
1	0.38	0.38	0.56	0.41	0.41	0.41	0.41	0.41	0.41	0.41
2	0.57	0.57	0.71	0.57	0.57	0.57	0.57	0.57	0.57	0.57
3	0.62	0.62	0.69	0.53	0.53	0.53	0.53	0.53	0.53	0.53
4	0.59	0.59	0.65	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Analysis Period	31	32	33	34	35	36	37	38		
1	0.41	0.41	0.56	0.38	0.38	0.38	0.38	0.38		
2	0.57	0.57	0.78	0.67	0.67	0.67	0.67	0.67		
3	0.53	0.53	0.73	0.60	0.60	0.60	0.60	0.60		
4	0.50	0.50	0.65	0.54	0.54	0.54	0.54	0.54		

Step 6: Compute Segment Service Measures

The methodology proceeds to calculate service measures for each segment and each time period starting with the first segment in Time Step 1. The computational details for each segment type are exactly as described in Chapters 11 through 13 for GP segments and in this chapter for ML segments.

The basic performance measures computed for each segment and each time step are the segment speed (Exhibit 38-50 and Exhibit 38-51) and density (Exhibit 38-52 and Exhibit 38-53). Other performance measures for comparing the two facilities are available as well. ML space mean speeds shown in Exhibit 38-51 include frictional effects computed during Step 7.

Exhibit 38-50
Example Problem 2: GP Segment Space Mean Speeds

Analysis Period	1	2	3	4	5	6	7	8	9	10
	Space Mean Speed (mi/h) by Segment									
1	60.00	54.09	59.77	60.00	55.79	43.88	53.97	59.56	53.93	58.98
2	60.00	54.09	59.77	60.00	55.25	42.95	53.97	59.56	52.84	58.80
3	60.00	54.09	59.77	60.00	55.32	44.54	53.97	59.56	53.03	58.83
4	60.00	54.09	59.77	60.00	55.39	41.59	53.97	59.56	53.19	58.85

Analysis Period	11	12	13	14	15	16	17	18	19	20
	Space Mean Speed (mi/h) by Segment									
1	41.79	59.48	52.98	59.74	53.84	59.05	37.73	56.89	54.05	59.82
2	42.76	59.51	52.98	59.74	52.84	58.89	38.49	57.00	54.05	59.82
3	42.79	59.51	52.98	59.74	53.03	58.92	47.18	58.21	54.05	59.82
4	44.02	59.55	52.98	59.74	53.19	58.94	47.40	58.24	54.05	59.82

Analysis Period	21	22	23	24	25	26	27	28	29	30
	Space Mean Speed (mi/h) by Segment									
1	53.65	58.97	39.92	57.92	54.62	59.81	50.52	56.41	51.98	59.19
2	53.11	58.89	41.89	58.13	54.62	59.81	48.06	51.73	51.98	59.19
3	53.27	58.91	45.59	58.51	54.62	59.81	48.71	52.93	51.98	59.19
4	53.41	58.93	45.80	58.53	54.62	59.81	49.30	54.05	51.98	59.19

Analysis Period	31	32	33	34	35	36	37	38
	Space Mean Speed (mi/h) by Segment							
1	53.89	59.18	40.65	59.61	54.24	59.88	53.84	58.44
2	53.41	59.11	39.03	59.58	54.24	59.88	53.39	58.33
3	53.53	59.13	39.64	59.59	54.24	59.88	53.52	58.37
4	53.65	59.14	42.15	59.64	54.24	59.88	53.64	58.39

Exhibit 38-51
Example Problem 2: ML Segment Space Mean Speeds

Analysis Period	1	2	3	4	5	6	7	8	9	10
	Space Mean Speed (mi/h) by Segment									
1	64.87	64.87	64.87	64.87	64.87	46.96	65.55	65.55	65.55	65.55
2	64.12	64.12	64.12	64.12	64.12	45.88	65.55	65.55	65.55	65.55
3	63.32	63.32	63.32	63.32	63.32	47.18	61.64	61.64	61.64	61.64
4	64.12	64.12	64.12	64.12	64.12	45.61	64.69	64.69	64.69	64.69

Analysis Period	11	12	13	14	15	16	17	18	19	20
	Space Mean Speed (mi/h) by Segment									
1	45.88	66.75	66.75	66.75	66.75	66.75	43.41	69.32	69.32	69.32
2	45.78	67.13	67.13	67.13	67.13	67.13	44.62	65.77	65.77	65.77
3	45.92	63.60	63.60	63.60	63.60	63.60	48.14	63.97	63.97	63.97
4	46.88	64.53	64.53	64.53	64.53	64.53	48.26	65.13	65.13	65.13

Analysis Period	21	22	23	24	25	26	27	28	29	30
	Space Mean Speed (mi/h) by Segment									
1	69.32	69.32	45.24	69.09	69.09	69.09	69.09	66.58	66.58	69.09
2	65.77	65.77	45.88	65.83	65.83	65.83	57.33	57.33	57.33	65.83
3	63.97	63.97	46.93	66.76	66.76	66.76	59.80	59.80	59.80	66.76
4	65.13	65.13	47.10	67.56	67.56	67.56	62.03	62.03	62.03	67.56

Analysis Period	31	32	33	34	35	36	37	38
	Space Mean Speed (mi/h) by Segment							
1	69.09	69.09	45.50	69.32	69.32	69.32	69.32	69.32
2	65.83	65.83	45.50	62.09	62.09	62.09	62.09	62.09
3	66.76	66.76	45.63	64.88	64.88	64.88	64.88	64.88
4	67.56	67.56	46.68	66.64	66.64	66.64	66.64	66.64

Exhibit 38-52
Example Problem 2: GP Segment Densities

Analysis Period	Density (pc/mi/ln) by Segment 1	2	3	4	5	6	7	8	9	10
1	16.67	18.71	14.00	11.11	14.33	30.41	22.58	17.20	21.69	19.91
2	24.17	26.45	21.53	16.11	19.90	37.96	29.89	24.34	28.32	27.20
3	23.33	25.59	20.70	15.55	19.28	35.52	29.03	23.50	27.54	26.34
4	22.50	24.73	19.86	15.00	18.65	36.81	28.17	22.66	26.76	25.48

Analysis Period	Density (pc/mi/ln) by Segment 11	12	13	14	15	16	17	18	19	20
1	32.50	20.59	22.58	12.13	22.15	20.74	41.19	24.60	25.59	20.47
2	36.98	26.88	29.03	18.40	28.00	27.16	41.02	28.06	29.03	23.81
3	35.79	26.04	28.17	17.57	27.22	26.30	32.50	26.62	28.17	22.98
4	33.68	25.18	27.31	16.73	26.44	25.44	31.31	25.75	27.31	22.14

Analysis Period	Density (pc/mi/ln) by Segment 21	22	23	24	25	26	27	28	29	30
1	24.08	22.46	37.10	22.44	23.87	21.64	33.98	35.35	35.82	20.18
2	27.20	25.89	35.97	26.23	27.74	25.40	37.49	42.91	39.69	23.98
3	26.42	25.03	31.99	25.20	26.88	24.57	36.71	40.98	38.83	23.14
4	25.64	24.17	30.77	24.34	26.02	23.73	35.93	39.21	37.97	22.29

Analysis Period	Density (pc/mi/ln) by Segment 31	32	33	34	35	36	37	38
1	22.21	20.27	34.01	20.54	22.58	18.44	22.57	21.04
2	25.72	24.10	36.03	23.91	26.02	21.78	25.69	24.51
3	24.94	23.25	34.25	23.07	25.16	20.95	24.91	23.64
4	24.16	22.39	31.05	22.21	24.30	20.11	24.13	22.77

Exhibit 38-53
Example Problem 2: ML Segment Densities

Analysis Period	Density (pc/mi/ln) by Segment 1	2	3	4	5	6	7	8	9	10
1	21.58	21.58	21.58	21.58	21.58	35.14	20.59	20.59	20.59	20.59
2	22.61	22.61	22.61	22.61	22.61	37.05	20.59	20.59	20.59	20.59
3	23.69	23.69	23.69	23.69	23.69	37.26	25.86	25.86	25.86	25.86
4	22.61	22.61	22.61	22.61	22.61	38.81	21.83	21.83	21.83	21.83

Analysis Period	Density (pc/mi/ln) by Segment 11	12	13	14	15	16	17	18	19	20
1	35.97	18.73	18.73	18.73	18.73	18.73	36.86	12.98	12.98	12.98
2	34.95	18.07	18.07	18.07	18.07	18.07	37.90	20.27	20.27	20.27
3	40.33	23.32	23.32	23.32	23.32	23.32	33.82	22.82	22.82	22.82
4	35.62	22.05	22.05	22.05	22.05	22.05	32.35	21.20	21.20	21.20

Analysis Period	Density (pc/mi/ln) by Segment 21	22	23	24	25	26	27	28	29	30
1	12.98	12.98	28.73	13.75	13.75	13.75	13.75	14.27	14.27	13.75
2	20.27	20.27	36.11	20.17	20.17	20.17	23.16	23.16	23.16	20.17
3	22.82	22.82	34.24	18.71	18.71	18.71	20.89	20.89	20.89	18.71
4	21.20	21.20	32.40	17.29	17.29	17.29	18.83	18.83	18.83	17.29

Analysis Period	Density (pc/mi/ln) by Segment 31	32	33	34	35	36	37	38
1	13.75	13.75	28.57	12.98	12.98	12.98	12.98	12.98
2	20.17	20.17	40.18	25.29	25.29	25.29	25.29	25.29
3	18.71	18.71	37.24	21.56	21.56	21.56	21.56	21.56
4	17.29	17.29	32.52	18.91	18.91	18.91	18.91	18.91

Step 7: Adjacent Frictional Effects

This facility does not have an active bottleneck but still has several GP segments that operate at a density above 35 pc/mi/ln. For these segments, the methodology invokes the frictional effect module, which results in a reduction in operating speed on the adjacent ML lane group. The corresponding ML speed drops by up to 8.5 mi/h in Segments 27 through 29 because of the frictional effect imposed onto the ML. Note that if the facility had been designed with barrier separation, no frictional effect would have been experienced by the ML traffic. The speeds shown in Exhibit 38-51 already reflect this adjustment.

Step 8: Lane Group LOS

On completion of the frictional effect adjustments, a LOS is assigned to each segment for each 15-min analysis period on the basis of the LOS table given in Exhibit 10-7 in Chapter 10. Exhibit 38-54 and Exhibit 38-55 show the distribution of LOS across all segments and time periods for the GP lanes and MLs, respectively.

Exhibit 38-54
Example Problem 2: GP Segment LOS

Analysis Period	LOS by Segment									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	B	B	B	B	B	D	C	B	C	C
2	C	C	C	B	C	E	D	C	D	D
3	C	C	C	B	B	E	D	C	D	D
4	C	C	C	B	B	E	D	C	C	D
Analysis Period	**LOS by Segment**									
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	D	C	C	B	C	C	E	C	C	C
2	E	D	D	C	D	D	E	D	D	C
3	E	D	D	B	C	D	D	D	D	C
4	D	C	C	B	C	D	D	D	C	C
Analysis Period	**LOS by Segment**									
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
1	C	C	E	C	C	C	D	E	E	C
2	C	D	E	D	D	C	E	E	E	C
3	C	C	D	C	C	C	E	E	E	C
4	C	C	D	C	C	C	E	E	E	C
Analysis Period	**LOS by Segment**									
	31	**32**	**33**	**34**	**35**	**36**	**37**	**38**		
1	C	C	D	C	C	C	C	C		
2	C	C	E	C	C	C	C	C		
3	C	C	E	C	C	C	C	C		
4	C	C	D	C	C	C	C	C		

Exhibit 38-55
Example Problem 2: ML Segment LOS

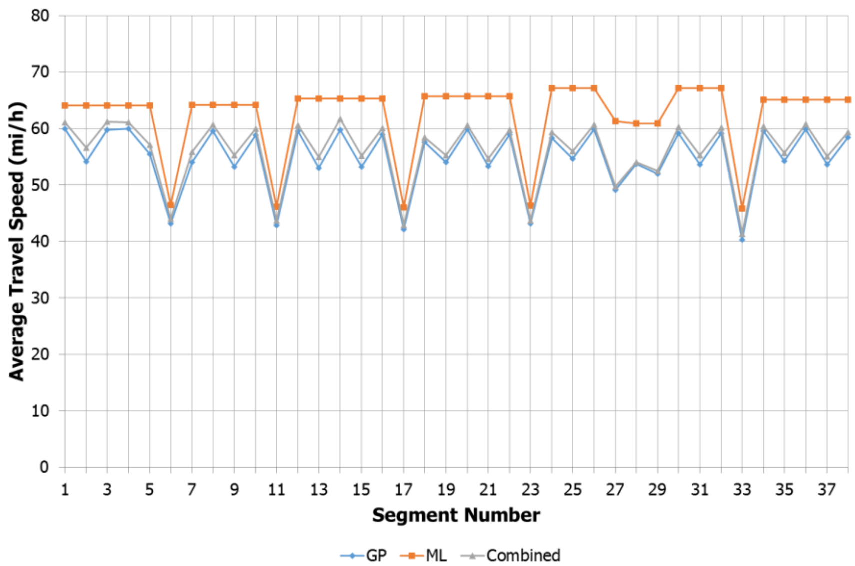
Analysis Period	LOS by Segment									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	C	C	C	C	C	E	C	C	C	C
2	C	C	C	C	C	E	C	C	C	C
3	C	C	C	C	C	E	D	D	D	D
4	C	C	C	C	C	E	C	C	C	C
Analysis Period	**LOS by Segment**									
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	E	C	C	C	C	C	E	B	B	B
2	E	C	C	C	C	C	E	C	C	C
3	E	C	C	C	C	C	D	C	C	C
4	E	C	C	C	C	C	D	C	C	C
Analysis Period	**LOS by Segment**									
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
1	B	B	D	B	B	B	B	B	B	B
2	C	C	E	C	C	C	C	C	C	C
3	C	C	E	C	C	C	C	C	C	C
4	C	C	D	B	B	B	C	C	C	B
Analysis Period	**LOS by Segment**									
	31	**32**	**33**	**34**	**35**	**36**	**37**	**38**		
1	B	B	D	B	B	B	B	B		
2	C	C	E	C	C	C	C	C		
3	C	C	E	C	C	C	C	C		
4	B	B	D	C	C	C	C	C		

Step 9: Compute Facility Service Measures

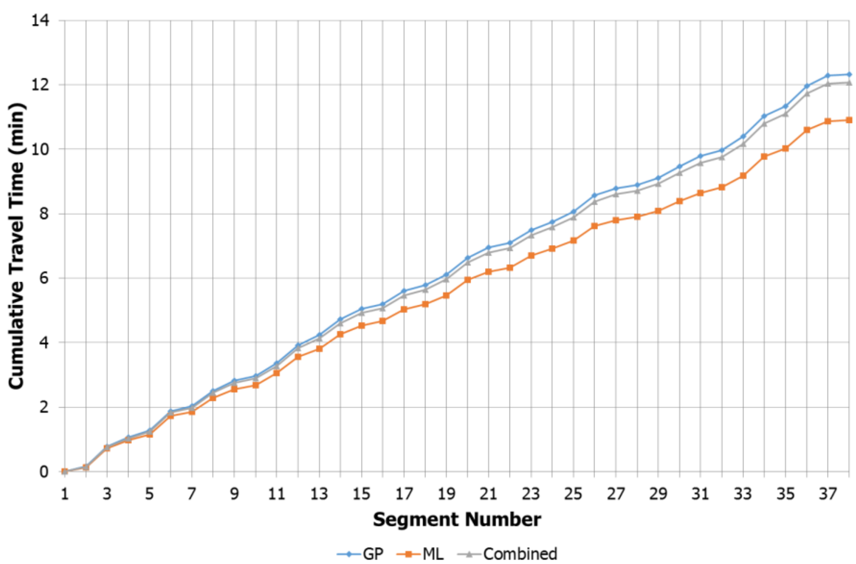
Facility LOS for a given analysis period is based on the length- and lane-weighted average density of the facility (see Equation 10-2 in Chapter 10). The results of these calculations show that the ML facility experiences LOS C operations during all analysis periods. The GP facility experiences LOS C during Analysis Periods 1 and 4 and LOS D during Analysis Periods 2 and 3.

Other performance measures can also be evaluated. For example, Exhibit 38-56 contrasts speed profiles and the cumulative travel time difference for the two facilities, averaged across all analysis periods.

Exhibit 38-56
Example Problem 2: Cumulative Speed and Travel Time Comparison for ML and GP Lanes



(a) Speed Comparison



(b) Cumulative Travel Time Comparison

Notes: GP = general purpose; ML = managed lane; combined = weighted average of GP and ML.

Exhibit 38-56(a) highlights speed drops in both the ML and the GP lanes in the five ML/GP access segments along the facility (Segments 6, 11, 17, 23, and 33). The speed drop is the result of lane-change turbulence in those access segments. The adjacent frictional effect is evident in Segments 27 through 29, where the GP lanes operate at LOS E and thus produce a speed drop on the ML. Exhibit 38-56(b) highlights the (slightly) superior performance on the ML, as opposed to the GP lanes.

6. REFERENCES

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

1. Wang, Y., X. Liu, N. Rouphail, B. Schroeder, Y. Yin, and L. Bloomberg. *NCHRP Web-Only Document 191: Analysis of Managed Lanes on Freeway Facilities.* Transportation Research Board of the National Academies, Washington, D.C., Aug. 2012. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w191.pdf.
2. Liu, X., B. J. Schroeder, T. Thomson, Y. Wang, N. M. Rouphail, and Y. Yin. Analysis of Operational Interactions Between Freeway Managed Lanes and Parallel, General Purpose Lanes. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2262*, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 62–73.
3. Schroeder, B. J., S. Aghdashi, N. M. Rouphail, X. C. Liu, and Y. Wang. Deterministic Approach to Managed Lane Analysis on Freeways in Context of *Highway Capacity Manual*. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2286*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 122–132.