Operational Analysis of Bus Lanes on Arterials

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Report 26

Operational Analysis of Bus Lanes on Arterials

KEVIN ST. JACQUES
Wilbur Smith Associates
Houston, TX

and

HERBERT S. LEVINSON
New Haven, CT

Subject Area
Public Transit

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TRANSPORTATION RESEARCH BOARD
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The nation’s growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in TRB Special Report 213—Research for Public Transit: New Directions, published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transit Association (APTA), Transportation 2000, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA; the National Academy of Sciences, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.
This report contains guidelines for estimating bus lane capacities and speeds along arterial streets. It recommends level-of-service thresholds for buses based on speed, and it presents procedures for estimating the speed of buses using dedicated bus lanes on arterial streets.

The capacity of a bus lane, where buses must follow each other without passing, is well established. There was relatively little information, however, on the bus flow capacity of an arterial that has an exclusive bus lane where buses have partial or exclusive use (i.e., dual bus lanes) of the adjacent lane. The level of service (LOS) of these bus facilities and their impact on arterial flow is not addressed in the current edition of the Highway Capacity Manual (HCM). Currently, bus impacts are addressed independently in Chapter 9, Signalized Intersections, and in Chapter 12, Transit Capacity, and not at all in Chapter 11, Urban and Suburban Arterials. A comprehensive and consistent procedure for assessing bus flow capacity and LOS, and the impacts of bus flow on arterials was needed.

Under NCTRP Project 55-2 and TCRP Project A-7, Wilbur Smith Associates/Herbert S. Levinson developed speed thresholds for determining LOS and revised them based on comments from transit agencies, reviewed available analysis techniques, and developed new analysis procedures based on simulation and limited field data. These procedures can be used to determine the capacity and speed of bus flow on arterials with at least one exclusive lane for buses, with either no, partial, or exclusive use of the adjacent lane. Both procedures reflect delays due to traffic signals and dwell times.

The procedures developed in this project are expected to be incorporated into the Year 2000 edition of the HCM and the Transit Capacity and Quality of Service Manual, which is the subject of TCRP Project A-15.
CHAPTER 5 Interpretation, Appraisal, and Implications

5.1 Speed as a Flow Level of Service Criteria, 46
5.2 Effects of Adjacent Lanes, 46
5.3 Potential Modifications to the HCM, 47
  5.3.1 Overview of Suggested Changes, 47
  5.3.2 Specific Modifications to Chapter 12, 47
  5.3.3 Specific Modifications to Chapter 9, 48
5.4 Service Planning Guidelines, 48
5.5 Research Possibilities, 48

APPENDIX A Literature Review

APPENDIX B Dwell Range Window Approach to Estimate Speed

REFERENCES
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OPERATIONAL ANALYSIS OF BUS LANES ON ARTERIALS

SUMMARY

This research analyzes the operation of buses along arterial street bus lanes, focusing on operating conditions in which buses have full or partial use of adjacent lanes, exploring the impacts of adjacent lanes on bus speeds and capacities, and deriving relationships and procedures for these impacts and interactions. The research demonstrates how increasing bus volumes can reduce speeds and how right turns from or across bus lanes can affect bus flow.

The research parameters and procedures, which complement and expand available information pertaining to bus use of arterials, provide important input for the Highway Capacity Manual (HCM) update and for a new transit capacity manual.

RESEARCH APPROACH AND FOCUS

The research, which was approached from both theoretical and practical procedures, refined and updated bus berth capacity formulas and parameters, drawing on the results of field studies and simulation runs. Available literature describing bus operations on city streets was reviewed; speed-related level of service criteria that reflect transit agency input were established; analytical relationships for estimating bus speeds were developed; and extensive, customized TRAF-NETSIM simulation runs were used to refine and calibrate these relationships and field test them for bus lanes in Houston, San Francisco, Los Angeles, and Chicago. Finally, the research translated these analyses into simple user-friendly procedures for application. The results show how the number of buses per hour, bus stops per mile, bus stop dwell times and service patterns, signal constraints, and traffic volumes in adjacent lanes affect bus lane speeds and capacities.

Three types of bus lanes were analyzed:

1. A curb bus lane where passing is impossible or prohibited and where right turns are either permitted or prohibited. The lane may operate in the same direction as other traffic or may operate contraflow.
2. A curb bus lane where buses can use the adjacent mixed-traffic lane for overtaking or “leap frogging” around stopped buses. Right turns by non-bus traffic may or may not be prohibited from the curb bus lane.
3. Dual bus lanes with non-bus right turns prohibited.
The Type 2 and 3 bus lanes allow bus stops to be split among alternate stopping locations, whereas the Type I bus lanes usually preclude such skip-stop operations.

The analyses focus on bus lanes along downtown streets, where passenger boardings generally are the heaviest, traffic signals are the most frequent, and most bus lanes are located. The procedures and parameters also apply to bus lanes on major radial arterials. It should be noted that bus service in most urban and suburban settings is too infrequent to warrant bus lanes, and bus berth capacity generally is not critical in these settings.

The research relates to bus lane operations in the United States and Canada. Procedures and parameters need adjustment for application elsewhere, especially in Asia.

LITERATURE REVIEW

A literature search, performed by the Transportation Research Information Service (TRIS), was supplemented by information assembled by the research team. Much of the information in these documents provided a picture of bus speed and bus capacity on streets with bus lanes. The literature review indicated that site-specific information is available on arterial bus capacities; bus travel times keyed to traffic congestion, bus stop spacing, and dwell time; and the effects of removing other traffic from bus lanes. This information provided a basis for refining estimates of bus berth capacity and for developing procedures for estimating bus lane speed. The literature review is presented in Appendix A.

Bus Stop Capacity

The capacity of a bus stop, in buses per hour, depends on the number of berths provided, green per cycle time available, and passenger dwell times. Dwell times vary substantially from the average; therefore, these variations and the probabilities of “failure” (queues forming at the bus stop) also are taken into account. These factors are reflected in the bus berth and bus stop capacities set forth in Chapter 12 of the HCM.

Berth Capacity Comparison

The capacities obtained from applying the HCM formulas and tables for various dwell times were consistent with those obtained from simulation runs. The number of effective berths obtained by simulation generally were similar to those set forth in the HCM.

<table>
<thead>
<tr>
<th></th>
<th>HCM</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 berths to 1 berth</td>
<td>1.75</td>
<td>1.83</td>
</tr>
<tr>
<td>3 berths to 1 berth</td>
<td>2.25</td>
<td>2.43</td>
</tr>
</tbody>
</table>

The field studies indicated a wide range in dwell times. A coefficient of variation of 40 to 60 percent of the mean dwell time was found to be representative of most dwell times and provided an input for revised calculations. Capacities based on a 60 percent coefficient of variation are about four buses per hour less than those set forth in the HCM, for a 50 percent effective green per cycle time and a 30 percent failure rate. A 20 percent absolute change in the coefficient of variation (as from 60 to 40 percent) results in a difference of about three buses per berth. Thus, a 40 percent coefficient of variation is very close to the values currently contained in the existing HCM. Basic bus berth capacity was revised slightly to more explicitly consider the variations for both average dwell times and various failure rates and to allow user input as desired.
The revised formulas indicate that capacity increases as the effective green per cycle ratio increases. However, the increase is not directly proportional because some of the dwell time occurs when the traffic signals are red. Capacity decreases as the variability in dwell times increases and as the allowable likelihood of failure is reduced.

**Levels of Service**

The levels of service (LOS) for bus stops are keyed to the approximate likelihood of queues forming behind a bus stop (i.e., the failure of the stop). The simulation analyses indicated that bus speeds drop rapidly when queues occur about 15 percent of the time. Accordingly, the maximum values of LOS D and E could be reduced to 15 percent and 25 percent, respectively. This results in the following possible changes in existing service levels. Percentages refer to approximate failure rates.

<table>
<thead>
<tr>
<th>LOS A ≤</th>
<th>HCM Table 12-17 (%)</th>
<th>Suggested Revision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS B ≤</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>LOS C ≤</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>LOS D ≤</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>LOS E ≤</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

**Adjustment Factors**

Adjustment factors were developed to reflect the capacity gains resulting from skip-stop operations and the capacity losses resulting from right-turn traffic conflicts. First, the provision of alternate block (skip-stop) stopping patterns allows the capacity of the bus lane to approach the sum of the capacities of the individual stops. However, when the adjacent lane operates at or near capacity, it becomes difficult for buses to enter and use this lane. Reduction factors were derived, drawing on simulation runs, to reflect the impedance to attaining the sum of the two capacities. Representative values of these factors for typical bus arrivals are as follows:

<table>
<thead>
<tr>
<th>Adjacent Lane v/c Ratio</th>
<th>Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.88</td>
</tr>
<tr>
<td>0.5</td>
<td>0.84</td>
</tr>
<tr>
<td>0.8</td>
<td>0.71</td>
</tr>
<tr>
<td>1.0</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Second, the conflicts between buses and right turns result in vehicles turning right preempting a portion of the green time available to buses. The time lost depends on the number of right turns and conflicting pedestrian volumes involved. For example, for a 50 percent effective green per cycle ratio and 100 right turns conflicting with 100 pedestrians per hour, right turns would have a volume-to-capacity (v/c) ratio of 15 percent, whereas 300 right turns would have a v/c ratio of 44 percent. These translate into capacity reduction factors of 85 percent and 56 percent, respectively, for near side bus stops.
Effects on Adjacent Lane Traffic

The introduction of single or dual bus lanes along arterial streets will reduce the vehicular capacity for other traffic. The amount of this reduction depends on (1) the type of bus lane, (2) the number of buses involved, and (3) whether the bus lane replaces a traffic lane.

A single-curb bus lane (Type 1) has a minimal impact on vehicular capacity when the lane is already used primarily by buses. A dual bus lane (Type 2) would reduce arterial capacity by up to two lanes, depending on the bus use of the roadway before such a lane is implemented. Where buses operate skip-stop or may enter the adjacent lane (Type 3), bus lane impacts will lie between that for the Type 1 and Type 3 bus lanes; only a portion of the buses will actually use the adjacent lane.

Bus Speeds

Bus travel times and speeds are important to the transit passenger, transit operator, traffic engineer, and transport planner. The transit passenger wants a quick and dependable trip. The transit operator (or service planner) measures and analyzes bus speeds to set, monitor, and refine schedules; estimate vehicle requirements; and plan new routes and services. The traffic engineer uses bus speeds to assess the impact of traffic controls or bus priority treatments, and the transport planner uses speed to quantify congestion and provide inputs into the transit demand and modeling process. Finally, many transit agencies view roadway or transitway effectiveness in terms of the person-miles per hour achieved during peak travel conditions. Speed estimates are useful for these purposes.

Levels of Service

The 1985 and 1994 editions of the HCM define levels of service for bus operations in terms of passengers per bus and buses per hour. The research introduces an additional criterion: bus speeds. The use of speed ranges for various bus operating environments to define service levels is easy to understand and reflects the transit passenger’s perceptions of how well the buses operate along a route. Moreover, bus travel speed as a performance measure is consistent with existing level of service criteria in the HCM for arterial streets and with proposals under consideration for a year 2000 HCM. It enables the performance of cars and buses along arterial roadways to be measured on a comparable basis and makes it possible to assess “person LOS.”

The suggested speed-related level of service values for local bus service are shown in Table S-1. The specific breakpoint values for buses are lower than those for general traffic because buses must experience both nominal traffic delays and delays associated with receiving and discharging passengers at stops.

Bus Speed Estimates

The best way to obtain bus speeds is by direct measurement at the specified locations during relevant time periods. This is not always practical, however, especially if evaluations of future conditions are requested or changes in bus stopping patterns or dwell times are anticipated. In such cases, estimates are necessary.

Bus speeds and travel times along arterial streets are influenced by the frequency and duration of stops, interference from bus and automobile traffic (including standing vehicles), and traffic signals. The interactions between dwell times at bus stops and delays at traffic signals reduce speeds and increase their variability. Consequently, bus speeds on
downtown streets have coefficients of variation ranging from about 15 to 30 percent, compared with a 10 to 15 percent variation for general traffic on central business district (CBD) streets.

Accordingly, further analyses were made of the relationships between bus speeds and stop frequency, stop duration, and traffic signal timing. Speeds were simulated using a customized version of TRAF-NETSIM, a general approach was developed for bus lane speeds, and a more detailed approach was derived for assessing the effects of traffic signal coordination patterns. The results of these analyses were compared with each other and with the results of field tests. Adjustment factors were then derived for bus-bus interference and adjacent lane availability. The general approach was suggested for inclusion in the HCM.

The general approach produced a look-up table for bus lane speeds for various stop frequencies and dwell times. Speeds reflect average values of traffic signal and right-turn delays found in actual practice. Representative values for CBD bus lanes follow:

<table>
<thead>
<tr>
<th>LEVEL OF SERVICE</th>
<th>HCM CRITERIA FOR ARTERIAL CLASS III (25-35 MPH FREE FLOW SPEED)</th>
<th>CBD STREETS (&gt; 7 STOPS/MI)</th>
<th>URBAN ARTERIALS (4 TO 7 STOPS/MI)</th>
<th>SUBURBAN ARTERIALS (1 TO 3 STOPS/MI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min/mi mi/hr</td>
<td>min/mi mi/hr</td>
<td>min/mi mi/hr</td>
<td>min/mi mi/hr</td>
</tr>
<tr>
<td>A</td>
<td>≤2.40 ≥25.0</td>
<td>≤6.0 ≥10.0</td>
<td>≤3.6 ≥16.7</td>
<td>≤2.8 ≥21.2</td>
</tr>
<tr>
<td>B</td>
<td>≤3.16 ≥19.0</td>
<td>≤9.0 ≥6.7</td>
<td>≤4.7 ≥12.7</td>
<td>≤3.7 ≥16.2</td>
</tr>
<tr>
<td>C</td>
<td>≤4.61 ≥13.0</td>
<td>≤12.0 ≥5.0</td>
<td>≤6.9 ≥8.7</td>
<td>≤5.5 ≥11.0</td>
</tr>
<tr>
<td>D</td>
<td>≤6.67 ≥9.0</td>
<td>≤15.0 ≥4.0</td>
<td>≤10.0 ≥6.0</td>
<td>≤7.6 ≥7.9</td>
</tr>
<tr>
<td>E</td>
<td>≤8.57 ≥7.0</td>
<td>≤18.0 ≥3.3</td>
<td>≤12.4 ≥4.7</td>
<td>≤10.0 ≥6.0</td>
</tr>
<tr>
<td>F</td>
<td>≥8.57 &lt;7.0</td>
<td>&gt;18.0 &lt;3.3</td>
<td>&gt;12.9 &lt;4.7</td>
<td>&gt;10.0 &lt;6.0</td>
</tr>
</tbody>
</table>

The detailed approach permits a more precise estimate of bus speeds when detailed traffic signal coordination information is available. It applies a series of equations that estimate

<table>
<thead>
<tr>
<th>Traffic Signal Delay Only</th>
<th>Traffic Signal Right-Turn Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Travel Time (min/mi)</td>
</tr>
<tr>
<td>6 stops/mi</td>
<td>20-min dwell</td>
</tr>
<tr>
<td></td>
<td>40-min dwell</td>
</tr>
<tr>
<td>8 stops/mi</td>
<td>20-min dwell</td>
</tr>
<tr>
<td></td>
<td>40-min dwell</td>
</tr>
</tbody>
</table>
bus speeds as a function of bus stop spacings, dwell times, and traffic signal cycle length, green time, and coordination patterns.

The availability of the lane adjacent to a bus lane makes it possible for buses to operate in a skip-stop pattern. This increases the distance between stops, thereby enhancing bus speeds. For example, alternate skipping of every other stop may effectively double bus speeds if dwell times remain the same. However, if mixed traffic in the adjacent lane and curb bus lane operate at or near capacity (i.e., v/c ratio greater than 0.8), skip-stop speeds would be only 15 to 20 percent greater than if buses stopped at every block; skipping buses would be delayed behind stopping buses because of the unavailability of the passing lane. An equation was developed to express the reductive effects of the unavailability of the adjacent lane on the ability to attain the enhanced skip-stop bus speeds.

Both the field observations and simulation analyses demonstrate that bus speeds along an arterial bus or curb lane decline as the lane becomes filled with buses. This is because there is a greater likelihood that one bus will delay subsequent buses, either by preempting berth space or by making weaving maneuvers. Suggested speed reduction factors were derived to reflect this bus-bus interference. Representative values are as follows:

<table>
<thead>
<tr>
<th>Bus Berth v/c Ratio</th>
<th>Speed Reduction Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>1.00</td>
</tr>
<tr>
<td>0.8</td>
<td>0.81</td>
</tr>
<tr>
<td>0.9</td>
<td>0.70</td>
</tr>
<tr>
<td>1.0</td>
<td>0.55</td>
</tr>
</tbody>
</table>

APPLICATION PROCEDURES

Application of the bus speed and capacity estimating procedures are straightforward. Both sets of procedures call for identifying existing conditions and parameters for the section of bus lane or roadway to be analyzed, including the controlling sections, in terms of dwell times, signal timing, and traffic conflicts. This involves obtaining information on roadway geometry and bus lane type, traffic signal and turn conflicts, bus stopping patterns and bus stop length, and peak-hour dwell time at major stops.

The next step is to estimate basic speed and capacity. These estimates, in turn, should be modified to reflect factors such as the following:

- Bus-bus interference;
- Availability of the adjacent lane for bus use; and
- Right-turn impedances.

Bus-berth capacities should be computed first because the berth v/c ratio serves as input to the bus speed adjustment factors. Capacities should be computed at the critical locations along a bus lane. Bus speed estimates, which generally should be made over sections of a route, may require some averaging of conditions at individual stops.

As a final step, the levels of service can be obtained for both bus speeds and existing bus flows by comparing them with established criteria.

POTENTIAL MODIFICATIONS TO THE HCM

The research findings provide important input for the year 2000 HCM and the ongoing transit capacity and quality of service research. The following opportunities exist for incor-
porating the findings within the framework of the 1985 and 1994 HCM. Most relate to Chapter 12, Transit Capacity; however, some also relate to Chapter 9, Signalized Arterials, and Chapter 11, Urban and Suburban Arterials.

The existing information in Chapter 12 describing bus berth capacity could be augmented by including the new capacity procedures for skip-stop operations (including dual bus lanes) and for right-turn impacts. The current HCM statement that capacity would be doubled by instituting a skip-stop pattern should be modified in light of these research findings. The information in Chapter 12 dealing with passenger capacity of a bus berth could be modified to reflect the new procedures, parameters, and service levels. Additional examples may be desirable.

Suggested additions to the HCM pertaining to bus speeds include (1) the new speed-related level of service criteria and (2) the methods for estimating bus lane speeds. These could be incorporated into Chapter 11 or into new sections on bus speeds in Chapter 12, perhaps in Section III, just before the discussions on bus priority treatments.

Information dealing with the effects of buses on other traffic should be consolidated into Chapter 9. The information on arterial bus lane speeds and service levels could be placed in Chapter 11.

**SERVICE PLANNING GUIDELINES**

The basic traffic and transit goals should be to improve the speed, reliability, and capacity of bus operations. Bus speeds and capacities depend on how frequently the bus stops are placed, how long the buses stop, traffic conditions along the bus lane or route, and whether buses can pass and overtake each other. It is desirable to minimize the number of bus stops along a bus route consistent with land use, street system, and passenger demands. In addition, where bus volumes and passenger boardings are heavy, multiple bus berths at stops are essential to provide sufficient capacity and to minimize bus-bus delays.

Passenger dwell times at bus stops should be minimized. This suggests the use of passes or fare cards, pay-as-you-leave fare collection, and possibly prepayment of fares at busy stops and the use of wide multichannel doors, low-floor buses, and sufficient major stops to distribute passenger loads.

It is also important to minimize the variations in dwell times at key bus stops during peak travel periods. It is desirable to separate local and express bus stops, where each service may have widely different dwell times. The provision of bus lanes, bus streets, and busways is desirable to minimize auto-bus conflicts.

Bus lane speeds can be enhanced by providing alternate skip-stops where alternate groups of buses stop at alternate locations. The main benefit of having the adjacent lane available for buses is the ability to operate skip-stop with alternate groups of buses stopping at alternate locations. This suggests dual bus lanes (normal flow or contraflow) where block spacing and passenger demands are conducive to skip-stops.

The location of bus stops can affect bus lane speeds. Curb bus lane speeds can be enhanced by prohibiting right turns at major boarding and alighting points or by providing far-side bus stops.

Dual bus lanes, with the prohibition of right turns and skip-stop operations, result in a virtual doubling of speeds and, to a lesser extent, route capacities. But where buses must share the adjacent lane with other traffic, the gains in speeds and capacities are less, especially when the adjacent lane operates at or near its capacity.

Bus service and stopping patterns must be tempered by the existing route structure, block spacings, and passenger demand. Overconcentration of passenger boardings would increase dwell times, thereby reducing speeds and capacities. From a speed perspective, lengthening the distance between stops throughout the urban area may prove beneficial.
Bus speeds are affected by the realities of operations on city streets, where there is much competition for curb space. Other buses, right turns, loading and goods delivery, and dwelling, parked, or parking vehicles will adversely affect bus speeds. Therefore, sound management and effective enforcement of bus lanes is essential.

This research addressed bus capacity in terms of buses per hour. Perhaps even more important is the movement of people. This involves providing enough stops and berths along a bus route to accommodate the peak passenger demands at the maximum load section. These procedures are discussed in the HCM and can be readily modified to reflect the suggested research results.

FUTURE RESEARCH

Several possible research areas emerged from the analyses, including the following: (1) refining bus speed analysis for buses operating in mixed traffic and (2) further simulation to determine how signal timing changes can minimize person-delay.
CHAPTER 1

OVERVIEW OF PROJECT AND PROCEDURES

This final report on TCRP Project A-7 documents the results of a research effort that analyzed the operational characteristics of bus lanes on arterial streets. The research was designed to develop procedures for possible use in updating the transit and signalized arterial chapters of the *Highway Capacity Manual* (HCM) (1).

1.1 RESEARCH PROBLEM STATEMENT

The interaction of buses and the general traffic stream is a complex phenomenon that is not clearly understood. Concepts of passenger car equivalents have been used to show how the presence of buses reduces vehicle capacity. Formulas have been derived for the capacity of a bus lane, assuming that buses have exclusive use of the lane and that they stay in the lane. However, little research has been conducted on the operation of dual bus lanes or the performance of buses when they are allowed to mix with traffic in the adjacent lane. This research addresses these issues.

1.2 RESEARCH OBJECTIVE

The research objective was to develop procedures for determining the capacity and level of service of bus flow on arterials with at least one lane for buses. Situations addressed include those in which buses have an exclusive lane and no use, partial use, or full use (i.e., dual bus lanes) of adjacent lanes. The research addressed the impacts of bus flow on arterial lanes but did not include assessing the capacity and level of service of the arterial. The procedures developed provide information that can be used to update the HCM, primarily Chapters 11 and 12 and possibly Chapter 9.

1.3 RESEARCH APPROACH

The research was approached from both theoretical and practical perspectives: (1) it looked empirically at findings from the pilot surveys and agency canvasses; (2) it used mathematical models and simulation techniques to define and calibrate relationships; and (3) it translated the results into simple, usable procedures. The intent was to show how parameters such as the number of buses per hour, stops per mile, bus dwell times, signal constraints, and traffic volumes in adjacent lanes affect bus speeds. Similarly, vehicle flows and speeds in lanes with mixed flow were related to the number of buses in these lanes.

Three types of bus lanes were analyzed:

1. A curb bus lane where passing is impossible or prohibited and where right turns either may be permitted or prohibited. The lane may operate in the same direction as other traffic or contraflow.
2. A curb bus lane where buses can use the adjacent mixed traffic lane for overtaking or “leap frogging” around stopped buses. Right turns by non-bus traffic may or may not be prohibited from the curb bus lane.
3. Dual bus lanes with non-bus right turns prohibited.

The transit chapter in the HCM defines level of service in terms of the number of buses per hour and the number of persons per bus. These criteria are suitable for transit agencies. The chapter dealing with signalized arterial roadways, however, defines level of service in terms of average travel speeds. Therefore, the research introduces an additional “flow” level of service concept for buses—travel speeds—that is consistent with the level of service concept for arterial streets. This allows the performance of both cars and buses along arterial roadways to be measured on a compatible basis and makes it possible to assess the “person LOS” along these roads.

The analyses focused on areas and corridors where bus volumes are high enough to warrant exclusive bus lanes. Generally, these bus lanes are located in the city center and its radial approach corridors. Bus service in most urban and suburban settings is too infrequent to warrant bus lanes, and capacity generally is not critical.

This report focuses on bus lane operations in the United States and Canada. Procedures and parameters may need adjustment for application elsewhere. Experience in Asia, for example, indicates that single and dual bus lanes may carry as many as 300 to 400 buses per hour and 15,000 to nearly 20,000 people per hour. These numbers are roughly double those in North America.

1.4 OVERVIEW OF PROCEDURES

The procedures for estimating bus lane capacities and speeds are straightforward. Figure 1-1 presents an overview
of suggested procedures for estimating bus lane capacities and bus speeds and identifies the relevant tables and equations that should be used. Bus lane capacities can be estimated according to the procedures provided in Chapter 2. Average bus speeds may be observed in the field or estimated by the procedures set forth in Chapter 3.

These procedures call for an identification of existing conditions and parameters in the section of bus lane or roadway to be analyzed, including the controlling or critical sections, in terms of dwell times, signal timing, and traffic conflicts. This involves obtaining information on (1) roadway geometry and bus lane type; (2) traffic signal and turn controls; (3) bus stopping patterns and bus stop length; and (4) peak-hour dwell times at major stops. The next step is to estimate the basic speed and capacity values. These, in turn, should be modified to reflect factors such as the following:

- Bus-bus interference;
- Availability of the adjacent lane for bus use; and
- Right-turn impedances.

Bus-berth capacities should be estimated first because the berth volume-to-capacity \( (v/c) \) ratio serves as input to the bus speed adjustment factors.

Finally, the bus operating levels of service can be obtained for both bus stops and bus flows in the bus lane by comparing them with established criteria. The bus volumes should be expressed in terms of peak 15-min flow rates.

In many situations, application of basic bus capacity equations or capacity look-up tables will prove adequate, with adjustments needed only for the number of effective berths and the presence or absence of alternating stop patterns. Similarly, the basic bus speed values in Table 3-3 (Chapter 3) can provide reasonable order-of-magnitude estimates. If there are heavy right-turning volumes, bus flows, and vehicle traffic in the adjacent lane, the adjustments outlined in Chapters 2 and 3 will be necessary.

Capacities should be computed at the critical locations along a route. In predicting bus speeds, estimates generally should be made over congruent sections of route and may require some averaging of the conditions at individual stops.

1.4.1 Estimating Bus Berth Capacity/Level of Service

After identifying existing conditions and parameters for the critical sections, the next step is to estimate the basic capacity of a bus lane. Obtaining these estimates involves the use of the bus berth and bus stop capacity equations or tables set forth in Chapter 2. Basic bus lane capacity is the capacity of the critical bus stop, which is the product of the capacity of the bus berth times the number of effective bus berths at the stop. Equation 2-10 computes the capacity of the lane, allowing user input for dwell time variations and acceptable failure rates. The number of effective bus berths can be obtained from Table 2-3.

The basic capacity values then should be adjusted to reflect the effects of the following:

- Availability of the adjacent lane to allow buses to leave the bus lane;
- Implementation of skip-stop patterns serving alternating bus stops; and
- The reductive effects of right turns across the bus lane.

The resulting equation for bus lane capacity on an arterial (with a bus lane) is presented in Equations 2-14a and 2-14b. The levels of service at critical bus stops can be obtained by comparing the bus volumes with the adjusted capacity and
using the ratios in Table 2-9. Alternatively, the level of service (failure rate) can be set initially; basic capacity then can be computed, adjustments can be applied, and the capacity can be compared with the bus volume.

1.4.2 Estimating Bus Speeds

Bus speeds for existing conditions can be obtained directly through travel time studies. Bus speeds for changes in these conditions or for future conditions must be estimated. In such cases, speed estimates to replicate existing conditions can be used to help calibrate the estimates for the proposed conditions. The ratios of the after-to-before speed estimates would be applied to the actual speeds to assess future conditions.

Bus speeds can be estimated from Table 3-3. For CBD bus lanes, Column E of this table generally should be used because the right-turn impacts are reflected in the subsequent reductions. Next, the speeds should be adjusted downward to reflect bus-bus interferences and adjacent lane availability.

Finally, the flow level of service should be obtained by comparing the resulting speeds with these values in Table 3-1. These level of service criteria will be applicable to buses on streets that have bus lanes as well as on streets with no bus lanes. Thus, the level of service criteria can be used to compare bus operations on all arterial streets. These criteria and the bus speed analytical procedures that were developed as part of this research can be used to compare differences in bus operating conditions.
CHAPTER 2

BUS LANE CAPACITIES

Transit capacity deals with the movement of both people and vehicles; therefore, it depends on the size and configuration of vehicles and how often they operate. Transit capacity also reflects the interactions between passenger traffic concentrations and transit vehicle flow. Moreover, it depends on the operating policies of designated transit agencies that normally specify service frequencies, minimum separation between successive vehicles, and allowable passenger loading.

The capacity of a bus lane is important for several reasons: (1) the ability of a bus lane in a central area to accommodate the number of buses and passengers that want to use it; (2) the need to estimate the number of berths required to serve a specified bus or passenger flow along an arterial street or in a terminal; and (3) the ability to estimate how bus speeds will decline as bus volumes approach capacity.

This chapter presents research findings pertaining to the capacity of bus lanes. It describes basic capacity concepts and principles, compares computed and simulated capacities, suggests modifications to existing bus berth capacity procedures, and presents adjustment factors that reflect the impedances of right turns and adjacent lane traffic.

The chapter focuses on the number of buses that can be served by a given stop or berth arrangement. Equally important, of course, is the number of people these berths can serve and whether there are enough berths in the appropriate locations to serve passenger demands at maximum load points. These procedures are presented in Chapter 12 of the 1985 HCM.

2.1 HCM CAPACITY FORMULA

The HCM equations for computing vehicle capacity under uninterrupted flow conditions stem from the basic equation:

\[ C_b = \frac{3600}{h} \]  

(2-1)

where:

\( C_b \) = capacity of bus berth, in buses per berth per hour

\( h \) = headway between successive buses waiting in line, in seconds.

The headway, \( h \), represents the sum of the dwell time at the stop, \( D \), plus the clearance between successive buses, \( t_c \).

Thus, under conditions of uniform dwell times (i.e., zero variance), the capacity of a bus berth becomes the following:

\[ C_b = \frac{3600}{t_c + D} \]  

(2-2)

where:

\( D \) = average dwell time, in seconds

\( t_c \) = clearance time between successive buses, in seconds.

When the HCM formulas were initially developed, it was necessary to take into account the variations in dwell time. Rather than use the average dwell time, various critical dwell times were used, because any given average dwell time had a probability of failure associated with it. Failure occurs when a queue forms behind the waiting bus, representing the point at which capacity is exceeded. Although not explicitly stated in the HCM (Chapter 12), the formula became as follows:

\[ C_b = \frac{3600}{t_c + D + ZS_D} \]  

(2-3)

where:

\( S_D \) = standard deviation of dwell times

\( Z \) = one-tail variate for the normal distribution.

Using values of the standard deviation obtained in several cities (about 0.4 to 0.5 times the mean dwell time, \( D \)), the formula was calibrated for various dwell times and probabilities of failure. The resulting values were rounded, and this formula was simplified to Equation 12-7 in the HCM.

\[ C_b = \frac{3600R}{t_c + D} \]  

(2-4)

where \( R \) = reductive factor keyed to various probabilities of failure.

The value \( R \) in this formula reflects the inability of buses to fully utilize a stop at all times and the critical dwell time and various probabilities of failure. The maximum capacities in the HCM were set for \( R = 0.833 \) and assumed a 30 percent failure. This value was defined as LOS E. Values of \( R \) also were computed for lower failure rates, and various levels of service were specified (Table 12-17 in the HCM).
An adjustment was then made to this formula for bus operations along signal-controlled roadways. It was assumed that only the effective green time \( g \) of the traffic signal cycle \( C \) would be available for movement. Because buses may pick up and discharge passengers on the red phase as well as the green, the dwell time was reduced by a factor of \( g / C \). The resulting equation (12-10b in the HCM) is as follows:

\[
C_b = \frac{(g/C)3600R}{t_e + (g/C)D} \tag{2-5}
\]

This equation assumes that the time spent loading and discharging passengers on both the green and red phases are proportionate to the green and red time per cycle, respectively.

To compute the capacity of a bus stop, this equation is multiplied in the HCM by the number of effective berths at the stop \( N_b \), the values for which are shown in HCM Table 12-19. HCM Figure 12-3 displays the resulting bus stop capacity as related to dwell times and number of loading positions (berths). The capacity of the busiest stop (i.e., with the longest dwell times) is considered to be the capacity of the bus lane in terms of buses per hour. The product of the buses per berth (Equation 2-5) and the number of effective berths, \( N_b \), results in the following HCM equation to calculate the capacity of the bus lane for a single bus lane where buses may not pass each other:

\[
C_b = \frac{(g/C)3600RN_b}{t_e + (g/C)D} \tag{2-6}
\]

where:

- \( C_b \) = capacity of the bus stop, in buses per hour = capacity of a single bus lane
- \( N_b \) = number of effective berths
- \( g \) = effective green time, in seconds (definition in HCM, page 9-2)
- \( C \) = cycle length, in seconds.

### 2.2 COMPARISON OF HCM AND NETSIM SIMULATION RESULTS

The capacities obtained by Equation 2-6 were compared with those obtained by TRAF-NETSIM simulations.

#### 2.2.1 Simulation Results

Iterative runs of TRAF-NETSIM were performed for given block spacings, dwell times, signal timings, and bus berth capacities. These parameters were held constant on iterative runs with increasing bus volumes to obtain information on bus speeds as bus volumes approached capacity. Two measures of performance output indicated the point at which capacity was reached: (1) simulated average bus speeds dropped significantly and (2) the number of buses serviced at the bus stop was less than the number of buses input as the bus flow rate. These two measures indicated a point at which no greater flow rate of buses would be achieved along the arterial and where buses queued excessively at the bus stop or at upstream signals. For Type 1 bus lanes, a third measure—the time at which bus stop capacity was exceeded—coincided with the other two indicators, increasing to a value of about 10 percent as volumes approached apparent capacity. Values of 20 and 30 percent bus stop capacity exceeded also were simulated at slightly higher serviced bus volumes and at greatly reduced bus speeds.

Representative capacity values for various dwell times for Type 1, Type 2, and Type 3 bus operations are shown in Table 2-1. These values represent the bus volumes processed before speeds drop by more than 20 percent and when bus stop capacity is exceeded between 5 and 10 minutes per hour (approximately 15 percent of the time). The values are remarkably consistent with those for many existing bus lanes. Operations with dual bus lanes or lanes with passing opportunities, such as those in Ottawa, New York City, and Portland, Oregon, report maximum bus flows of up to 200 buses per hour.

The bus capacities obtained from the simulation runs for one-, two-, and three-berth stops are presented in Table 2-2.

#### 2.2.2 Comparison of Effective Berths

The capacities obtained in the simulation for one, two, and three bus berths at a bus stop were compared with those suggested in the HCM for “effective berths,” as shown in the following:

### Table 2-2: Comparison of Effective Berths

<table>
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<tr>
<th>Ratio to Single Berth</th>
<th>HCM Table 12-19</th>
<th>Simulation</th>
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<td>5</td>
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</table>

The comparative analysis of the Type 1 bus lane capacities for one, two, and three berths generally validated the values for effective berths in Table 12-19 of the HCM. A two-berth bus stop in the simulation appears to average 1.83 times the capacity of a one-berth stop, which is about 5 percent higher than the HCM value of 1.75. The simulated capacity of a three-berth bus stop appears to be 2.44 times that of a one-berth stop, which is about 9 percent higher than the 2.25 value from the HCM.

#### 2.2.3 Comparison with HCM Equations

The capacities resulting from the simulation were compared with those obtained using the HCM bus stop capacity.
The simulations and formulas show similar patterns. There is a downward trend in bus lane capacity as dwell times increase. Disparities reflect anomalies in the simulation (especially for short dwell times), differences in dwell time variations, and differences in failure rates. The patterns are remarkably close for comparable dwell time variations and failure rates. Overall, the simulation results indicate that the HCM formula accurately reflects the conditions it portrays and provides a reasonable representation of simulated bus lane capacities for a Type 1 bus lane.

2.3 REVISED BUS LANE CAPACITY EQUATIONS

The basic bus berth capacity equations were reformulated to provide a more precise assessment of bus dwell time variability. This was accomplished by using Equation 2-3 directly for uninterrupted flow conditions and by modifying Equation 2-5 accordingly. Thus, the capacity of a bus berth under uninterrupted and interrupted flow can be described by the following modified equations:

Unsignalized  \[ C_b = \frac{3600}{t_c} + (D + Z_u + S_D) \]  (2-7)

Signalized  \[ C_b = \frac{(g/C)3600}{t_c + g/C (D) + Z_u S_D} \]  (2-8)

where:

- \( t_c \) = clearance time between buses (i.e., 10 to 15 sec)
- \( D \) = average (mean) dwell time, in seconds
- \( g/C \) = effective green time per signal cycle
- \( S_D \) = standard deviation of dwell time, in seconds
- \( Z_u \) = one-tail normal variate corresponding to probability that queue will not form behind bus stops.

Percentage failure represents the probability that bus stop capacity is exceeded (queue forms behind a bus stop) and is keyed to level of service in Table 12-17 of the HCM. The
value $Z_a$ from the basic statistics represents the area under one tail of the normal curve beyond the acceptable levels of probability of a queue forming at the bus stop and thus represents the probability that a queue will not form behind the bus stop. Typical values of $Z_a$ for various failure rates are shown in Table 2-3.

Equations 2-7 and 2-8 also can be expressed in terms of the coefficient of dwell time variation, $C_v$, which is the standard deviation divided by the mean, expressed in decimal form.

Unsignalized

$$C_b = \frac{3600}{t_r + D + Z_a C_v D} \tag{2-9}$$

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<th>2 BERTH STOP</th>
<th>3 BERTH STOP</th>
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<td>D=50</td>
<td>60</td>
<td>124</td>
<td>96</td>
</tr>
<tr>
<td>D=60</td>
<td>60</td>
<td>124</td>
<td>90</td>
</tr>
<tr>
<td>C=60, L=400, D=10</td>
<td>98</td>
<td>146</td>
<td>220</td>
</tr>
<tr>
<td>D=20</td>
<td>65</td>
<td>142</td>
<td>208</td>
</tr>
<tr>
<td>D=30</td>
<td>65</td>
<td>142</td>
<td>162</td>
</tr>
<tr>
<td>D=40</td>
<td>65</td>
<td>142</td>
<td>112</td>
</tr>
<tr>
<td>D=50</td>
<td>65</td>
<td>142</td>
<td>108</td>
</tr>
<tr>
<td>D=60</td>
<td>65</td>
<td>142</td>
<td>102</td>
</tr>
</tbody>
</table>

Average $= 1.83$ Average $= 2.44$

* Point of capacity determined by coinciding the following: buses served=buses input; speed drops by over 20 percent; bus stop capacity exceeded over 10 percent of the time.

** C = Cycle Length (seconds), L = Block Length = Distance between Stops (feet), D = Average Dwell Time (seconds)

SOURCE: Simulations
The revised formulas indicate the following:

- Capacity decreases as mean dwell times increase.
- Capacity increases as the g/C ratio increases.
- The increase in capacity is not directly proportional to the increase in g/C because some of the clearance time, \( t_c \), is not affected by the g/C ratio.
- Capacity decreases as the variability in dwell time increases. For the same mean dwell time, bus lane capacity would be greater for a stream of buses with similar dwell times than for buses whose dwell times are much higher or lower than the average. Thus, the mixing of bus routes at a bus stop that experience long dwell times (such as park and ride) with those that experience short dwell times (such as local service) may reduce the overall capacity of the bus lane.
- Capacity reflects the level of failure that is accepted.

To compute the capacity of a bus berth in buses per hour, it is necessary to establish the critical dwell times, clearance times, and effective green-per-cycle ratios. The capacity of a bus stop is then obtained by multiplying the berth capacity by the number of effective berths. The critical dwell times are a function of the average dwell time and its variation, as well as the desired (acceptable) level of failure.

\[ C_b = \frac{(g/C)3600}{t_c + (g/C)D + Z_c D} \]  

(2-10)

The field studies produced important information on the variations in dwell times at bus stops. Table 2-4 presents the variations observed at stops along five streets in downtown Houston. The coefficients of variation ranged from 60 to 100 percent.

Figure 2-3 contains detailed dwell time variations found for individual stops and time periods along Spring Street in Los Angeles, Geary Street in San Francisco, and Louisiana Street in Houston. This information provides a basis for estimating the variation values to be incorporated in the equations. This figure indicates the following:

- There is considerable scatter in the coefficients of variation, especially when dwell times are low.
- A coefficient of variation of 40 to 60 percent is representative of most dwell times of 20 sec or more, but tends to understate the variability when dwell times are less.
• A constant standard deviation of 20 to 25 sec reflects the data. However, when keyed to low failure rates (high \( z \) values), it tends to mute the differences between long and short dwells. This condition could be alleviated by using a standard deviation that increases somewhat as dwell time increases; however, this increases the computational complexity.

Accordingly, the bus berth capacity estimates were derived using a 60 percent coefficient of variation. A value of 40 to 80 percent could be used, depending on field observations in a community.

2.3.2 Representative Capacity Values

Bus berth capacity values, computed using Equations 2-9 and 2-10, for various dwell times at different failure rates are shown in Table 2-5 for g/C values of 0.5 and 1.0. These g/C values are comparable with those set forth in the existing HCM. The g/C value of 1.0 applies to bus-only roadways.
with uninterrupted flow (as found in Pittsburgh and Ottawa) and provides an upper limit of bus berth capacity. Both values also apply in bus terminals.

The calculations assumed a clearance time of 15 sec between buses and a 60 percent coefficient of dwell time variation. Thus, for a 30-sec dwell time and a 25 percent failure rate, a berth could accommodate about 63 buses per hour under uninterrupted flow and 43 buses per hour with a g/C value of 0.5. Intermediate values can be obtained by applying Equation 2-10 or can be approximated by interpolation. Table 2-6 compares the capacity values obtained by Equation 2-10 with those set forth in the HCM. The two values in Table 2-6 are essentially the same for uninterrupted flow conditions; Table 2-5 values are approximately four buses per hour lower for signalized conditions. Table 2-7 further compares the computed values with those set forth in the HCM and shows the effects of varying the coefficient of dwell time variation: a 20 percent change results in about a three to four bus difference at the lower acceptable failure rates and a two to three bus difference at the higher acceptable failure rates.

### 2.3.3 Bus Stop Level of Service

Table 12-17 of the HCM defines level of service of bus stops in terms of the approximate probability of queues forming behind the bus stop, which is considered a failure of the bus stop capacity. Various simulation analyses indicate that bus speed drops rapidly when queues occur (bus stop exceeds capacity) about 10 to 15 percent of the time. This suggests that the maximum value of LOS D could be reduced to 15 percent and LOS E to 25 percent. The resulting potential changes in the bus stop level of service criteria are shown in Table 2-8.

Table 2-9 presents the bus v/c ratios associated with various service levels and dwell times. These ratios provide a basis for assessing the performance of individual bus stops, or groups of stops, where adjustments are made for right turns and bus bypass opportunities. The table also indicates the suggested value for use with other g/C ratios and dwell times.

## 2.4 CAPACITY ADJUSTMENT FOR AVAILABILITY OF ADJACENT LANE

The main difference among the three types of bus lanes is the availability of the adjacent lane for buses to pass other buses, right-turn queues, and other bus lane obstructions. A Type 1 bus lane has no use of the adjacent lane, as in a contraflow lane or physically channelized lane. A Type 2 bus lane has partial use of the adjacent lane depending on use of this lane by other traffic. A Type 3 bus lane (dual bus lanes) has full use of the adjacent lane, with only occasional use by authorized vehicles other than buses, and right turns are prohibited.

When all buses stop at every curbside bus stop in an online berth arrangement, the availability of the adjacent lane becomes necessary only for lane obstruction passing. The ability to spread out the stops, alternating route stop patterns along the arterial, substantially improves bus speeds and capacities. This is why many transit systems, including those in New York City and Houston, have instituted two-block and three-block patterns for bus stops along arterial streets. This block skipping pattern allows for a faster trip through the section and reduces the number of buses stopping at each bus stop.
The provision of these alternate block stopping patterns enables bus lane capacity to nearly equal the sum of the capacities of the stops involved. Thus, an arterial with an alternate two-block stopping pattern would, ideally, have a capacity equal to the sum of the two stops, assuming unimpeded use of the adjacent lane. In reality, this may not always be possible because of the irregularity of bus arrivals and traffic signal delays. (To effectively double the capacity of a segment with a three-bus berth capacity at each stop by instituting a two-block (x,y) stop pattern, three x-pattern buses must arrive at the upstream entry to the section during one signal cycle, followed by three y-pattern buses). Buses alternating stops also must be able to use the adjacent traffic lane to bypass stopped buses. The buses may be impeded in this maneuver when the adjacent lane operates at capacity.

Figure 2-3. Observed bus dwell time variations.
TABLE 2-5  Bus berth capacity, $C_b$ (buses per berth per hour)

<table>
<thead>
<tr>
<th>Failure Rate</th>
<th>A. UNINTERRUPTED FLOW</th>
<th>Average Dwell Time, Seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>1.0%</td>
<td>92</td>
<td>57</td>
</tr>
<tr>
<td>2.5%</td>
<td>98</td>
<td>62</td>
</tr>
<tr>
<td>5.0%</td>
<td>103</td>
<td>66</td>
</tr>
<tr>
<td>7.5%</td>
<td>107</td>
<td>69</td>
</tr>
<tr>
<td>10%</td>
<td>110</td>
<td>71</td>
</tr>
<tr>
<td>15%</td>
<td>145</td>
<td>76</td>
</tr>
<tr>
<td>20%</td>
<td>120</td>
<td>78</td>
</tr>
<tr>
<td>25%</td>
<td>124</td>
<td>84</td>
</tr>
<tr>
<td>30%</td>
<td>128</td>
<td>87</td>
</tr>
<tr>
<td>50%</td>
<td>144</td>
<td>103</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure Rate</th>
<th>B. SIGNALIZED WITH GREEN/CYCLE = 0.5</th>
<th>Average Dwell Time, Seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>1.0%</td>
<td>53</td>
<td>34</td>
</tr>
<tr>
<td>2.5%</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>5.0%</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>7.5%</td>
<td>63</td>
<td>43</td>
</tr>
<tr>
<td>10%</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>15%</td>
<td>69</td>
<td>48</td>
</tr>
<tr>
<td>20%</td>
<td>72</td>
<td>51</td>
</tr>
<tr>
<td>25%</td>
<td>75</td>
<td>54</td>
</tr>
<tr>
<td>30%</td>
<td>78</td>
<td>58</td>
</tr>
<tr>
<td>50%</td>
<td>90</td>
<td>72</td>
</tr>
</tbody>
</table>

NOTE: Dwell time Coefficient of Variation = 60%

TABLE 2-6  Comparison of bus berth capacity of Table 2-5 with that of Table 12-16 of the HCM

<table>
<thead>
<tr>
<th>Dwell Time (Sec)</th>
<th>g/C = 0.5</th>
<th>g/C = 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HCM</td>
<td>Table 2-5</td>
</tr>
<tr>
<td>15</td>
<td>67</td>
<td>68</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>46</td>
</tr>
<tr>
<td>45</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>60</td>
<td>33</td>
<td>28</td>
</tr>
<tr>
<td>75</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>105</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>120</td>
<td>20</td>
<td>18??</td>
</tr>
</tbody>
</table>

Assumes:  
(1) Clearance Time, $t_c = 15$ Seconds  
(2) Probability that capacity will be exceeded (Failure) = 30 percent  
(3) Dwell time Coefficient of Variation = 60 percent
2.4.1 Operating Experience

Full utilization of the adjacent lane by other traffic can render the lane practically unavailable for buses to use to maneuver in and out of the bus lane. Under these conditions, a Type 2 bus lane would operate in a similar manner as a Type 1 bus lane. Such conditions exist along Fifth Avenue in New York City, north of 58th Street, during the AM peak period. Bus volume in the southbound curb (bus) lane approaches 200 buses per hour in a three-block skip-stop arrangement. In the mile between 72nd and 35th Streets, buses spend 5.6 min in motion and 9.4 min delayed. Bus-bus delays account for about 5.5 min, signalized delays about 3.5 min, and passenger delays about 0.4 min. Traffic volumes in the adjacent two lanes are at capacity—about 950 vehicles per lane per hour. Consequently, buses are unable to leave the curb lane to leap-frog other buses. East-west cross traffic coming from the Queensboro Bridge limits both bus and car capacities and results in backups in both traffic streams.

When the adjacent general purpose lanes operate below capacity, buses are able to leave the curb lane to pass stopped buses. This can substantially reduce the amount of bus-bus delays because bus volumes approach the capacity of the bus lane. Examples of typical adjacent lane use appear in Table 2-10:

- In Houston, with a two-block skip-stop arrangement, about a third of the buses use the adjacent lane when the other traffic in this lane exceeds 300 vehicles per hour.
- Videotape images of bus lane operations on Louisiana Street in Houston were studied to assess the relationship between traffic in the adjacent lane and the ability of buses to leave the bus lane to pass other buses. With a two-block skip-stop operation and 163 buses per hour, the Louisiana Street bus lane operates at about two-thirds of capacity, and buses are observed to use the adjacent lane about 30 percent of the time. Some non-stopping buses have no need to leave the bus lane because the buses ahead proceed on the green. Traffic in the adjacent lane exceeds 300 vehicles per hour (v/c of approximately 0.5) and does not significantly impede bus use of the adjacent lane for passing other buses. Analysis of the peak 15 min indicates an adjacent lane volume of approximately 500 buses per hour, at which

| TABLE 2-7 Comparison of berth capacities using HCM Table 12-18 and Equation 2-10 for various failure rates ($C_v = \text{coefficient of variation}$) |
|---|---|---|
| **Failure Rate** (Approximate Percent of Time Queues Form Behind Bus Stop) | **Buses Per Berth Per Hour** | Results Using Equation 4-10 |
| | | $C_v = 0.6$ | $C_v = 0.4$ | $C_v = 0.8$ |
| 1.0% | 13 | 14 | 18 | 11 |
| 2.5% | 20 | 16 | 19 | 13 |
| 10% | 26 | 20 | 24 | 17 |
| 20% | 30 | 24 | 28 | 21 |
| 30% | 33 | 28 | 31 | 26 |

**NOTE:** Assumes: $t_s = 15$ seconds
$D = 60$ seconds
$g/C = 0.5$

<p>| TABLE 2-8 Possible modifications to HCM level of service criteria for bus berths |
|---|---|
| <strong>Failure Rate</strong> | <strong>HCM Table 12-17</strong> | <strong>Suggested Revision</strong> |
| LOS A ≤ | 1.0% | 1.0% |
| LOS B ≤ | 2.5% | 2.5% |
| LOS C ≤ | 10% | 7.5% |
| LOS D ≤ | 20% | 15% |
| LOS E ≤ | 30% | 25% |</p>
<table>
<thead>
<tr>
<th>Suggested Level of Service</th>
<th>Approx. Percent of Failure</th>
<th>Average Dwell Time, Seconds</th>
<th>Suggested Indices (Rounded) (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ratio to Max</td>
<td>Ratio to E</td>
</tr>
<tr>
<td>A</td>
<td>1.0</td>
<td>0.64</td>
<td>0.74</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>0.68</td>
<td>0.79</td>
</tr>
<tr>
<td>C</td>
<td>7.5</td>
<td>0.74</td>
<td>0.86</td>
</tr>
<tr>
<td>D</td>
<td>15.0</td>
<td>0.80</td>
<td>0.93</td>
</tr>
<tr>
<td>E</td>
<td>25.0</td>
<td>0.86</td>
<td>1.00</td>
</tr>
<tr>
<td>MAX</td>
<td>50.0</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Suggested Level of Service</th>
<th>Approx. Percent of Failure</th>
<th>Average Dwell Time, Seconds</th>
<th>Suggested Indices (Rounded)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ratio to Max</td>
<td>Ratio to E</td>
</tr>
<tr>
<td>A</td>
<td>1.0</td>
<td>0.59</td>
<td>0.71</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>0.63</td>
<td>0.76</td>
</tr>
<tr>
<td>C</td>
<td>7.5</td>
<td>0.70</td>
<td>0.84</td>
</tr>
<tr>
<td>D</td>
<td>15.0</td>
<td>0.77</td>
<td>0.92</td>
</tr>
<tr>
<td>E</td>
<td>25.0</td>
<td>0.83</td>
<td>1.00</td>
</tr>
<tr>
<td>Max</td>
<td>&gt;</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

(1) These are similar to the values for "R" in the HCM, Chapter 12.
point buses experience delays in obtaining access to the adjacent lane to pass other buses.

- In New York City, with a three-block skip-stop arrangement, most buses avoid the curb lane and use the adjacent lane, even when this lane has more than 400 other vehicles per hour in it. Buses, being larger and more formidable than passenger cars, tend to preempt the adjacent lane.

The Madison Avenue bus lane experience presents a more complex picture of lane use and bus flow. In May 1981, New York City DOT implemented a dual bus lane in midtown Manhattan between 42nd and 59th Streets. The dual bus lanes, which operate from 2 to 7 p.m. on weekdays, replaced peak-hour curb lanes. Buses operate on an alternating three-block stop pattern. Salient PM peak-hour bus operating characteristics are summarized in Tables 2-11 and 2-12. Notable findings are as follows:

- With a single curb bus lane during the PM peak hour, buses make heavy use of the adjacent lane and sometimes spill over into the next travel lane. About 20 percent of the 200 buses per hour from 5:00 to 6:00 p.m. actually use the curb lane, compared with 73 percent that use the adjacent lane and 7 percent that use the next travel lane. The adjacent lane operates at about 75 percent of capacity. Because of the extensive maneuvering of buses from one lane to the next and because they interact with cars and trucks, PM peak-hour bus speeds are under 3 mph.

- After the dual bus lanes were implemented (and northbound right turns were prohibited from 42nd to 59th streets), 84 percent of the buses used the second bus lane and 16 percent used the curb side stops. Adjacent lane use increased after the lane was dedicated to buses. Bus speeds increased to 5 mph.

- The decline in bus travel times (increased bus speeds) is associated with a corresponding decrease in travel time variability. The standard deviation of the travel time decreased by more than 50 percent.

These observations indicate that buses generally are able to use the adjacent traffic lane, except when the adjacent lane operates at or near its capacity.

### 2.4.2 Simulations

Bus operations were simulated for a Type 2 bus lane by using the customized TRAF-NETSIM program. The program was used to perform sensitivity analyses on the effect of varying adjacent traffic lane volumes on bus lane operations. Initial simulations utilized a calibrated model of Louisiana Street (Houston) bus lanes and incorporated four lanes adjacent to the bus lane. The moderate traffic volumes in the adjacent lanes, with no right turns, allowed the model to place the traffic away from the bus and adjacent lanes. There was no significant impact on the skip-stop bus operations for adjacent traffic volumes up to approximately 40 percent of the estimated capacity of the four adjacent lanes.

To better address heavy-volume conditions, a new model was used to measure the direct impacts of traffic in the adjacent lane. This two-lane model incorporated only one traffic lane adjacent to the bus lane. Traffic in the general traffic lane was increased from 0 to 700 vehicles per hour, in increments of 100 vehicles per hour. The capacity of the one general purpose lane was estimated to be approximately 700 vehicles per hour under input conditions. Table 2-13 summarizes the results. Simulations of a Type 2 bus lane with

<table>
<thead>
<tr>
<th>Location:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New York City</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fifth Ave. (48th Street)</td>
<td>Buses</td>
<td>36</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>Other vehicles</td>
<td>24</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>60</td>
<td>380</td>
</tr>
<tr>
<td>Sixth Ave. (45th Street)</td>
<td>Buses</td>
<td>14</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Other vehicles</td>
<td>22</td>
<td>392</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>36</td>
<td>476</td>
</tr>
<tr>
<td>Houston Louisiana St.</td>
<td>Buses</td>
<td>115</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Other vehicles</td>
<td>165</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>270</td>
<td>363</td>
</tr>
</tbody>
</table>

(1) 45-minute expanded to one hour

SOURCE: WSA Field Studies in Houston

(11) New York City

---

TABLE 2-10 Observed bus use of adjacent traffic lanes in PM peak hour
increasing traffic volumes in the adjacent lane indicated the following:

- When the v/c ratio of traffic in the adjacent lane was zero (i.e., no adjacent traffic, or the Type 2 bus lane was operating in a similar manner as a Type 3 bus lane), the maximum number of buses processed under an alternating two-block skip-stop operation was approximately 1.5 times the capacity of that when buses stopped every block in a Type 1 bus lane. Bus speeds were approximately twice those of the buses stopping at every block. The inability to double the capacity of a two-block skip-stop results from the inability of having the properly sequenced alternating pattern of bus arrivals in the queue at each signal, which would require advance platooning of buses.

TABLE 2-11 Madison Avenue (New York) lane use and distribution—5:00 to 6:00 p.m. (21)

<table>
<thead>
<tr>
<th>LANE 1</th>
<th>No. of Vehicles</th>
<th>%</th>
<th>After Dual Lanes</th>
<th>No. of Vehicles</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.0</td>
<td>82</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>LANE 2</td>
<td>144</td>
<td>11.0</td>
<td>508</td>
<td>36.1</td>
<td></td>
</tr>
<tr>
<td>LANE 3</td>
<td>602</td>
<td>46.0</td>
<td>627</td>
<td>44.6</td>
<td></td>
</tr>
<tr>
<td>LANE 4</td>
<td>523</td>
<td>40.0</td>
<td>155 B</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>LANE 5</td>
<td>39</td>
<td>3.0</td>
<td>35 B</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1308</td>
<td>100.0</td>
<td>1407</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

ESTIMATED BUS DISTRIBUTION

<table>
<thead>
<tr>
<th>LANE 1</th>
<th>No. of Buses</th>
<th>%</th>
<th>After Dual Lanes</th>
<th>No. of Buses</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>LANE 2</td>
<td>0</td>
<td>0.0</td>
<td>0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>LANE 3</td>
<td>15*</td>
<td>7.5</td>
<td>0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>LANE 4</td>
<td>146*</td>
<td>73.0</td>
<td>155</td>
<td>83.5</td>
<td></td>
</tr>
<tr>
<td>LANE 5</td>
<td>39</td>
<td>19.5</td>
<td>35</td>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>100.0</td>
<td>200</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

B = buses
* = estimated
Note: Bus Lane in Lane 5 Before and Lane 4 After.

TABLE 2-12 Madison Avenue (New York) changes in bus travel times resulting from dual bus lane—5:00 to 6:00 p.m. (in minutes) (21)

<table>
<thead>
<tr>
<th></th>
<th>Local Buses</th>
<th></th>
<th>Express Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Time</td>
</tr>
<tr>
<td>Time</td>
<td>17.8</td>
<td>10.7</td>
<td>17.8</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.6</td>
<td>1.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>26%</td>
<td>18%</td>
<td>-50%</td>
</tr>
</tbody>
</table>

Percent Change

\[-39.9\]

\[-58.7\]

\[-30.8\]
When the v/c ratio of traffic in the adjacent lane approached 1.0 (i.e., little or no availability of the adjacent traffic lane, or the Type 2 bus lane was operating in a similar manner as a Type 1 bus lane), buses were constrained to the bus lane. The maximum number of buses processed under an alternating two-block operation, with practically no use of the adjacent lane, was about 20 percent greater than for buses stopping at the bus stops at each block in a Type 1 bus lane. Bus speeds were only slightly greater than those when buses stopped every block. The slight increase in capacity results from the skip-stop operation, because even when buses are constricted to using the single bus lane, only a portion of the buses in the queue will serve passengers at each stop.

When the v/c ratio of traffic in the adjacent lane was less than 0.5, there was little reduction in the number of buses processed on the arterial. When the v/c ratio reached 0.7, bus capacity was reduced by approximately 15 percent, representing a factor of approximately 1.3 times the capacity of stopping at every block in a Type 1 bus lane.

### 2.4.3 Capacity Adjustment Factors (Split Stops)

The application of capacity adjustment factors is straightforward. The total number of buses per hour that can be accommodated by a series of split stops represents the sum of the capacities of each stop times the reductive factors reflecting nonplatooned arrivals and the effects of high volumes of vehicular traffic in the adjacent lane. Accordingly, the following equations were derived to represent these relationships:

\[ C_i = (C_1 + C_2 + \ldots + C_n)f_i \]  

where:

\[ C_1, C_2, \ldots, C_n \] = capacities of the individual bus stops in the sequence

<table>
<thead>
<tr>
<th>Dwell Time sec</th>
<th>Adjacent Lane Traffic Volume veh/hr</th>
<th>Adjacent Lane v/c Ratio</th>
<th>Max. Number of Buses Processed buses/hr</th>
<th>Index of Bus Capacity</th>
<th>Index to Type 1 Bus Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>240</td>
<td>1</td>
<td>1.52</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>0.14</td>
<td>238</td>
<td>0.99</td>
<td>1.51</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
<td>0.29</td>
<td>240</td>
<td>1</td>
<td>1.52</td>
</tr>
<tr>
<td>20</td>
<td>300</td>
<td>0.43</td>
<td>240</td>
<td>1</td>
<td>1.52</td>
</tr>
<tr>
<td>20</td>
<td>400</td>
<td>0.57</td>
<td>232</td>
<td>0.97</td>
<td>1.47</td>
</tr>
<tr>
<td>20</td>
<td>500</td>
<td>0.71</td>
<td>206</td>
<td>0.86</td>
<td>1.30</td>
</tr>
<tr>
<td>20</td>
<td>600</td>
<td>0.86</td>
<td>198</td>
<td>0.82</td>
<td>1.25</td>
</tr>
<tr>
<td>20</td>
<td>700</td>
<td>1</td>
<td>186</td>
<td>0.77</td>
<td>1.18</td>
</tr>
<tr>
<td>20</td>
<td>Type 1, stop every block</td>
<td>158</td>
<td>158</td>
<td>0.66</td>
<td>1.00</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0</td>
<td>180</td>
<td>1</td>
<td>1.45</td>
</tr>
<tr>
<td>40</td>
<td>100</td>
<td>0.14</td>
<td>178</td>
<td>0.99</td>
<td>1.44</td>
</tr>
<tr>
<td>40</td>
<td>200</td>
<td>0.29</td>
<td>162</td>
<td>0.9</td>
<td>1.31</td>
</tr>
<tr>
<td>40</td>
<td>300</td>
<td>0.43</td>
<td>162</td>
<td>0.9</td>
<td>1.31</td>
</tr>
<tr>
<td>40</td>
<td>400</td>
<td>0.57</td>
<td>162</td>
<td>0.9</td>
<td>1.31</td>
</tr>
<tr>
<td>40</td>
<td>500</td>
<td>0.71</td>
<td>158</td>
<td>0.86</td>
<td>1.27</td>
</tr>
<tr>
<td>40</td>
<td>600</td>
<td>0.86</td>
<td>154</td>
<td>0.86</td>
<td>1.24</td>
</tr>
<tr>
<td>40</td>
<td>700</td>
<td>1</td>
<td>154</td>
<td>0.86</td>
<td>1.24</td>
</tr>
<tr>
<td>40</td>
<td>Type 1, stop every block</td>
<td>124</td>
<td>124</td>
<td>0.67</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The table above summarizes the simulation bus volumes processed with varying adjacent lane volumes (400-ft block spacing, 80-sec cycle length, alternating two-block stop operations).
$C_c$ = combined capacities

$f_k$ = capacity adjustment (impedance) factor (defined in Equation 2-12a).

$$f_k = \frac{1 + Ka(Ns - 1)}{Ns} \quad (2-12a)$$

where:

$K$ = adjustment factor for ability to fully utilize the bus stops in a skip-stop operation

- 0.50 for random arrivals
- 0.75 for typical arrivals
- 1.00 for platooned arrivals

$a$ = adjacent lane impedance factor (defined in Equation 2-12b)

$N_s$ = number of alternating skip stops in sequence.

$$a = 1 - x \left(\frac{v}{c}\right)^3 \quad (2-12b)$$

where:

$x$ = constant value (selected as 0.8)

$v$ = traffic volumes in adjacent lane, in vehicles per hour

$c$ = capacity of adjacent lane, in vehicles per hour.

A value for $x$ of 0.8 in this equation best approximates the simulations. As noted previously, these values result in added capacity with skip stops, even when the adjacent lane is fully utilized by cars, because nonstopping buses have a zero dwell time at the stop. When there is no spreading of stops, there is no increase in capacity rendered by the adjacent lane.

Figure 2-4 depicts this lane adjustment factor for a bus lane with two-block alternating stops. As indicated in Equation 2-11, these factors should be applied to the sum of the capacities computed for the individual stops. In general, the traffic impacts of the adjacent lane only become significant when the lane operates above 75 percent of its capacity.

### 2.5 EFFECTS OF RIGHT TURNS

Right-turning traffic physically competes with buses for space in the bus lane at an intersection. Traffic generally turns from the bus lane, although in some cases (e.g., in Houston) some right turns are made from the adjacent lane. The right-turning traffic may queue behind buses at a near-side bus stop. Conversely, right-turning traffic may block buses or preempt green time from them. The interference of right-turning traf-
traffic on bus operations can be further magnified by significant pedestrian crossing volumes parallel to the bus lane. Placement of the bus stop at the intersection—whether near-side, far-side, or midblock—also can influence the amount of delay induced by, and to, the right-turning traffic.

Conflicts between buses and right-turning traffic are greatest where there is a near-side stop and buses are unable to freely use the bus lane. Cars turning right may block access to the bus stop; conversely, buses receiving or discharging passengers on a green signal may block right-turning traffic. The amount of interference diminishes as the distance between the stop line and bus stop increases. Far-side and midblock stops, therefore, minimize the effects of right-turning traffic on bus speeds, when buses can use the adjacent lane. Placing stops where there are no right turns (e.g., along Madison Street in Chicago) can further minimize impacts. Right turns usually are prohibited with dual or contraflow bus lanes.

Just as right turns across bus lanes can delay buses along the arterial, pedestrians crossing the side street parallel to the path of the bus lane can cause delays to right-turning vehicles. This, in turn, can cause increased delays to buses in the bus lane. The delays to right turn movements introduced by pedestrians are concentrated at the beginning of the green signal interval on the arterial, when queued groups of pedestrians step off the curb.

By crossing or utilizing space in the bus lane to execute the turn, right-turning vehicles reduce the capacity of the bus lane operation along the arterial by preempting a portion of the green time available to buses. Thus, bus lane capacity will be approached more quickly than in locations without the presence of right turns. For bus volumes less than half of bus lane capacity, there generally is little impact on the resulting speed of bus operations from a moderate volume of right turns unless pedestrian volumes are very heavy.

### 2.5.1 Simulations

To perform sensitivity analyses on the effect of varying right-turn volumes on bus lane operations, simulations of bus operations were performed for a near-side bus stop on a Type 2 bus lane. The results of these TRAF-NETSIM simulations are shown in Figure 2-5. They indicate that when bus volumes are less than 50 percent of bus lane capacity, right-turn volumes up to 100 vehicles per hour do not have a significant impact on bus speeds and delays. As bus volumes approach bus lane capacity, 100 right-turning vehicles per hour reduce bus lane capacity by approximately 15 percent. Right-turn volumes of 200 vehicles per hour begin to noticeably reduce bus speeds at about 25 percent of bus lane capacity, reducing bus lane capacity by about 35 percent. For right-turn volumes of 300 vehicles per hour, bus speeds were reduced even at low bus flow rates, and bus lane capacity was reduced by about one-half. At 400 right turns per hour, bus lane capacity was reduced by almost two-thirds. Right turns in central business districts (CBDs) commonly range from 100 to 200 vph. Thus, as bus volumes approach bus lane capacity, right turns appear to reduce bus capacity in proportion to the v/c ratio of the right-turn movement (vR/cR).

### 2.5.2 Capacity Reduction Factors

Procedures for estimating the capacity of right turns are described in Table 9-11 in the HCM. The right-turn capacity factors reflect the impeding effects of pedestrians crossing the intersecting street in front of right-turning traffic. These capacity-reduction factors are shown in Table 2-14, which, along with their resulting saturation flows and headways, assume only right turns in the lane. Thus, if the capacity of a lane is 700 vph, and 100 pedestrians per hour cross in front of the right-turning traffic, the right-turn factor is 0.80, which is multiplied by 700 to obtain the approximate right-turn capacity of 540 vehicles (right turns) per hour. If the peak-hour right-turn volume (flow rate) is 200, vR/cR becomes 37 percent.

The right-turn v/c ratios for a 50 percent g/C split are shown in Table 2-15. The resulting ratios generally confirm the simulation results. When right-turning traffic (i.e., less than 100 units per hour) and pedestrian volume are light, only about 15 percent of the available capacity is required. Conversely, for both heavy pedestrian and right-turn flows (i.e., 400 units per hour), almost 75 percent of the available capacity is required by the right-turning vehicles.

The effects of right turns on bus lane capacity can be estimated by multiplying the bus lane capacity without right turns by an adjustment factor. The values of this adjustment factor, fR, may be estimated from the following equation:

\[
f_R = 1 - \frac{v_R}{c_R} \tag{2-13}
\]

where:

- \(f_R\) = right-turn adjustment factor
- \(L_b\) = bus stop location factor, from Table 2-16
- \(v_R\) = volume of right turns at specific intersection
- \(c_R\) = capacity of right-turn movement at specific intersection.

Suggested factors for the bus stop location factor, \(L_b\), are presented in Table 2-16. The factors range from 0.5 (for a far-side stop with the adjacent lane available for buses) to 1.0 for a near-side stop with all buses restricted to a single lane. These factors reflect the ability of buses to move around right-turning vehicles.

### 2.6 REFINED BUS LANE CAPACITY EQUATIONS

Equations to compute bus lane capacities should incorporate various factors that increase or decrease capacity. The more significant factors include the following:
• The stop pattern of the bus routes (e.g., every block and alternating skip stops);
• Congestion in the lane adjacent to the bus lane, which may constrict bus operations to the designated bus lanes; and
• Volumes of right-turning vehicles, which must use the bus lane or cross the paths of buses using the bus lane to execute their maneuvers.

The set of adjustment factors for (1) the availability of the adjacent lane and the spreading of stops and (2) the impact of right turns define the following equations for estimating the modified bus lane capacity.

Adjusted Bus Lane Capacity (Non-Skip Stop)

\[ \text{CAP} = C_b N_b f_R \]  \hspace{1cm} (2-14a)

Adjusted Bus Lane Capacity (Skip Stop)

\[ \text{CAP} = f_k (\text{CAP}_1 + \text{CAP}_2 + \ldots + \text{CAP}_n) \]  \hspace{1cm} (2-14b)

where:
\[ C_b = \text{capacity of a bus berth (Equation 2-10)} \]
\[ N_b = \text{number of effective berths at bus stop (HCM Table 12-19)} \]
\[ f_K = \text{capacity adjustment factor for skip-stop operations (Equation 2-12)} \]
\[ f_r = \text{capacity adjustment factor for right turns (Equation 2-13)} \]
\[ \text{CAP}_n = \text{capacity of one set of routes that stop at the same alternating skip-stop pattern.} \]

2.7 EFFECTS OF BUSES ON ADJACENT-LANE TRAFFIC

The introduction of single or dual bus lanes reduces the vehicular capacity of the roadway for other types of traffic. The extent of this capacity reduction is determined by (1)

\[
\text{TABLE 2-14 Effect of right turns on saturation flow}
\]

<table>
<thead>
<tr>
<th>Parallel Pedestrian Volume</th>
<th>Factor(^{1(1)})</th>
<th>Saturation Flow(^{(2)})</th>
<th>Headway</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.85</td>
<td>1445</td>
<td>2.5</td>
</tr>
<tr>
<td>50 (Low)</td>
<td>0.83</td>
<td>1410</td>
<td>2.6</td>
</tr>
<tr>
<td>100</td>
<td>0.80</td>
<td>1360</td>
<td>2.3</td>
</tr>
<tr>
<td>200 (Mod)</td>
<td>0.75</td>
<td>1275</td>
<td>2.8</td>
</tr>
<tr>
<td>300</td>
<td>0.71</td>
<td>1205</td>
<td>3.0</td>
</tr>
<tr>
<td>400 (High)</td>
<td>0.66</td>
<td>1120</td>
<td>3.2</td>
</tr>
<tr>
<td>500</td>
<td>0.61</td>
<td>1035</td>
<td>3.5</td>
</tr>
<tr>
<td>800</td>
<td>0.47</td>
<td>800</td>
<td>4.5</td>
</tr>
<tr>
<td>1000</td>
<td>0.37</td>
<td>630</td>
<td>5.7</td>
</tr>
<tr>
<td>1200</td>
<td>0.28</td>
<td>475</td>
<td>7.6</td>
</tr>
<tr>
<td>1500</td>
<td>0.12</td>
<td>205</td>
<td>17.6</td>
</tr>
<tr>
<td>1700</td>
<td>0.05</td>
<td>85</td>
<td>42.4</td>
</tr>
</tbody>
</table>

(1) SOURCE: HCM Table 9-11b, and Cases 2 and 5
(2) Assumes 1700 vehicles per hour of green as basic saturation flow for through-traffic on CBD streets.

\[
\text{TABLE 2-15 Right-turn v/c ratio for 50 percent g/C ratio}
\]

<table>
<thead>
<tr>
<th>Parallel Pedestrian Volume (Pedestrians/Hour)</th>
<th>Capacity With 50% Green(^{(3)})</th>
<th>RIGHT TURN VOLUME TO CAPACITY RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/c = 0.5</td>
<td>100</td>
</tr>
<tr>
<td>0</td>
<td>720</td>
<td>0.14</td>
</tr>
<tr>
<td>50</td>
<td>700</td>
<td>0.14</td>
</tr>
<tr>
<td>100</td>
<td>680</td>
<td>0.15</td>
</tr>
<tr>
<td>200</td>
<td>640</td>
<td>0.16</td>
</tr>
<tr>
<td>300</td>
<td>600</td>
<td>0.17</td>
</tr>
<tr>
<td>400</td>
<td>560</td>
<td>0.18</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>0.25</td>
</tr>
<tr>
<td>1200</td>
<td>240</td>
<td>0.42</td>
</tr>
<tr>
<td>1500</td>
<td>100</td>
<td>1.00</td>
</tr>
</tbody>
</table>

(1) Estimated at 50% of right turn saturation of flow of 1445 vph.

* Exceeds capacity
the type of bus lane, (2) the number of buses involved, and (3) whether the bus lane replaces a curb parking lane.

2.7.1 General Observations

The following impacts are associated with the provision of a single or dual bus lane:

- If the lane is used primarily by buses, the vehicle capacity loss would be relatively small. However, when the lane is introduced for relatively low existing bus flows (i.e., fewer than 40 buses per hour), the loss in vehicular capacity could be as high as 30 to 50 percent of one travel lane.
- The introduction of a single dedicated curb lane for buses onto a street with no previous bus operations would reduce the street capacity by one lane if buses stayed in the lane (Type 1) and right turns were prohibited or made from the second lane. Allowing right turns from a Type 1 bus lane would reduce street general traffic capacity by less than one full lane.
- A dual bus lane (Type 3) would reduce arterial capacity by up to two lanes. Because dual lanes usually would be implemented when buses already preempt most of the curb lane, the actual capacity reduction in arterial traffic would be less. The Madison Avenue (New York) dual bus lane experience indicates that the prohibition of right turns, elimination of weaving movements, and strict enforcement of regulations actually increase general traffic flow and speeds over what was experienced with an existing Type 2 bus lane.
- The effects of the Type 2 bus lane where buses may enter the adjacent lane will be between those of the Type 1 and Type 3 bus lanes. For low volumes of bus flow, buses entering the mixed flow traffic lane would have little effect on the capacity of the adjacent lane. As bus volumes in a Type 2 lane increase, their impact on the adjacent lane would increase to a point at which some traffic is discouraged from using the lane adjacent to the bus lane. The passenger car equivalent of a bus traveling without making stops is estimated in the HCM at about 2.0 passenger cars. However, for Type 2 bus lanes, merging, weaving, and diverging movements could raise this equivalency to 3 or 4 or more.
- The HCM (Chapter 12, p. 12-10) states: “Where the buses stop in a lane that is not used by moving traffic (for example, in a curb parking lane), the time loss to other vehicles is approximately 3 to 4 seconds per bus. For this case, buses would either accelerate or decelerate across the intersection, thereby reducing the impeditive effects to other traffic.” This statement describes the effect of buses leaving and reentering the rightmost travel lane to serve passengers at the curb. It also applies to the lane adjacent to a bus lane where buses accelerate or decelerate upon entering or leaving the lane.

2.7.2 Simulations and Equations

Simulations were conducted to assess the impacts of buses on other traffic where buses enter or leave a Type 2 bus lane. The delay imposed on non-bus vehicles by buses in the adjacent lane varied at an increasing rate, up to a value from 2 to 9 sec per car per bus, with an average value of about 4 sec, as the bus volume approached capacity. The effects of bus lane operations on the adjacent general traffic lane can be expressed by multiplying the base general lane capacity by an adjustment factor. This factor would be applied in a similar manner as it would be applied in the method for reducing saturation flow for bus blockage in HCM Table 9-9. The suggested reduction formula follows:

$$f_p = 1 - \left( 4 \frac{N_p}{3600} \right)$$  \hspace{1cm} (2-15)

where:

- $f_p$ = bus-passing activity factor
- $N_p$ = number of buses making the maneuver from the curb lane to the adjacent lane.

However, the delay to through traffic in the adjacent lane will be minimal unless buses leave the bus lane. Therefore, an adjustment is needed to determine the actual number of
buses, \( N_p \), that would pass other buses that are using the curb bus lane. The simulations and field observations indicate that when the buses operate at less than one-half of the capacity of the bus lane, they have little need to pass each other even in a skip-stop operation because of the low arrival headways relative to capacity. Bus use of the adjacent lane increases at an increasing rate as bus activity approaches capacity. Thus, \( N_p \) may be approximated by the following relationship:

\[
N_p = \frac{N_s - 1}{N_s} v_b \left( \frac{v_b}{c_b} \right)^3 \tag{2-16}
\]

where:

- \( N_s \) = number of stops skipped
- \( v_b \) = volume of buses in bus lane
- \( c_b \) = bus capacity of bus lane.

As expressed in this equation, the number of buses in the adjacent lane would be half the total bus flow when an alternating two-block stop operation approaches capacity. Two-thirds of the buses would use the adjacent lane for a three-block stop operation. However, these impacts would not come into full effect until the volumes of buses approached capacity.

### 2.7.3 Operational Observations

Field studies and observations in Chicago, Houston, and New York City verify the anticipated adjacent lane use and impacts of buses.

**Madison Street**

Review of videotape of street traffic operations on Madison Street in Chicago revealed only minor delays to buses and other vehicles in the adjacent lane. The Madison Street bus lane becomes a right-turn lane at every other block, forcing buses to move into the adjacent lane after every stop. Bus volumes were approximately 48 buses per hour, and adjacent lane traffic volumes were approximately 500 vehicles per hour, or about 65 percent of capacity of the adjacent lane.

**Louisiana Street**

Videotape images of Louisiana Street in Houston echoed many of the observations made in Chicago. Traffic volumes in the lane adjacent to the bus lane are approximately 300 vehicles per hour—only one-half of the volumes in each of the two other through lanes for both the intersection with the left turn and the intersection with the right turn. Of the 122 buses observed during the peak 45 min (160 buses per hour [bph] or about 67 percent of bus lane capacity), 36 buses were observed in the adjacent lane at the intersection. This represents about 30 percent passing on a two-block stop bus operation and is roughly predicted by the equation for the factor \( N_p \) developed herein.

**New York City**

The three-block skip-stop pattern on Manhattan Avenue resulted in about three-quarters (\( \pm 75 \) percent) of the buses using the adjacent lane of Fifth, Sixth, and Madison avenues. Assuming capacity operations of the curb lane, application of Equation 2-16 would result in an estimate of 67 percent of the buses using the adjacent lane.
BUS TRAVEL SPEEDS AND SERVICE LEVELS

Bus travel times and speeds are important to the transit passenger, transit operator, traffic engineer, and transportation planner. The transit passenger wants a quick and dependable trip. The transit operator (or service planner) measures and analyzes bus speeds to set, monitor, and refine schedules; estimate vehicle requirements; and plan new routes and services. The traffic engineer uses bus speeds to assess the impacts of traffic control and bus priority treatments. The transportation planner uses speeds to quantify congestion and provide input into the transit demand and modeling process.

The best way to determine bus speeds is by direct measurement at specified locations, during relevant time periods. But this is not always practical, especially if evaluation of future conditions are required and changes in bus stopping patterns and dwell times are anticipated. In such cases, estimates of bus speeds are necessary.

This chapter presents research findings pertaining to bus speeds by (1) defining speed-related level-of-service criteria; (2) deriving various analytical relationships for estimating bus speeds; and (3) comparing these relationships with results obtained from simulations of bus operations and actual field studies. Various procedures can be used to estimate the impacts on bus travel speed of changes in bus stopping patterns, traffic conditions, and bus lane provisions, including passing opportunities in adjacent lanes and dual bus lanes.

3.1 LEVELS OF SERVICE

The 1995 *Highway Capacity Manual* (HCM) (1) defines levels of service for transit vehicles in terms of (1) the number of passengers per vehicle and (2) the number of vehicles per lane, track, or “channel” per hour. Both these measures are useful to transit planners and operators. However, neither of them describe how well a bus moves in the traffic stream.

A speed-related definition of bus levels of service on city streets is desirable to assess the quantity of bus flow by a method more compatible with HCM procedures for assessing arterial street operations. Arterial street levels of service in the HCM are defined in terms of average travel speed. Accordingly, average travel speed (or its complement, minutes per mile) is suggested as a level of service measure for buses operating on arterial and central business district (CBD) streets. This measure is easily understood and can be obtained readily for existing conditions.

The specific level of service threshold values for local bus service will be lower than those for general traffic. This is because buses must experience normal traffic delays and delays associated with receiving and discharging passengers at stops. Accordingly, a series of level of service criteria were derived, reviewed with the TCRP panel and representative transit agencies, and refined as appropriate.

The recommended level of service criteria are presented in Table 3-1 for bus operations on three different types of streets, CBD streets, urban arterials, and suburban arterials. The level of service criteria given in the HCM for low-speed arterials is shown for comparison.

3.2 BASIC BUS TRAVEL SPEED RELATIONSHIPS

Bus speeds and travel times along arterial streets are influenced by (1) the frequency and duration of stops, (2) interferences from bus and auto traffic (including standing vehicles), and (3) traffic signals. The interaction between dwell times at bus stops and delays at traffic signals reduces speeds and increases their variability. Consequently, bus speeds on downtown streets have coefficients of variation ranging from about 15 to 30 percent, as depicted in Table 3-2. In contrast, general traffic speeds on CBD streets have about a 15 percent coefficient of variation (29).

Further analyses were made of the basic relationships among bus speeds, stop frequency, stop duration, and traffic signal timing: (1) speeds were simulated using a customized version of TRAF-NETSIM; (2) a general approach was developed for determining bus-lane speeds; and (3) a detailed analytical approach was derived for assessing the effects of traffic signal timing and coordination patterns. The results of these analyses were compared with each other and with field tests results. The analyses and comparisons are described in the following sections. Subsequent sections contain adjustment factors to account for the effects of bus-bus interference, traffic in the adjacent lane, and right turns.
3.2.1 Simulation Analyses

A series of bus simulation analyses were performed to show how arterial bus speeds vary as a function of bus stop spacing, bus lane type, and dwell time variations. The microscopic traffic simulation computer program, TRAFNETSIM, was used to validate and identify basic bus speed relationships. A customized version that allowed buses to leave the bus lane to pass lane obstructions was applied. This capability was not available in the initial FHWA version of the program available when this research began.

The computer simulation of a street segment containing a bus lane allowed analysis of a large range of variables on bus operations. The simulation analyzed the effect of the following variables when the others were held constant:

- Progressive versus simultaneous signal timing offsets;
- Signal cycle lengths;

| TABLE 3-1 | Suggested speed-related level of service criteria for buses on arterials |
|---|---|---|---|---|---|---|
| LEVEL OF SERVICE | HCM CRITERIA FOR ARTERIAL CLASS III (25-35 MPH FREE FLOW SPEED) | CBD STREETS (Typically > 7 STOPS/MI) | URBAN ARTERIALS (4 TO 7 STOPS/MI) | SUBURBAN ARTERIALS (1 TO 3 STOPS/MI) |
| | min/mi | m/hr | min/mi | m/hr | min/mi | m/hr | min/mi | m/hr |
| A | <2.40 | >25.0 | <6.0 | >10.0 | <3.6 | >16.7 | <2.8 | >21.2 |
| B | <3.16 | >19.0 | <9.0 | >6.7 | <4.7 | >12.7 | <3.7 | >16.2 |
| C | <4.61 | >13.0 | <12.0 | >5.0 | <6.9 | >8.7 | <5.5 | >11.0 |
| D | <6.67 | >9.0 | <15.0 | >4.0 | <10.0 | >6.0 | <7.8 | >7.9 |
| E | <8.57 | >9.0 | <18.0 | >3.3 | <12.9 | >4.7 | <10.0 | >6.0 |
| F | >8.57 | >7.0 | >18.0 | <3.3 | >12.9 | <4.7 | >10.0 | <6.0 |

<p>| TABLE 3-2 | Variations in central business district peak-hour bus speeds in bus lanes |
|---|---|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>City</th>
<th>Location</th>
<th>Time</th>
<th>Ave. Speed (mph)</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM Peak Hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Houston</td>
<td>Milam St.</td>
<td>4:30-5:30PM</td>
<td>5.7</td>
<td>1.0</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>Travis St.</td>
<td>4:30-5:30PM</td>
<td>5.0</td>
<td>1.1</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>Main St. (SB)</td>
<td>4:45-5:45PM</td>
<td>5.1</td>
<td>1.2</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td>Main St. (NB)</td>
<td>4:15-5:15PM</td>
<td>5.2</td>
<td>1.0</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Louisiana St.</td>
<td>4:30-5:30PM</td>
<td>5.4</td>
<td>1.5</td>
<td>28%</td>
</tr>
<tr>
<td>Chicago</td>
<td>Madison St.</td>
<td>5:00-6:00PM</td>
<td>6.8</td>
<td>1.8</td>
<td>26%</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>Spring St.</td>
<td>4:30-5:30PM</td>
<td>6.1</td>
<td>1.0</td>
<td>16%</td>
</tr>
<tr>
<td>New York City</td>
<td>Madison Ave. (Before Dual Bus Lanes)</td>
<td>5:00-6:00PM</td>
<td>2.4</td>
<td>N/A</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>Madison Ave. (After Dual Bus Lanes)</td>
<td>5:00-6:00PM</td>
<td>4.8</td>
<td>N/A</td>
<td>18%</td>
</tr>
<tr>
<td>San Francisco</td>
<td>Geary St.</td>
<td>5:00-6:00PM</td>
<td>4.3</td>
<td>1.1</td>
<td>25%</td>
</tr>
<tr>
<td>AM Peak Hour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Houston</td>
<td>Milam St.</td>
<td>7:00-8:00AM</td>
<td>4.4</td>
<td>0.7</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>Main St. (SB)</td>
<td>7:15-8:15AM</td>
<td>5.5</td>
<td>1.1</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>Main St. (NB)</td>
<td>7:30-8:30AM</td>
<td>3.8</td>
<td>1.3</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>Louisiana St.</td>
<td>7:30-8:30AM</td>
<td>6.0</td>
<td>1.0</td>
<td>17%</td>
</tr>
</tbody>
</table>

a Coefficient of variation of travel times
SOURCE: WSA Field Studies; (20)
• Effective green per cycle ratios;
• Block length;
• Average dwell time; and
• Dwell time variations.

The variables were analyzed for Type 1, Type 2, and Type 3 bus lanes. Several thousand separate conditions were simulated in the sensitivity analysis of each of the variables.

The results of the simulations indicate the sensitivity of bus speeds to changes in specific parameters. Inspection of the results revealed that they were reasonable and showed, for example, that (1) bus speeds increase as block spacing and stop spacing increase; (2) speeds decrease as dwell time increases; (3) speeds decrease as cycle length increases (though this effect is muted for longer block and stop spacing and long dwell times); and (4) skip-stop operation increases bus speed.

3.2.2 General Approach

A general approach for estimating bus lane speeds that builds on established travel time and speed relationships for buses in mixed traffic was developed (see Table A-6 in Appendix A). This approach allows bus speeds to be estimated without detailed information on traffic signal timing and operation. It derives speeds from the relationships among bus stop spacing, dwell times, average traffic delays, and bus speeds.

Table 3-3 was derived from Table A-6 (Appendix A) by removing the delays due to various factors that are not applicable to bus lane operation. For single, normal-flow bus lanes (Columns B, C, and D), the delay due to congestion was reduced from the values in Table A-6, as the latter delay values included the effect of single-occupancy vehicles. For dual and contraflow bus lanes (Column E), the delay due to right turns also was removed. For bus lanes without traffic signals (Column A), the delay due to signals was removed. Given the type of bus lane, stops per mile, average dwell time, and, for single bus lanes, area type, bus speeds, and travel time rates are read directly from the table. Adjustments for skip-stop operation and interference between buses are described later.

3.2.3 Auxiliary Approach for Detailed Bus Speed Estimates

An auxiliary approach allows direct computation of estimated bus speeds from a series of equations. This approach permits a more precise determination of anticipated bus speeds under specific conditions, where detailed information on traffic signal timing and coordination patterns are available. It determines bus speed relationships as a function of bus stop spacing, the dwell time at each stop, and the traffic signal cycle length, effective green time, and coordination pattern. The resulting values can be adjusted to account for bus-bus interferences as bus volumes increase and to account for bus interferences from adjacent and turning traffic. Appendix B contains a detailed discussion of this approach, illustrative applications, and comparisons with the general approach. A brief overview of the method follows:

3.2.3.1 Dwell Range Window Concept

The system of traffic signals along an arterial roadway, in association with the dwell times at bus stops, determines how buses operate. There are three basic types of operation:

1. Buses arrive at a stop to serve passengers, dwell into the red phase, and then proceed on the green phase toward the downstream stop. This represents dwell times within the “dwell range window.”
2. Buses arrive on the green phase at a bus stop, serve passengers, and then may proceed on the same green phase to the next downstream stop before the red phase on that signal begins. This represents dwell times less than the lower extent of the dwell range window.
3. Buses arrive at a stop, dwell through the red phase and into the green phase before proceeding to the next downstream stop. This represents dwell times greater than the upper extent of the dwell range window.

3.2.3.2 Computation Procedures

Step-by-step computational procedures were developed for the estimation of bus speeds for each of the three conditions. These steps are as follows: (1) identifying the speeds allowed by the progression; (2) estimating the maximum and minimum dwell times that fit within the dwell range window; and (3) adjusting the computed speeds to reflect simulation results, wherever the actual dwell times fall outside the dwell range window.

3.2.4 Validation of Basic Bus Speed Relationships

The basic bus travel speed relationships were field-tested on a four-block control section of Louisiana Street in the CBD of Houston, Texas. Travel time and dwell time measurements were made of all buses using the bus lane, and a section of the street was videotaped. The Louisiana Street bus lane operated under the following conditions:

• Simultaneous operation (offset = 0 sec)
• Effective green time per cycle = g/C = 0.48
• Cycle length = 80 sec
• Block length = 330 ft
• Buses stops near-side at each block
• Bus routes distributed into two alternating two-block stop patterns.
<table>
<thead>
<tr>
<th>Dwell Time per Stop (sec.)</th>
<th>Stops per Mile</th>
<th>Central Bus. District (Delay = 7.0 min/mile)</th>
<th>Central City (Delay = 0.6 min/mile)</th>
<th>Suburbs (Delay = 0.6 min/mile)</th>
<th>Central Bus. District (Delay = 1.2 min/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Travel Time (min/mile)</td>
<td>Speed (mph)</td>
<td>Travel Time (min/mile)</td>
<td>Speed (mph)</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>2.40</td>
<td>25.0</td>
<td>4.40</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.27</td>
<td>18.3</td>
<td>5.27</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.30</td>
<td>14.0</td>
<td>6.37</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5.33</td>
<td>11.3</td>
<td>7.33</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.00</td>
<td>8.6</td>
<td>9.00</td>
<td>6.7</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>2.73</td>
<td>22.0</td>
<td>4.23</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.93</td>
<td>15.3</td>
<td>5.93</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5.30</td>
<td>11.3</td>
<td>7.30</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>6.67</td>
<td>9.0</td>
<td>7.67</td>
<td>6.9</td>
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<td>10</td>
<td>8.67</td>
<td>6.9</td>
<td>10.67</td>
<td>5.6</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>3.07</td>
<td>19.5</td>
<td>5.07</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.60</td>
<td>13.0</td>
<td>5.60</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6.30</td>
<td>9.5</td>
<td>8.30</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8.00</td>
<td>7.5</td>
<td>10.00</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10.33</td>
<td>5.8</td>
<td>12.33</td>
<td>4.9</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>3.40</td>
<td>17.6</td>
<td>5.40</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.26</td>
<td>11.4</td>
<td>7.26</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>7.30</td>
<td>8.2</td>
<td>9.30</td>
<td>6.5</td>
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<tr>
<td></td>
<td>8</td>
<td>9.33</td>
<td>6.4</td>
<td>11.33</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>12.00</td>
<td>5.0</td>
<td>14.00</td>
<td>4.3</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>3.74</td>
<td>16.0</td>
<td>5.74</td>
<td>10.5</td>
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<td></td>
<td>4</td>
<td>5.92</td>
<td>10.1</td>
<td>7.92</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8.30</td>
<td>7.2</td>
<td>10.30</td>
<td>5.8</td>
</tr>
<tr>
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<td>10.67</td>
<td>5.6</td>
<td>12.67</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>13.67</td>
<td>4.4</td>
<td>15.67</td>
<td>3.8</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>4.07</td>
<td>14.7</td>
<td>6.07</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.58</td>
<td>9.1</td>
<td>8.58</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>9.30</td>
<td>6.5</td>
<td>11.30</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>12.00</td>
<td>5.0</td>
<td>14.00</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>15.33</td>
<td>3.9</td>
<td>17.33</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**SOURCE:** Computed

*Note: Column E may be used for single normal flow bus lanes where capacity analysis includes deductions for right turn interferences.*
Dwell time observations were made from 4:00 to 5:45 p.m. for each bus that used the bus lane; dwell times were found to range from 0 to 91 sec. Bus dwell times, averaged by 15-min intervals, ranged from 21 to 36 sec. A comparison of observed dwell times and bus speeds with those estimated by the general approach (Table 3-3) and the detailed approach (Equations 1, 2, and 3 in Appendix B) is presented in Table 3-4.

Both approaches provided reasonable estimates of observed bus speeds. The general approach produced estimates up to 1.2 mph greater than the observed speeds. The detailed approach resulted in bus speed estimates up to 1.0 mph greater than the observed speeds.

However, both sets of estimates did not fully reflect actual operating conditions. The videotapes of bus operations indicated that bus-bus interferences appeared to introduce additional delay for bus travel. The volume of vehicles turning right across the bus lane also affected bus stop service and bus lane queuing and added delay to the start-up lost time at the intersection. Finally, the volume of automobiles in the adjacent lane appeared to affect the ability of buses to leave the bus lane to execute the skip-stop pattern and occasionally caused the bus to dwell at an intermediate signal. These additional factors would reduce the predicted average bus speeds.

### 3.3 Refined Bus Speed Relationships

The basic bus speed relationships reflect the effects of bus stop spacing, dwell time, and traffic signal controls. Several other factors inherent in the traffic stream also affect bus speeds, including the impacts of skip stops and adjacent lane availability, the bus-bus interferences under heavy bus volume conditions, and the impacts of right turns, especially in areas of high pedestrian concentration. Each of these factors was explored, drawing upon both actual operating experience and computer simulation.

#### 3.3.1 Adjustments for Skip-Stop Operations

The general and detailed approaches to bus speed operation intrinsically account for skip-stop operations by considering only the bus stops in the skip-stop pattern. For example, if bus stops are located 400 ft apart at each intersection, the two-block skip-stop distance between bus stops is 800 ft. Thus, a bus with a two-block stop pattern would be able to proceed along the arterial at about twice the speed of a bus with a one-block stop pattern, and a bus with a three-block stop pattern at three times the speed, assuming uniform block distances and dwell times.

For alternating skip-stop patterns, the ability of a bus to leave the curb bus lane to pass stopped buses becomes a factor in the ability to attain the twofold and threefold increases in speed. The availability of the adjacent lane, or of a protected (pullover) bus berth, increases the ability of buses to execute a skip-stop pattern. A dual bus lane (Type 3) typically has both lanes available to buses. A single bus lane with a protected berth, such as on Albert and Slater Streets in Ottawa, Ontario, Canada, operates like a Type 3 lane because the lane adjacent to the bus berths allows passing of stopped buses. A Type 2 bus lane operates like a Type 3 bus lane when there is no traffic in the adjacent lane; however, the Type 2 lane functions like a Type 1 lane when the adjacent lane is full of traffic (v/c = 1) and precludes the buses from

<table>
<thead>
<tr>
<th>Time Period</th>
<th>No. of Buses</th>
<th>Average Dwell Time</th>
<th>Average Observed Speed</th>
<th>General Approach (Table 3-3)</th>
<th>Basic Bus Speed for Dwell Window</th>
<th>Bus Speed Adjusted for Dwell Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:00-4:15 PM</td>
<td>20</td>
<td>24 seconds</td>
<td>5.6 MPH</td>
<td>6.4 MPH</td>
<td>5.6 MPH</td>
<td>6.2 MPH</td>
</tr>
<tr>
<td>4:15-4:30 PM</td>
<td>21</td>
<td>21 seconds</td>
<td>6.0 MPH</td>
<td>6.5 MPH</td>
<td>5.6 MPH</td>
<td>6.5 MPH</td>
</tr>
<tr>
<td>4:30-4:45 PM</td>
<td>22</td>
<td>31 seconds</td>
<td>5.5 MPH</td>
<td>5.9 MPH</td>
<td>5.6 MPH</td>
<td>5.5 MPH</td>
</tr>
<tr>
<td>4:45-5:00 PM</td>
<td>25</td>
<td>31 seconds</td>
<td>4.6 MPH</td>
<td>5.9 MPH</td>
<td>5.6 MPH</td>
<td>5.6 MPH</td>
</tr>
<tr>
<td>5:00-5:15 PM</td>
<td>26</td>
<td>36 seconds</td>
<td>4.4 MPH</td>
<td>5.6 MPH</td>
<td>5.6 MPH</td>
<td>5.2 MPH</td>
</tr>
<tr>
<td>5:15-5:30 PM</td>
<td>25</td>
<td>29 seconds</td>
<td>5.1 MPH</td>
<td>6.1 MPH</td>
<td>5.6 MPH</td>
<td>4.9 MPH</td>
</tr>
<tr>
<td>5:30-6:00 PM</td>
<td>16</td>
<td>29 seconds</td>
<td>5.6 MPH</td>
<td>6.1 MPH</td>
<td>5.6 MPH</td>
<td>5.5 MPH</td>
</tr>
</tbody>
</table>

(1) SOURCE: Computer simulation analysis
leaving the bus lane. With a v/c = 1 in the adjacent lane, skip-stop operation is still possible in the single bus lane under low bus flow conditions, but becomes increasingly difficult as bus volumes increase.

Buses operating in dual bus lanes and on multilane streets may pass each other when bus stops are divided or split among the bus routes, establishing a skip-stop pattern of skipping one or two bus stops to arrive at a scheduled stop. The ability of buses to pass other buses to skip bus stops depends on the availability of the adjacent lane or a protected (pullover) bus berth in the bus lane. Where dual bus lanes or protected bus berths are provided, anticipated bus speeds can be calculated using the distance between bus stops served. Where congestion in the adjacent lane results in essentially no passing-lane availability, the buses will progress as if they were stopping at each stop, with a zero dwell time at the intermediate stops. When partial use of the adjacent lane is available, the bus speed will be somewhere in between.

Partial availability of the adjacent lane was simulated to derive a relationship between volumes of adjacent lane traffic and bus speeds. TRAF-NETSIM simulation results indicate that adjacent lane v/c ratios less than 0.4 do not significantly impact the availability of the adjacent lane for buses to make the passing maneuver and that v/c ratios greater than 0.4 have a gradually increasing impact. It also was found that when bus volumes were significantly below bus lane capacity, buses generally stayed in the bus lane unless the lane was obstructed.

An equation was derived to express the speed adjustment factor for skip-stop operation as a function of both the traffic in the adjacent lane and the buses in the curb lane. The factor would be multiplied by the basic bus speed for the skip-stop operation.

\[
f_s = 1 - \left( \frac{d_1}{d_2} \right) \left( \frac{v}{c} \right)^2 \left( \frac{v_B}{c_B} \right)
\]

(3-1)

where:

- \(f_s\) = stop pattern adjustment factor
- \(d_1\) = distance for one-block stop pattern, in feet
- \(d_2\) = distance for multiple-block stop pattern, in feet
- \(v\) = volume in adjacent lane, in vehicles per hour
- \(c\) = vehicular capacity of adjacent lane, in vehicles per hour
- \(v_B\) = volume of buses in bus lane at individual stop, in bph
- \(c_B\) = capacity of single bus lane at individual stop, in bph.

The factor \((d_1/d_2)\) adjusts the skip-stop speed back to the bus speed for stopping at every stop when the adjacent lane is not available. When the adjacent lane is partially available, the equation would compute a bus speed partway between the one-block stop and the multiblock stop pattern. The factor \(v/c\) is squared, whereas the factor for the bus v/c ratio is not, reflecting the results of the simulations.

Table 3-5 presents the resulting adjacent lane traffic factors for varying adjacent lane and bus v/c ratios under an alternating two-block skip-stop operation. These factors would be applied to the skip-stop speeds. Typical peak-hour conditions, with both the bus lane and the adjacent lane operating at v/c ratios of about 0.8, would result in skip-stop speeds approximately 75 percent of the skip-stop speed without bus-out and bus-bus interference (or 50 percent greater than the non-skip-stop speed). Thus, the stop pattern adjustment factor, \(f_s\), is a reductive factor to reflect less than optimal conditions for skip-stop operations.

### 3.3.2 Adjustments for Bus-Bus Interference

Bus speeds within a bus (or curb) lane along an arterial street decline as the lane becomes saturated with buses. This | Auto Volume-to-Capacity Ratio in Adjacent Lane | Bus Volume-To-Capacity Ratio | Bus Volume-To-Capacity Ratio |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>0.2</td>
<td>1.00</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>0.5</td>
<td>1.00</td>
<td>0.96</td>
<td>0.90</td>
</tr>
<tr>
<td>0.8</td>
<td>1.00</td>
<td>0.84</td>
<td>0.74</td>
</tr>
<tr>
<td>1.0</td>
<td>1.00</td>
<td>0.75</td>
<td>0.60</td>
</tr>
</tbody>
</table>

**SOURCE:** Equation 3-1
is because as the number of buses using the lane increases, there is a greater probability that a bus will delay another bus, either by using available berths (stops) or by requiring the other bus to make weaving and passing maneuvers.

A series of simulation runs were made to assess these impacts, assuming various bus volumes, dwell times, berth capacities, cycle lengths, block spacing, and effective green per cycle ratios. Bus speeds were identified for differing bus flow rates, bus v/c ratios, and dwell time variations. The speeds were then expressed as an index of maximum observed speeds for each condition simulated. Representative indices as a function of bus volumes are shown in Table 3-6. The data show a sharp drop in bus lane speeds as bus volumes approach capacity. (The sample simulations have not been adjusted for apparent anomalies.) Figure 3-1 presents the average indices obtained from 12 simulation run sets for both Type 1 and Type 2 bus lanes. These indices are based on an 80-sec cycle, g/C of 50 percent, 400-ft block spacings, 20- to 50-sec dwell times, and a 33 percent coefficient of dwell time variation. The sharp decline in the index as the bus v/c ratio exceeds 0.9 is apparent. The figure also presents speed indices calculated for Hotel Street in Honolulu (17), where the declines occurred at lower bus v/c ratios, and a series of curves that were developed based on these patterns. These curves served as guidelines in developing the suggested factors set forth in Table 3-7. Note that for bus v/c ratios less than 0.7, there is a negligible impact on bus speeds due to other buses.

3.3.3 Effects of Right Turns

Right turns from a bus lane can adversely affect bus speeds, especially where right-turning vehicle and parallel pedestrian volumes are heavy. The impacts are greatest for near-side stops where buses and turning traffic compete for the same roadway space (see Table 3-3).

3.3.3.1 Field Observations

Selected field observations were conducted on Louisiana Street in Houston and Geary Street in San Francisco to further identify right-turn impacts and to verify simulation results. Videotape images of these streets indicate that when bus volumes are less than half of lane capacity, 100 to 200 right turns per hour do not inhibit the movement of the buses in the lane. However, as bus flow rates increase, a level of uncertainty among motorists as to how to position themselves to execute the right turn appears to develop. This confusion stems from the combination of high variations in bus dwell times, buses dwelling into the green phase, and pedestrian crossing volumes. The position of the bus stop at the stop line (near-side) appears to be a primary cause for right-turn confusion. Far-side bus stops, conversely, appear to experience very little delay resulting from right turns.

3.3.3.2 Simulation Studies

Simulation studies were performed to assess the effects of right-turn volumes on bus speeds at near-side bus stops on a Type 2 bus lane. The simulations assumed a two-block skip-stop pattern, with stops spaced 400 ft apart. The TRAFNETSIM simulations indicate that when bus volumes are less than half of bus lane capacity, right-turn volumes of less than 100 vph have a negligible effect on bus speeds and delays. As bus volumes and right turns increase, there is an increasing effect on bus speeds. The impacts of right-turning

<table>
<thead>
<tr>
<th>Input Bus Volume</th>
<th>Type 1 1 Block Stops</th>
<th>Type 2 2 Block Skip-Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>60</td>
<td>0.94</td>
<td>1.00</td>
</tr>
<tr>
<td>80</td>
<td>0.94</td>
<td>1.00</td>
</tr>
<tr>
<td>100</td>
<td>0.91</td>
<td>1.00</td>
</tr>
<tr>
<td>120</td>
<td>0.88</td>
<td>0.97</td>
</tr>
<tr>
<td>140</td>
<td>0.54</td>
<td>1.00</td>
</tr>
<tr>
<td>160</td>
<td></td>
<td>0.90</td>
</tr>
<tr>
<td>180</td>
<td></td>
<td>0.88</td>
</tr>
<tr>
<td>200</td>
<td>0.43</td>
<td>0.29</td>
</tr>
</tbody>
</table>

**SOURCE:** Simulations

**Note:** Speed Index represents ratio of speed to highest speed for the set of conditions.
vehicle volumes on bus speeds derived from the simulations are presented in Table 3-8. This table shows the likely speed restrictions associated with various combinations of bus volumes, right-turn volumes, and dwell times.

More detailed discussion on how right-turn volumes affect bus travel speed and bus lane capacity appeared in Chapter 2. A capacity adjustment factor that reduces the capacity of the bus lane relative to the number of right turns is derived. The impact of right turns on bus speed is implicitly reflected in the bus-bus interference and lane availability factors; both of these factors utilize the bus v/c ratio \( \frac{v_B}{c_B} \) to reduce speeds. As the \( c_B \) value decreases, the bus v/c ratio increases for any given flow rate. Thus, as bus volumes and right turns increase, bus lane capacity and average bus speed decrease.

### 3.3.4 Final Bus Speed Relationships

Bus speed estimates for a section of an arterial street should take into account the adjustment factors for bus-bus interference, bus stop patterns, and, as appropriate, right turns.
3.3.4.1 General Approach

Bus speeds can be estimated by the following equation:

\[
\text{BUS SPEED} = V_0 f_S f_b
\]  

(3-2)

where:

- \(V_0\) = speed from Table 3-3
- \(f_S\) = bus stop pattern factor from Table 3-5.

Right-turn impacts are included in Table 3-3, Columns B, C, and D. These values may be used where buses stop every block and where conflicting right-turn impacts are generally light. However, both the bus-bus and adjacent lane factors reflect the impacts of right turns. Therefore, Table 3-3, Column E, should be used for the basic speed estimate when the adjustment factors are applied. (The factors in Column E of Table 3-11 eliminate the 0.8 minutes per mile right-turn delay associated with Table 3-11, Column B.)

3.3.4.2 Auxiliary Approach

The detailed approach, set forth in Appendix B, results in (1) computing speeds based on the dwell range window analyses and (2) adjusting these speeds for bus-bus interferences and adjacent lane availability. The formula is as follows:

\[
\text{BUS SPEED} = \left( \frac{d}{C} + o \right) f_D f_V f_S f_b
\]  

(3-3)

where:

- \(d\) = distance between bus stops, in feet or meters
- \(C\) = cycle length, in seconds
- \(o\) = cycle length offset, in seconds
- \(f_D\) = dwell range window factor (see Appendix B)
- \(f_V\) = dwell variation factor (see Appendix B)
- \(f_S, f_b\) = as in Equation 3-2.

3.4 FIELD EVALUATION OF BUS SPEED RELATIONSHIPS

Field surveys were conducted along bus lanes in Houston, Chicago, Los Angeles, and San Francisco to obtain basic bus flow parameters and to validate bus travel speed estimates. Information was obtained on bus stop location, berth capacity, block lengths, and signal timings and offsets. The entry and exit times of buses in each study section were recorded to allow calculation of average speeds. Dwell times for each bus at each bus stop in the study section were recorded. Type 2 bus lanes were videotaped to determine bus and traffic volumes in adjacent lanes and to examine bus-car interactions. The data collected in each city were analyzed by time interval for individual bus stops and block segments. The data also were averaged for each bus lane surveyed by time period. Measured bus speeds were compared with those obtained from Table 3-3 and Equation 3-3.

Table 3-9 describes the survey sites and summarizes the information analyzed. Table 3-10 compares the predicted and observed bus speeds. Both the general and detailed speed prediction procedures give good estimates of bus speeds.

It should be noted that the estimates shown for the detailed approach include reductions for bus-bus and other interferences, whereas those for the general approach do not. The general approach can be enhanced by including appropriate speed adjustment factors for bus-bus interference and skip-stop operations (see Equation 3-2).
The general approach (Table 3-3 and Equation 3-2) is quick and user-friendly and provides a reasonable basis for estimating bus speeds along arterial streets. The approach utilizes the travel times between stops and dwell times at stops as a base and then incorporates average estimates of traffic delays. The results are sufficiently accurate for most purposes.

The general approach is the suggested methodology for updates of the HCM. The more complex auxiliary approach (Equation 3-3 and Appendix B) provides a means to evaluate the impacts of changes in signal timing and coordination patterns or bus stop locations. Descriptions and applications of this auxiliary approach are presented in Appendix B.
This chapter contains examples of procedures for applying the research findings. A series of examples illustrate how bus capacities and speed can be estimated. In these examples, bus and car volumes are assumed as the flow rates based on the peak 15 min.

4.1 EXAMPLE 1: TYPE 1 CURB LANE (NO PASSING—ALL BUSES MAKE ALL STOPS)

4.1.1 Description

A curb bus lane operates along a downtown street where bus stops are 660 ft apart. All buses make all stops. Existing bus volumes average 30 buses in the PM peak hour with 40-sec average dwell times. Each bus stop can accommodate two buses. Traffic signals provide a 50 percent green time. Both right turns and the conflicting pedestrian volumes are less than 100 per hour at the bus stops.

It is desired to find (1) the capacity of the bus stop and the related level of service and (2) the average bus speeds and the associated “flow” level of service.

4.1.2 Solution

The solution is straightforward. First, the capacity of the bus lane is computed. Then the speed is estimated and adjustments are made for bus-bus interference as necessary. The level of service, in terms of the bus v/c ratio and speeds, are calculated for both performance measures.

4.1.2.1 Compute Bus Berth Capacity

Bus berth capacity can be obtained directly from Table 2-5, Part B. The capacity at LOS E, with a 25 percent failure and a 40-sec dwell time is 35 buses per berth. Table 2-3 indicates that there would be 1.75 effective berths at the bus stop (based on the HCM). Thus, the effective bus stop capacity is 61 buses per hour. For fewer than 100 pedestrians per hour and 50 right turns per hour, the right-turn adjustment is negligible. Thus, the bus v/c ratio is 30/61 or 0.49. Table 2-9, Part B, shows that the bus stop operates at LOS B (the bus v/c ratio of 0.49 is less than 0.63 for the 40-sec dwell time).

4.1.2.2 Estimate Bus Speeds

The basic speed estimate is obtained directly from Table 3-3 for the 660-ft spacing (eight stops) per mile. Because right turns are permitted and the lane operates in the CBD but right turns are few, Column B is entered. A 40-sec dwell time with eight stops per mile results in a speed of 5.3 mph. Because the bus v/c ratio is less than 0.5, there is no adjustment for bus-bus interference. Table 3-1 shows that this speed falls within the range shown for LOS C for CBD streets (5.0 to 6.7 mph). Thus, the bus lane operates at LOS C.

4.2 EXAMPLE 2: TYPE 1 CURB BUS LANE (NO PASSING—ALL BUSES MAKE ALL STOPS)

4.2.1 Description

A curb bus lane operates on a downtown street. Bus stops are spaced about 750 ft apart (seven stops per mile), and all buses make all stops. Each bus berth can accommodate two buses. Existing bus volumes average 48 in the peak hour. Buses average 35 sec per stop with 80 percent coefficient of variation. Traffic signals provide a 60 percent g/C ratio. Right-turn conflicts with pedestrians exist, but both volumes are negligible.

It is desirable to determine (1) the capacity of the bus stop and the related level of service and (2) the average bus speeds through the area and their associated flow level of service.

4.2.2 Solution

The analyses of and solution for this example are similar to those for the first example, except that the bus berth capacity will be computed.

4.2.2.1 Compute Bus Berth Capacity

The capacity of the bus stop can be estimated by applying Equation 2-10.

\[
C_b = \frac{g/C(3600)}{t_c + (g/C)D + Z_cC_pD}
\]
where:

- \( g/C \) = green/cycle = 0.6
- \( t_c \) = clearance time = 15 sec
- \( D \) = average dwell time = 30 sec
- \( C_v \) = 80 percent (input as 0.8)
- \( Z_a \) = 0.675 for a 25 percent failure (LOS E) (Table 2-3)
- \( C_b \) = capacity per berth, in buses per hour.

Thus,

\[
C_b = \frac{(0.6)3600}{15 + 0.6(30) + (0.675)(0.8)(30)} = \frac{2160}{4912} = 44
\]

The capacity per berth is 44 buses per hour. Because there are 1.75 effective berths (HCM Table 12-19), the total capacity of the bus stop is 77 buses per hour.

The combined effects of right turns and conflicting pedestrians can be estimated from Table 2-14 and Equation 2-13. For 100 pedestrians per hour, the right-turn saturation flow rate is 1,360 vph. A \( g/C \) ratio of 0.60 results in a capacity of 816. A right-turn volume of 100 results in a right-turn v/c ratio of 0.123. This number is inserted in Equation 2-13 to obtain the right-turn adjustment factor, \( F_R \). The bus stop location factor, \( L_{b,\text{near}} \), is assumed as 1 (near-side stop—no passing).

\[
F_R = 1 - L_{b,\text{near}} \left( \frac{v_R}{v_s} \right) = 1 - 1(0.123) = 0.877
\]

The adjusted bus stop capacity becomes (77)(0.877) = 68.

The bus v/c ratio is 48/68 or 0.71. This is slightly greater than the average index for LOS C (Table 2-9, Part B, right-most column). Note that for a 30-sec dwell time, the cut-off value is 0.74, suggesting an LOS C operation. Thus, the bus stop is considered to operate at LOS C.

4.2.2.2 Estimate Bus Speeds

The basic bus speed estimates are obtained from Table 3-3. Column E is used because the effects of right turns are reflected in the initial capacity estimates. A 30-sec dwell time results in a travel time rate of 7.50 min per mile when buses make six stops per mile and 9.20 min per mile when buses make eight stops per mile. Interpolation for seven stops per mile results in a travel time rate of 8.35 min per mile or 7.19 mph.

It is necessary to adjust this speed for bus-bus interference. Table 3-7 indicates that for a bus stop v/c ratio of 0.71, the speed reduction factor (by interpolation) is 0.88. Thus, the estimated bus speed is (7.19)(0.88) = 6.33 mph.

Note that if the right-turn adjustment factor were not applied to the berth capacity estimates, the resulting bus berth v/c ratio would be 0.62 and the resulting bus interference adjustment factor would be 0.93. Table 3-3, Column B, results in 0.8 min per mile more travel time than Column E. This results in an adjusted bus travel time rate of 9.15 min per mile and a speed of 6.56 mph. Thus, the resulting speed estimate becomes (6.56)(0.93) = 6.10 mph.

Table 3-1 shows a range of 5.0 to 6.7 mph for LOS C. Thus, for both estimates, the speed-related LOS is C for the bus lane.

4.3 EXAMPLE 3: TYPE 2 BUS LANE WITH SKIP STOPS

4.3.1 Description

Buses using a curb bus lane along a downtown street operate in a skip-stop pattern, with each of two alternating sets of buses making six stops per mile. The PM peak-hour volume of 100 buses is equally divided between the two sets of near-side stops. Each bus stop provides length for three berths. Dwell times average 20 sec at Stops A and 40 sec at Stops B, each with a 60 percent coefficient of variation. Right turns of 200 vehicles per hour conflict with 400 pedestrians per hour crossing parallel to the bus lane at Stops A. Right turns are prohibited at Stops B. Traffic in the lane adjacent to the bus stop operates at a v/c ratio of 0.8.

It is desired to find (1) the capacity and related level of service for each bus stop and (2) the average speeds and their associated level of service along the bus lane.

4.3.2 Solution

The solution requires estimating the capacity of each bus stop, taking into account the adjustments for right turns and use of the adjacent lane. Next, the basic bus speeds are estimated (from Table 3-3) by using an average dwell time. Then, speeds are adjusted to account for bus-bus interference and availability of the adjacent lane. Finally, a level of service determination is made.

4.3.2.1 Compute Bus Berth Capacity

The capacity of each stop is estimated by applying Equations 2-14a and 2-14b.

\[
\text{Bus Lane Capacity (CAP)} = C_b N_b f_R
\]

where:

- \( C_b \) = capacity of a bus berth
- \( N_b \) = number of effective berths
- \( f_R \) = capacity of adjustment for right turns.

The capacity of the pair of stops is the sum of the individual capacities adjusted by the adjacent lane factor.

\[
\text{Bus Lane Capacity (CAP)} = f_R (\text{CAP}_A + \text{CAP}_B)
\]

where \( f_R \) = capacity adjustment for skip-stop operations.
The basic capacities, $C_b$, are obtained from Table 2-5, Part B, assuming a 25 percent failure rate:

- Stops A with 20-sec average dwell time—54 buses per hour
- Stops B with 30-sec average dwell time—43 buses per hour.

The number of effective berths are obtained from Table 2-3. For three berths, the number of effective berths is 2.25. Thus, $N_b = 2.25$.

The right-turn impacts for Stops A are estimated from Tables 2-14 and 2-15. The 50 percent g/C, 200 right turns, and 400 conflicting pedestrians per hour at Stops A result in a $v_d/c_R$ ratio of 0.36. This is introduced into Equation 2-13.

$$f_R = 1 - L_b \frac{v_d}{c_R} = 1 - L_b (0.36)$$

The bus stop location factor, $L_b$, is estimated from Table 2-16 to be 0.9. Thus, the right-turn adjustment factor, $f_R = 1 - (0.9)(0.36) = 0.68$. At Stops B, $f_R = 1.0$.

The capacities of the two stops, adjusted for the number of berths and right turns are as follows:

- Stops A—$54 \times 2.25 \times 0.68 = 82$
- Stops B—$43 \times 2.25 \times 1.0 = 97$

The effects of adjacent lane availability, $f_K$, can be estimated from Equation 2-12, assuming typical arrivals ($K = 0.75$) and an $x$ value of 0.8. The effects may be obtained directly from Table 2-15. For a $v/c$ ratio of 0.80 in the adjacent lane, $f_K$ becomes 0.71. The adjusted capacity of the pair of stops becomes the following:

Bus Lane Capacity (CAP) = $f_K (\text{CAP}_A + \text{CAP}_B)$

= $(0.71)(82 + 97) = 127$ buses

The $v/c$ ratio for each stop becomes the following:

- Stop A = $\frac{50}{(82)(0.71)} = 0.86\%$
- Stop B = $\frac{50}{(77)(0.71)} = 0.73\%$

Table 2-9 indicates that the berths at stops A would operate at LOS D (bus $v/c$ ratio between 0.81 and 0.89 for the 20-sec dwell time) and the berths at Stops B at LOS C (bus $v/c$ ratio between 0.66 and 0.74 for 30-sec dwell time). Note that if the suggested rounded indices were used (last two columns in Table 2-9), Stops A would operate at LOS E ($v/c = 0.86$ would be greater than the 0.70 to 0.85 range for LOS D) and Stops B would still operate at LOS C. Thus, on balance, the pair of bus stops would operate at LOS D.

### 4.3.2.2 Estimate Bus Speeds

Bus speed estimates along the bus lane can be obtained by utilizing the bus stop frequency (six per mile) and by averaging the dwell times for each stop. Skip-stop bus operations require special consideration of the bus stop $v/c$ ratios. If there is a significant difference between the $v/c$ ratios at individual stops, the largest ratio should be used. If the differences are small, as in this case, the composite ratio (i.e., $100 \text{ buses}/127 \text{ capacity} = 79\%$) should be used.

The basic bus speed can be obtained from Table 3-3 (Column E) by interpolation. This is necessary to avoid the “double-counting” of right-turn impacts if Column B is used. A spacing of six stops per mile results in travel time rates of 6.50 min per mile for 20-sec dwell times and 7.50 min per mile for 30-second dwell times. Thus, the average is 7.00 min per mile or 8.6 mph.

Adjustments are then made for bus-to-bus interference and availability of the adjacent lane by applying Equation 3-2.

**BUS SPEED** = $V_0 f_S f_0$

where:

- $V_0$ = unadjusted bus speed = 8.6 mph
- $f_S$ = bus stop pattern factor
- $f_0$ = bus-bus interference factor.

The effects of traffic in the adjacent lane on the ability to double bus speeds by skipping stops can be computed by Equation 3-1 or obtained directly from Table 3-5. For an 0.8 $v/c$ ratio in the adjacent lane and 0.8 bus-berth $v/c$ ratio, the factor, $f_S$, is 0.74.

The effects of bus-bus interference can be estimated from Table 3-7. For a bus-berth $v/c$ ratio of 0.8, the factor, $f_0$, is 0.81. Thus, the refined bus speed is $(0.74)(0.81)(8.6)$ mph or 5.2 mph. This corresponds to LOS C (5.0 to 6.7 mph) as set forth in Table 3-1 for a CBD location.

### 4.4 EXAMPLE 4: TYPE 2 DUAL BUS LANES WITH SKIP STOPS

#### 4.4.1 Description

Dual bus lanes operate along a downtown street. Buses operate on a skip-stop basis with each set of 60 PM peak-hour buses stopping every 900 ft (six stops per mile). Three near-side berths are provided at each stop, and all right turns are prohibited along the roadway. Bus dwell times average 50 sec at each stop with a 60 percent coefficient of variation. Signals operate with an approximate 50 percent g/C ratio.

It is desirable to find (1) the capacity and related level of service of the bus berths and (2) the travel speed and its related level of service.
4.4.2 Solution

The solution involves first estimating the capacity of each stop and then estimating the bus speeds. The computations are less complex than for Type 2 bus lanes because right-turn and adjacent lane impacts are not involved.

4.4.2.1 Compute Bus Berth Capacity

Bus berth capacity can be obtained directly from Table 2-5, Part B. A 50-sec dwell time and a 25 percent acceptable failure result in a capacity of 30 buses per berth per hour. The number of effective berths is obtained from Table 2-3; the three berths translate into 2.25 effective berths. Thus, the capacity for each stop is (2.25)(30) or 68 buses per hour. The bus berth v/c ratio is 60/68 or 0.88 at each stop. Table 2-9 shows a v/c ratio of 0.85 to 1.00 for LOS E. Thus, the berths at each stop would operate at LOS E.

The capacity of the dual bus lanes on the arterial could be \((2)(68)\) or 136 buses per hour if advance platooning of buses were to place bus arrivals in their proper order (three buses for Stop A, three buses for Stop B, etc.) as they enter the bus lanes. Rather than purely random arrivals, the cumulative effect of operating in the skip-stop pattern tends to place buses in a somewhat ordered arrival sequence. An adjustment factor, \(f_K = 0.88\), would be applied to adjust for the ability to fully utilize the bus stops in the skip-stop operation (see Equation 2-12). The resulting capacity of the skip-stop operation in the dual lane is \((0.88)(68 + 68)\) or 120 buses per hour. The resulting bus volume capacity ratio is 1.00.

4.4.2.2 Estimate Bus Speeds

Basic bus speeds can be estimated directly from Table 3-3. Because there are no right turns, Column E is read for six stops per mile and a 50-sec dwell time. This translates into 6.3 mph.

An adjustment for bus-bus interference in necessary. Table 3-7 shows a reductive factor of 0.55 for a 1.00 bus v/c ratio. Thus, the estimated bus speed is \((0.55)(6.3)\) = 3.5 mph. Table 3-1 indicates that the speed-related LOS is E (i.e., between 3.3 and 4.0 mph).

4.5 EXAMPLE 5: ESTIMATE ARTERIAL BUS LANE SPEEDS

4.5.1 Description

Buses operating in a curb bus lane along an urban arterial roadway stop every ½ mi with 15-sec average dwell times. Within the CBD, buses stop every block (½ mi) with a 40-sec dwell time. Approximately 30 buses use the lane in the peak hour. Two bus berths are provided at each bus stop in the CBD, and one berth is provided at stops elsewhere.

It is desired to find the expected average bus speeds through the CBD and along the rest of the route and associated levels of service. If the bus lane is 10 mi long and the portion through the CBD is 1 mi in length, what is the anticipated route trip time?

4.5.2 Solution

The solution represents a straightforward application of Table 3-3. Because bus volumes are low relative to berth capacities, adjustments for bus-bus interference are not necessary. Using Table 3-3, for four stops per mile and interpolating between the dwell time values for 10 and 20 sec (13.2 mph and 15.5 mph), the average speed of buses along the arterial is estimated at 14.3 mph (4.2 min/mi). From the level of service criteria presented in Table 3-1, this speed corresponds to LOS A for the urban arterial bus lane. Similarly, from Table 3-3, it is determined that buses passing through the CBD would have an average speed of 5.3 mph (11.3 min/mi). From Table 3-1, this speed corresponds to LOS C. Thus, the LOS drops from A to C when proceeding through the CBD. The total trip time (one-way) is estimated to be \((9 \text{ mi} \times 4.2 \text{ min/mile}) + (1 \text{ mi} \times 11.33 \text{ min/mi}) = 49.1 \text{ min}.\)

The average overall speed is 12.2 mph.

4.6 ADDITIONAL APPLICATIONS

The procedures can be applied to assess the following:

- Negative and positive impacts of various changes in traffic controls and transit operations;
- Benefits resulting from establishing a skip-stop service pattern, changing from near- to far-side bus stops, and increasing the number of bus berths; and
- Benefits to bus operations resulting from prohibiting right turns and changing traffic signal timing.

Additional methods for assessing detailed speed impacts resulting from changes in traffic signal timing and coordination are presented in Appendix B. The equations in this appendix incorporate information on cycle length, green times, and offsets as well as bus acceleration rates, cruise speeds, dwell times, and dwell time variations. They can be used for fine-tuning signal systems to minimize total bus passenger and person delay.
CHAPTER 5

INTERPRETATION, APPRAISAL, AND IMPLICATIONS

This research analyzed the operation of buses on arterial street bus lanes, focusing on operating conditions in which buses have full or partial use of adjacent lanes. In this context, the research explored the effects of adjacent lanes on bus speeds and capacities and derived relationships that quantify these impacts. It also showed how increasing bus volumes can reduce speeds and how right turns from or across bus lanes affect bus flow.

Thus, the research quantified the interaction of buses in traffic—the impacts of stopping patterns, traffic signals, and lane-use characteristics on bus operation. Extensive simulation runs provided a basis for formulating, calibrating, and refining analytical relationships that were translated into simple tables, charts, and formulas. The research, therefore, augments and expands available information pertaining to bus use of arterials and provides important input for the HCM update and for a new transit capacity manual.

The analyses focused on bus lanes along downtown streets, where bus volumes and passenger boardings are the heaviest and where most bus lanes are provided. Traffic signals usually are located at every intersection, resulting in limited progression and maximum impact on bus flow. The procedures and parameters also apply to bus lanes along major radial arterials with heavy bus flow.

The research emphasized the estimation of bus speeds. Speed-related levels of service for local bus operations on arterial streets were established; thus, it will be possible to assess bus operations along arterials in a way that is consistent with the assessment of arterial street traffic flow.

The research focused on bus capacity in terms of buses per hour. Perhaps even more important is the movement of people, which involves providing enough stops and berths along a peak passenger demand section. These procedures are described in the 1985 HCM (1) and can be readily modified to reflect the procedures and parameters suggested in this research.

5.1 SPEED AS A FLOW LEVEL OF SERVICE CRITERIA

Representatives of transit properties normally are concerned with the number of passengers vehicles can (or should) carry and, in turn, with the number of vehicles they can (or should) operate. Both these factors are addressed in detail in existing capacity references. The HCM defines levels of service in terms of both passengers per vehicle and vehicles per hour.

The research adds a new dimension to bus levels of service—bus speed. Speed is suggested as another bus transit performance measure, and levels of service based on speed are presented for various bus operating environments. The use of speed ranges to define levels of service is easy to understand and reflects transit passengers’ perceptions of how well buses operate along a route. Moreover, bus travel speed as a performance measure is consistent with existing level of service criteria for arterial streets and with proposals under consideration for a year 2000 HCM.

Speed is also important from a transit operations and planning perspective. It influences fleet requirements and operating costs, and it provides a basis for making traffic improvements and installing bus lanes. An important goal in timing downtown traffic signals and in establishing bus lanes is to minimize total person delay.

Finally, many transit agencies view a roadway or transit effectiveness in terms of the person-mile per hour achieved during peak travel conditions. Speed estimates are useful for these purposes.

5.2 EFFECTS OF ADJACENT LANES

Bus speeds are determined by how frequently bus stops are placed, how long buses dwell at each stop, traffic conditions along the route, and whether buses can pass and overtake one another. The primary benefit of having the adjacent lane available for buses is the ability to adopt skip-stop service patterns with alternate groups of buses stopping at alternate stops. In this manner, stops for each route can be spread further apart, thus increasing average bus speeds. Designation of dual bus lanes and the prohibition of right turns for a two-block skip-stop pattern can virtually double average bus speeds and nearly double route capacities. However, if buses must share the adjacent lane with other traffic, speed and capacity gains are less whenever the adjacent lane operates at or near its capacity. In addition, the availability of the adjacent lane enables buses to pass errant, stalled, or delayed vehicles without crossing barriers or going into an opposing traffic stream.
Such bus service and stopping patterns, however, must be tempered by the existing route structure, block spacings, and passenger demand. Overconcentration of passenger boardings tend to increase dwell times, thereby potentially reducing anticipated gains in speed and capacity. Thus, in practice, opportunities for skip stops may be limited. From a bus speed perspective, lengthening the distance between stops throughout the urban area may prove beneficial.

The research reaffirms the basic relationships between capacity and various factors, including the following:

- Passenger dwell times and their variations at stops;
- Green time available for buses; and
- Number of berths available.

When stops are spread along a route in a skip-stop pattern, the capacity of the bus lane increases by 50 to 100 percent, less adjacent lane interferences.

5.3 POTENTIAL MODIFICATIONS TO THE HCM

Highway and transit capacity are in a state of flux. Work is proceeding on the year 2000 HCM, and work has been initiated on TCRP Project A-15, Development of Transit Capacity and Quality of Service Principles, Practices, and Procedures. The materials contained in the present research will provide important input to both these efforts.

The following opportunities exist for incorporating research findings within the framework of the 1985 and 1994 versions of the HCM. Most of these potential modifications relate to Chapter 12, Transit Capacity. In addition, certain revisions should be incorporated into Chapter 9, Signalized Arterials, and into Chapter 11, Urban and Suburban Arterials.

5.3.1 Overview of Suggested Changes

Major additions to the existing HCM include incorporating (1) new speed-related level of service criteria and (2) methods of estimating bus lane speeds. These additions could be incorporated into Chapter 11; alternatively, a section on bus speeds could be added to Chapter 12, Section III, immediately before the discussions on bus priority treatments. Existing materials in Chapter 12 describing bus berth capacity could be augmented by incorporating the new capacity procedures for skip-stop operations (including dual bus lanes) and for right-turn impacts. It also may be desirable to incorporate the revised capacity equations and the resulting bus stop level of service criteria (use of 25 percent failure for LOS E versus the 30 percent failure in the HCM). These changes, if included, would require changes in some of the values and formulation of equations for estimating passenger capacity of the berth as well as changes in the sample problems. The following modifications should be considered.

5.3.2 Specific Modifications to Chapter 12

The following modifications to Chapter 12 should be considered.

1. *Modify Basic Berth Capacity.* The HCM uses the following equation for estimating the capacity of a bus berth under signalized traffic flow conditions:

\[ C_e = \frac{(g/C) 3600 R}{t_s + (g/C) D} \]  

(5-1)

where \( R = 0.833 \) for LOS E (30 percent acceptable bus stop failure).

The simulations and field studies suggest that a more precise, but slightly more complex, statement could be developed to allow for differing dwell time variations. The refined bus capacity equation is as follows:

\[ C_e = \frac{(g/C) 3600}{t_s + (g/C) D + Z_a S_d} \]  

(5-2)

where:

- \( S_d = \) standard deviation of dwell times
- \( Z_a = \) one-tail normal variate for probability that queue will not develop at the bus stop.

The results from using the two equations are similar. Analyses of Equation 5-2 for a dwell time variation of 60 percent \( (i.e., S_d = (0.6D) \) results in an average \( R \) factor of about 0.70 to 0.75 for 25 percent failure (LOS E). Thus, for computational simplicity, it may be desirable to retain the existing formulation.

2. *Modify Level of Service Criteria.* The level of service criteria for bus berths in Table 12-17 of the HCM could be modified as follows:

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>1985 HCM</th>
<th>Suggested Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>75</td>
</tr>
<tr>
<td>D</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>E (Capacity)</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>E (Perfect Conditions Capacity)</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

3. *Revise the Effects of Spreading Stops* (presented on p. 12-30 of the HCM). Three conditions should be addressed and pertinent values indicated.

a. *Where buses have complete use of the adjacent lane.*

The current wording suggests a doubling of capacity if stops are spread across two alternating bus stops. The research indicates that a doubling would only occur if the bus arrivals were platooned in
advance and there was little or no traffic in the adjacent lanes and no change in dwell times. Thus, some downward adjustments may be needed to account for arrivals that are purely random and, more typically, partially platooned.

b. Where buses do not have full availability of the adjacent lane. The v/c ratio of the adjacent lane should be considered.

c. Capacities of each stop based on the dwell times at a particular stop. It also should be noted that the capacities of each stop should be based on the dwell times at a particular stop. The sum of the capacities should be discounted where buses do not have full use of the adjacent lane.

4. Incorporate the Effects of Right Turns. It also may be desirable to include reductive factors for the effect of right turns on bus flow in Chapter 12.

5. Expand/Modify Problems. If the revised capacity and/or level of service criteria are adopted, they may require changes in pp. 12–19 through 12–28 of the HCM as well as changes in many of the problems on pp. 12–39 through 12–47.

6. Include Bus Speeds. A section on bus lane speeds and speed-based levels of service should be added to Chapter 9 and/or Chapter 12. The additions should include (1) bus-speed-related level of service criteria and (2) basic tables showing bus speed values for Table 3-3 and relevant adjustment factors.

7. Include Detailed Travel Time Equations. The dwell range window concept appears to help in understanding the effects of the traffic signal system on bus speeds under typical bus lane conditions. This material may be applicable to Chapters 9 and 11 as well as to Chapter 12 and could be included in an appendix to either chapter.

5.3.3 Specific Modifications to Chapter 9

The following modification to Chapter 9 should be considered:

• Consolidate and Update Information on the Effects of Buses on Vehicular Capacity. The materials in Chapter 12 on p. 10, Bus Flow and Equivalency Studies and Effects of Buses on Vehicular Capacity, should be moved to Chapter 9. Information should be added describing how the number of buses making lane changes can be estimated for streets with Type 2 bus lanes.

5.4 SERVICE PLANNING GUIDELINES

The basic traffic and transit operational and planning goal should be to improve the speed, reliability, and capacity of bus operations on city streets. Several planning and policy guidelines that emerge from the research investigations are consistent with this goal:

- It is desirable to minimize the number of bus stops along a route consistent with land use, street system, and passenger demands. Simultaneously, where bus volumes and passenger boardings are heavy, multiple bus berths at stops are essential to provide sufficient capacity and to minimize bus-bus delays.
- The passenger dwell times at bus stops should be minimized. This need suggests the use of passes or farecards, pay-as-you-leave fare collection, and possibly prepayment of fares at busy stops. It also suggests the use of wide multichannel doors and low floor buses. Enough major stops should be provided to distribute passenger loads.
- Equally important is the need to minimize the variations in dwell times at key bus stops during peak travel periods. This need suggests the separation of local and express bus stops, where each service may have significantly different dwell times.
- Bus lane speeds can be enhanced by providing alternate or skip-stop route patterns in which alternate groups of buses stop at alternate bus stop locations. This emphasizes the importance of having usable adjacent lanes for use by buses, as with dual bus lanes and suggests dual contraflow bus lanes where block spacing and passenger demands are conducive to skip stops. The provision of bus lanes, bus streets, and busways to minimize auto-bus conflicts may be desirable.
- Curb bus lane speeds also can be enhanced by prohibiting right turns at major boarding and alighting points or by providing far-side stops at intersections with heavy right-turn volumes.

This report shows how the effects of these actions can be estimated for bus lanes. Bus speeds are affected by the realities of operations on city streets, where there is much competition for curb space. Bus volumes, right turns, loading and goods delivery, and parked vehicles adversely affect speeds; therefore, sound management and effective enforcement of bus lanes is essential. Good judgment is essential in applying the various adjustment factors.

5.5 RESEARCH POSSIBILITIES

This research emphasized arterial street bus lane operations and presented procedures for estimating bus speeds along arterials by using average values for the aggregate traffic delays involved. Further analyses of bus speeds and the interaction of bus dwell times, traffic signals, and bus priority treatments along arterial roadways is desirable to refine and strengthen these bus speed and capacity relationships for
various operating conditions, including bus flow in mixed traffic.

Traffic signals account for several minutes per mile delay to buses in exclusive lanes. Some of this delay might be reduced if the signals were timed to minimize total person delay, rather than vehicle delay. Further research on the interaction between buses and traffic signals is desirable. Simulation could be used to analyze the effects of bus advances and extension (or preemption) on bus and auto travel times. The objective is to minimize total person delay, while maintaining the integrity of overall signal system coordination.
A review was made of the available literature pertaining to bus flows, bus capacities, bus travel times, and their interactions. This information provides an important resource for traffic and transit professionals.

A.1 BUS FLOW AND CAPACITY

Bus flow and capacity have been analyzed in a number of studies. Peak-hour bus flows from which capacity ranges have been identified have been tabulated, bus capacity formulas have been derived, and level of service criteria have been established. The 1985 Highway Capacity Manual (HCM) (1), for example, addresses transit capacity from both planning and operating perspectives. The HCM defines level of service in terms of both passengers per vehicle and vehicles per hour; suggests passenger car equivalents for buses keyed to effective green per cycle (g/C) ratios and dwell times; and contains detailed capacity formulas.

A.1.1 Observed Flows and Capacities

Various observations of peak-hour bus flows on urban arterials provided a framework for capacity estimates. The maximum number of buses operating on city streets was first tabulated in a 1961 progress report of the Transit Subcommittee of the HRB Committee on Highway Capacity (2). Further listings are presented in the 1965 HCM (3), NCHRP Report 143 on bus use of highways (4), and a 1975 paper, Bus Capacity Analyses (5). More recent listings are contained in the 1985 Highway Capacity Manual (1) and in the Transportation Planning Handbook (6). Selected listings are shown in Table A-1. These references suggest maximum bus flows of 200 buses per hour (up to 10,000 persons per hour) where buses can use adjacent lanes and flows of 80 to 120 buses per hour where buses are limited mainly to a single lane (experience in Asia suggests a doubling of these bus and passenger volumes).

The HCM defines level of service criteria for central business district (CBD) and non-CBD environments based on actual operating experience. These values are summarized in Table A-2. Where stops are not heavily used, as along many outlying arterials, the service volumes could be increased by about 25 percent.

The HCM also contains planning guidelines for person-capacity, assuming that the key boarding points are sufficiently dispersed to achieve these bus loads. These guidelines are shown in Table A-3.

*The Canadian Transit Handbook* (7) suggests maximum flows of 90 buses per hour in mixed traffic and 120 buses per hour in exclusive bus lanes (1). These values translate into 3,600 and 4,800 seated passengers per hour, respectively.

Peak-hour bus flows and capacities are governed by how long buses remain at stops; therefore, it is reasonable to assume that flows are less in the evening peak period when loading conditions govern. These differences were recognized in a 1991 study of bus flows on Manhattan (New York City) streets (8). The specified maximum and desirable capacities are summarized in Table A-4.

A.1.2 Capacity Formulas

Various formulas have been developed over the years for estimating the capacity of a bus berth, bus stop, and bus route. These formulas show how the number of buses that can be accommodated at a given stop relates to the dwell times at stops and the clearance times between successive buses. The dwell times, in turn, are influenced by the amount of passenger boarding and alighting activity and the service time per passenger.

Passenger service times for various loading and unloading conditions were first set forth in the 1961 HRB Transit Subcommittee progress report (2) and the 1965 HCM (3). The 1965 HCM, in turn, suggested that the capacity of a curbside stop should be based on twice the average dwell time to account for variations in arrivals. Passenger service times also are presented in NCHRP Report 155 on planning and design guidelines for bus use of highways (9) and in the 1985 HCM (1).

Formulas for estimating bus stop capacity and berth requirements to accommodate a given passenger demand are presented in NCHRP Report 155 and in a 1975 paper on bus capacity analysis (5). These formulas were incorporated in 1980 in *Transportation Research Circular 212: Interim Materials on Highway Capacity* (10).

These earlier formulas were modified in the 1985 HCM to include the effects of the effective green time per cycle ratio and the variability of bus arrivals at stops, two factors that
The general equation for computing the number of vehicles that may be accommodated per effective berth at a bus stop was as follows:

\[ C_v = \frac{(g/C)3600R}{(g/C)D + t_c} \]  

where:

- \( C_v \) = buses per hour per channel per berth
- \( D \) = bus dwell time at stop, in seconds
- \( t_c \) = clearance time (headway) between buses, in seconds (usually 10 to 15 sec)
- \( R \) = reductive factor to account for variations in dwell times and arrivals, assumed to be 0.833 for buses for LOS E (lower for other service levels)
- \( g/C \) = effective green time per cycle.

If there is more than one berth, the HCM contains factors for converting the number of actual berths to effective berths. Equation A-1 does not account for the ability of a bus to pass a stopped bus, nor the reductive effects of right turns from or across the bus lanes, and it does not provide for speed-related levels of service.

The HCM formula was applied to Manhattan streets in a study of bus service times and capacities published in Transportation Research Record 1266 (11). This study found that the reductive factor (\( R \)) of 0.83 closely approximated conditions on Manhattan streets.

A 1991 European study (12) analyzed the capacity of bus lanes, assuming random arrivals of buses and up to three loading positions. The results for levels of service C/D were compared with those in the 1985 HCM. The study found little increase in capacity when there are more than three stopping positions, thereby validating the 1985 findings relative to bus berth efficiency.

**A.2 BUS TRAVEL TIMES**

Most transit agencies check bus running times as a basis for preparing schedules and monitoring on-time performance. Speed and delay measurements of bus operations on arterial streets are sometimes part of transit and traffic studies. However, there have been relatively few systematic analyses of bus travel times.

**A.2.1 Transit Agency Perspective**

Transit agencies establish bus schedules that reflect the frequency and duration of stops and street traffic conditions along each bus route (13). The schedules are varied to reflect differing conditions throughout the day. Performance is monitored to determine how well buses adhere to the established schedules. Buses generally should operate on time between 80 and 90 percent of the time. "On time" usually is defined as between 1 min early and 3 to 5 min late; specific requirements are keyed to the type of bus route (local,
express, or feeder) and service frequency. However, specific speed-related level of service criteria, such as those set forth in the HCM for arterial streets, have not been used.

A.2.2 Travel Time Analysis

Detailed analyses of bus and rail transit travel times appear in a 1982 study prepared for the Urban Mass Transit Administration (14). This work is summarized in the paper Analyzing Transit Travel Time Performance, published in Transportation Research Record 915 (15). This paper contains a detailed analysis of transit speeds, delays, and dwell times. The analysis revealed that car speeds are consistently 1.4 to 1.6 times as fast as bus speeds and that the typical bus spends about 48 to 75 percent of the time moving—9 to 26 percent at passenger stops and 12 to 26 percent in traffic delays.

Table A-5 summarizes peak-hour bus travel times for CBD, central city, and suburban environments. Peak-hour bus travel times are approximately 4.2 min per mile in the suburbs, 6.0 min per mile in the city, and 11.50 min per mile in the CBD. About one-half to two-thirds of total travel time is spent in motion; the remainder is almost equally divided between traffic delays and time spent at bus stops.

Bus travel times and speeds also were derived as a function of stop frequency, stop duration, and bus acceleration-deceleration times observed in the field. Further analysis of these times in relation to traffic delays led to the values shown in Table A-6 (16). Bus speeds tend to decline as bus volumes increase, although these patterns are influenced by other factors as well. The travel times without traffic delay would be experienced only where buses operate on unsignalized roadways and where full signal preemption for buses exists. The table provides a basis for estimating bus speeds and was used in subsequent analysis.

<table>
<thead>
<tr>
<th>TABLE A-2</th>
<th>Suggested HCM bus flow service volumes for planning purposes (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LEVEL OF SERVICE</strong></td>
<td><strong>DESCRIPTION</strong></td>
</tr>
<tr>
<td><strong>ARTERIAL STREETS</strong></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Free Flow</td>
</tr>
<tr>
<td>B</td>
<td>Stable Flow, Unconstrained</td>
</tr>
<tr>
<td>C</td>
<td>Stable Flow, Interference</td>
</tr>
<tr>
<td>D</td>
<td>Stable Flow, Some Platooning</td>
</tr>
<tr>
<td>E</td>
<td>Unstable Flow, Queuing</td>
</tr>
<tr>
<td>F</td>
<td>Forced Flow, Poor Operation</td>
</tr>
<tr>
<td><strong>MAIN CBD STREET</strong></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Free Flow</td>
</tr>
<tr>
<td>B</td>
<td>Stable Flow Unconstrained</td>
</tr>
<tr>
<td>C</td>
<td>Stable Flow, Interference</td>
</tr>
<tr>
<td>D</td>
<td>Stable Flow, Some Platooning</td>
</tr>
<tr>
<td>E</td>
<td>Unstable Flow, Queuing</td>
</tr>
<tr>
<td>F</td>
<td>Forced Flow, Poor Operation</td>
</tr>
</tbody>
</table>

<sup>a</sup> Results in more than one-lane operation.
### TABLE A-3  Suggested bus passenger service volumes for planning purposes (hourly flow rates based on 50 seats per bus) (I)

<table>
<thead>
<tr>
<th>LEVEL OF SERVICE (STREET)</th>
<th>BUSES PER HOUR PER LANE</th>
<th>LEVEL OF SERVICE (PASSENGERS/SEAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A 0.00-0.50</td>
<td>B 0.51-0.75</td>
</tr>
<tr>
<td>URBAN ARTERIAL STREETS (PASSENGERS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 25 or less</td>
<td>625</td>
<td>940</td>
</tr>
<tr>
<td>B 26 to 45</td>
<td>1,125</td>
<td>1,690</td>
</tr>
<tr>
<td>C 46 to 80</td>
<td>2,000</td>
<td>3,000</td>
</tr>
<tr>
<td>D 81 to 105</td>
<td>2,625</td>
<td>3,940</td>
</tr>
<tr>
<td>E 106 to 135</td>
<td>3,375</td>
<td>5,060</td>
</tr>
<tr>
<td>CBD STREETS (PASSENGERS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 20 or less</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>B 21 to 40</td>
<td>1,000</td>
<td>1,500</td>
</tr>
<tr>
<td>C 41 to 60</td>
<td>1,500</td>
<td>2,250</td>
</tr>
<tr>
<td>D 61 to 80</td>
<td>2,000</td>
<td>3,000</td>
</tr>
<tr>
<td>E 81 to 100</td>
<td>2,500</td>
<td>3,750</td>
</tr>
</tbody>
</table>

Note: Ratio shown for level of service (passengers) is "passengers per seat" on average bus. Thus 1.00 means 50 passengers for the assumed 50 seats.
Values would be 6 percent higher for a 53-seat bus.
Values for articulated buses would be 15 to 20 percent greater.

### TABLE A-4  Suggested maximum and desired capacities for midtown Manhattan (8)

<table>
<thead>
<tr>
<th>Type of Operation</th>
<th>AM Maximum</th>
<th>AM Desired(1)</th>
<th>PM Maximum</th>
<th>PM Desired(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual bus lanes</td>
<td>200</td>
<td>180</td>
<td>180</td>
<td>150</td>
</tr>
<tr>
<td>Single bus lane with passing opportunities</td>
<td>120</td>
<td>90</td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>Single bus lane with no passing opportunities</td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>Buses in curb lane with mixed traffic</td>
<td>70</td>
<td>60</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>

(1) 90% of maximum

### TABLE A-5  Estimated peak-hour transit travel times by components (I5)

<table>
<thead>
<tr>
<th>Components</th>
<th>CBD</th>
<th>City</th>
<th>Suburbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving</td>
<td>5.50 ± 1.00</td>
<td>3.90 ± 0.30</td>
<td>3.00 ± 1.02</td>
</tr>
<tr>
<td>Passenger Stops</td>
<td>3.00 ± 1.00</td>
<td>1.20 ± 0.30</td>
<td>0.50 ± 0.10</td>
</tr>
<tr>
<td>Traffic Delay</td>
<td>3.00 ± 1.00</td>
<td>0.90 ± 0.30</td>
<td>0.70 ± 0.12</td>
</tr>
<tr>
<td>TOTAL</td>
<td>11.50 ± 3.00</td>
<td>6.00 ± 0.30</td>
<td>4.20 ± 0.30</td>
</tr>
</tbody>
</table>

(a) Values presented after ± are standard deviations.
<table>
<thead>
<tr>
<th>Time Per Stop (sec)</th>
<th>Stops per Mile</th>
<th>Without Traffic Delays</th>
<th>Central Business District 3.0 min/m delay</th>
<th>Central City 0.9 min/m delay</th>
<th>Suburban 0.7 min/m delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Travel Time (min/m)</td>
<td>Speed (mph)</td>
<td>Travel Time (min/m)</td>
<td>Speed (mph)</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>2.40</td>
<td>25.0</td>
<td>5.40</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.27</td>
<td>18.3</td>
<td>6.27</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4.30</td>
<td>14.0</td>
<td>7.30</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5.33</td>
<td>11.3</td>
<td>8.33</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.00</td>
<td>8.6</td>
<td>10.00</td>
<td>6.0</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>2.73</td>
<td>22.0</td>
<td>5.73</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.93</td>
<td>15.3</td>
<td>6.93</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5.30</td>
<td>11.3</td>
<td>8.30</td>
<td>7.2</td>
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<tr>
<td></td>
<td>8</td>
<td>6.67</td>
<td>9.0</td>
<td>9.97</td>
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<tr>
<td></td>
<td>10</td>
<td>8.67</td>
<td>6.9</td>
<td>11.67</td>
<td>5.1</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
<td>3.07</td>
<td>19.5</td>
<td>6.07</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.60</td>
<td>13.0</td>
<td>7.60</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6.30</td>
<td>4.5</td>
<td>9.30</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8.00</td>
<td>7.5</td>
<td>11.00</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10.33</td>
<td>5.8</td>
<td>13.33</td>
<td>4.5</td>
</tr>
</tbody>
</table>
A.2.3 Bus Volume Impacts

Bus speeds tend to decrease as the number of buses in a given lane increase, especially when buses are not able to leave the bus lane. A 1978 bus demonstration project along Hotel Street in Honolulu (17) revealed a drop in bus speeds as bus volumes increased (see Figure A-1). Hotel Street is a two-lane 36-ft-wide collector street that serves mixed traffic. Although there was only one moving lane each way, cars and commercial vehicles were able to pass one or two buses loading or unloading at stops.

Buses were metered into both directions of Hotel Street at flow rates of 60, 100, 138, and 150 buses per hour; however, only 100 to 120 buses could actually pass through the system. Bus capacity was estimated at 95 to 100 buses per hour each way at speeds of 2 to 3 mph. For flows of 60 buses per hour, speeds were approximately 5 mph with a decline of about 0.07 to 0.10 mph per bus for bus volumes exceeding 60 buses per hour.

The effects of bus-bus congestion also were addressed in a 1986 study of bus priority proposals in New York City (18). The results are summarized in Table A-7. Delay resulting from bus-bus congestion on Fifth Avenue (220 buses per hour, passing difficult) averaged 2.2 min per mile in the AM rush hour. Conversely, bus-bus congestion on Sixth Avenue (150 buses per hour, passing possible) was insignificant. Bus-bus congestion accounted for about 15 percent of the total travel time along Fifth Avenue and for less than 1 percent along Sixth Avenue.

A.2.4 Bus Lane Impacts

Several studies have documented the effectiveness of bus lanes in reducing travel times. The 1961 transit progress report (2) cited increases in peak-hour bus speeds of about 1.5 to 2.0 mph when bus lanes were designated. Results of a 1975 study, Bus Rapid Transit Options in Densely Developed Areas (19), illustrated in Figure A-2, demonstrate how time savings vary inversely with the preexisting bus speed (the slower the speed before the bus lane, the greater the time savings). These generalized relationships are shown in Figure A-3 for various kinds of bus priority treatments.

The Madison Avenue experience in New York City best illustrates the impacts of bus-bus-traffic interaction. Bus stops are provided for sets of bus routes at alternating locations, resulting in a skip-stop pattern of operations with considerable movement of buses into the second lane of the five-lane one-way street. Right turns from Madison Avenue resulted in serious weaving movements across the bus lane, and the curb lane was sometimes occupied by delivery and service vehicles. To alleviate the problems of slow bus speeds and poor reliability, dual bus lanes were installed between 42nd and 59th Streets in 1981. The lanes operate...
TABLE A-7  Bus travel times by component, Fifth and Sixth Avenues, New York City (18)

<table>
<thead>
<tr>
<th>Travel Time Component</th>
<th>Fifth Avenue A.M. Peak Period 86th St to 34th St.</th>
<th>Sixth Avenue P.M. Peak Period 4th St. to 59th St.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Volume Per Hour</td>
<td>220</td>
<td>150</td>
</tr>
<tr>
<td>Bus Passing Opportunities</td>
<td>Difficult</td>
<td>Possible</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Travel Time Component</th>
<th>Minutes/Mile</th>
<th>% of Total</th>
<th>Minutes/Mile</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running Time</td>
<td>8.1</td>
<td>53.9</td>
<td>6.0</td>
<td>51.1</td>
</tr>
<tr>
<td>Passenger Service</td>
<td>1.4</td>
<td>9.5</td>
<td>3.5</td>
<td>30.2</td>
</tr>
<tr>
<td>Traffic Signals</td>
<td>3.0</td>
<td>20.0</td>
<td>2.0</td>
<td>15.9</td>
</tr>
<tr>
<td>Right Turns/Traffic Congestion (1)</td>
<td>0.3</td>
<td>1.7</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Buses</td>
<td>2.2</td>
<td>14.9</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Total Travel Time</td>
<td>15.0</td>
<td>100.0</td>
<td>11.7</td>
<td>100.0</td>
</tr>
<tr>
<td>Bus Speed, mph</td>
<td>4.0</td>
<td></td>
<td>5.1</td>
<td></td>
</tr>
</tbody>
</table>

(1) Right turns on Fifth Avenue
Right turns plus Traffic Congestion on Sixth Avenue

Figure A-2. Time savings—central business district and arterial on-street priority treatments (15).
between 2:00 and 7:00 p.m., during which time right turns are prohibited along Madison Avenue. Figure A-4 illustrates current lane arrangements.

The travel time and reliability improvements resulting from the dual bus lanes were documented in a 1984 report, Madison Avenue Dual Exclusive Bus Lane Demonstration, New York City (20), and in a 1982 presentation to TRB (21). Bus peak-hour travel times declined 42 percent for express buses and 34 percent for local buses. Bus reliability increased 57 percent and non-bus traffic was not adversely affected by the high occupancy vehicle (HOV) facility. For the 5:00 to 6:00 p.m. peak hour, travel time coefficients of variation decreased from 42 to 24 percent for express buses. The number of buses per hour in the second lane ranged from 110 to 130, whereas the number of buses in the curb lane was about 45. Buses operated on approximately a three-block stop pattern.

A.3 SIMULATION STUDIES

Various simulation studies have been reported in the literature during the past several decades (22–28). These studies have been used to depict bus operations and to assess the impacts of various changes in traffic and bus operations. The more promising simulations include those associated with NETSIM, a microscopic simulation model whose ongoing development is being sponsored by FHWA. The simulation of downtown Ottawa, Ontario, Canada, bus lane operations with BLOSSIM (21) revealed that bus flow rates of 150 to 170 buses per hour can be achieved, depending on the strat-
A selected. Multiple-door channels on articulated buses, widespread use of passes, and the provision of right-turn lanes on the outside of bus lanes, with the availability of the adjacent lane for passing purposes, enable these flow rates to be achieved in what are essentially downtown bus lanes.

A.4 IMPLICATIONS

The literature review uncovered the available information on bus capacities, bus travel times keyed to traffic congestion and stopping, and the effects of removing other traffic from the bus lanes. The relationships of travel time to dwell time and stop frequency provide broad planning guidelines. Similarly, the observed time savings resulting from the installation of bus lanes provides information for the disaggregation of traffic-related delays.

Bus travel times by component of delay are presented in Figure A-5. This information was derived from Tables A-5 and A-6 and Figure A-3. Five sources of travel time or delay are identified:

- Time in motion;
- Time spent at stops (dwell time);
- Time spent at signals;
- Time spent at signals;

![Figure A-5. Bus lane travel times by time component.](source)
• Right-turn delays; and
• Traffic congestion/interference delays.

Two points are significant:

1. As indicated in previous analyses, the time saved by the installation of bus lanes is a function of how much congestion exists before the lanes are installed.

2. The contraflow curve is probably similar to the dual bus lane in performance. Note that it shows a difference up to 2 min under congested operations.

This information was used in developing more detailed travel time information for various types of single and dual bus lanes.
APPENDIX B

DWELL RANGE WINDOW APPROACH TO ESTIMATE SPEED

The bus speed relationships for buses operating in bus lanes are complex. Stop spacing and dwell times are two major factors that influence bus speed. The effect of traffic signal operations along the arterial also is significant. As bus flow rates increase, the effects of bus-bus interference, automobile turning across bus lanes, and the ability to use adjacent lanes further affect bus speed.

In much the same way that green bandwidths are adjusted to improve traffic progression, bus movement along an arterial can be affected by the signal system timing. Unlike other traffic, buses make numerous stops along the arterial to serve passengers. The interaction between stops for passengers and stops at traffic signals influence bus speed.

The following approach has been designed to assess this interaction. The benefits of the approach follow:

- Allows direct computation of bus speeds from a series of equations and associated tables;
- Permits a more precise determination of anticipated bus operational speeds under specific conditions where information on detailed traffic signal coordination patterns are available or can be estimated;
- Develops bus speed relationships as a function of bus stop spacing, dwell time at each stop, and traffic signal operations (cycle length, green time, and coordination pattern) and allows the values obtained to be adjusted for bus-bus interference as bus volumes increase; and
- Incorporates the ability of buses to execute a skip-stop pattern into the analyses.

Further discussion of these bus speed relationships, procedures for their use, comparisons with the general approach (Chapter 3), and some applications follow.

B.1 DWELL RANGE WINDOW CONCEPT

Signalized intersections usually are the primary causes of delay along an arterial street and a constraint in throughput capacity for all traffic. The system of traffic signals along an arterial have long been recognized as defining a green bandwidth for progression of traffic along the street. When evaluating bus lane operations, the system of signals along the arterial defines a characteristic “dwell range window” for each condition. The dwell range window concept defines three types of bus operations:

1. Buses arrive at bus stops to serve passengers, dwell into the red phase, and then proceed on the green phase toward the downstream stop. This represents dwell times within the dwell window and is depicted in the time-space diagram in Figure B-1.
2. Buses arrive on the green phase at bus stops to serve passengers and then may proceed on the green phase to the next stop downstream before the red phase on that signal cycle. This represents dwell times less than the lower extent of the dwell range window and is depicted in the time-space diagram in Figure B-2.
3. Buses arrive at a bus stop to serve passengers and dwell through the red phase and into the green phase before proceeding to the next downstream bus stop. This represents dwell times greater than the upper extent of the dwell range window and is depicted in the time-space diagram in Figure B-3.

The effect of signal operations along an arterial on bus operation stop spacing and dwell time conditions is discussed in the following sections.

B.2 BUS SPEED COMPUTATION PROCEDURES

A step-by-step computational procedure was developed for determining the probable average bus speed under specific arterial and bus operating conditions.

B.2.1 Step 1: Compute Basic Bus Speed and Dwell Range Window

The basic bus speed equation is as follows:

\[
\text{BUS SPEED} = \frac{d}{(C + o)} \quad (B-1)
\]

where:

- \( \text{BUS SPEED} \) = estimated average bus speed for specified segment, in feet per seconds or meters per second;
- \( d \) = distance between bus stops served, in feet or meters;
- \( C \) = signal cycle length, in seconds; and
- \( o \) = signal cycle offset to next signal, in seconds.

The basic bus speed is characteristic of the progression of a bus along an arterial that dwells into the red phase of the signal and then proceeds on the green phase (Type 1 operation).
This computed bus speed is applicable for bus dwell times that fall within the dwell range window defined by the following equations:

\[ D_U = C + o - t \]  
\[ D_L = g + o - t \]  

where:

\( D_U \) = maximum dwell time for buses to serve bus stop on red phase, in seconds;

\( D_L \) = minimum dwell time above which buses serve bus stop on red phase, in seconds;

\( C \) = signal cycle length, in seconds;

\( o \) = signal cycle offset to next signal, in seconds;

\( g \) = effective green per cycle (green plus clearance time amber, plus all red time less start-up lost time, in seconds per cycle); and

\( t \) = time to travel between bus stops, in seconds.

The time to travel between bus stops, \( t \), will be characteristic of the prevailing conditions of bus stop spacing. The time, \( t \), to start up from a stop, accelerate to cruise speed, and then decelerate to a stop at the next bus stop can be expressed by the following equations:

For \( d \leq \frac{V_c^2}{2a_1} + \frac{V_c^2}{2a_2} \):

\[ t = \left( V_c \right) + \left( \frac{d}{V_c} \right) + \left( \frac{V_c^2}{2a_2} \right) + LT \]  

\[ (B\text{-}3a) \]

For \( d > \frac{V_c^2}{2a_1} + \frac{V_c^2}{2a_2} \):

\[ t = \left( \frac{d}{a_1} \right)^{\frac{1}{2}} + \left( \frac{d}{a_2} \right)^{\frac{1}{2}} + LT \]  

\[ (B\text{-}3b) \]

where:

\( t \) = travel time between bus stops, in seconds

\( V_c \) = cruise speed, in feet per second

\( d \) = distance between stops, in feet

\( a_1 \) = acceleration rate, in feet per second\(^2\)

\( a_2 \) = deceleration rate, in feet per second\(^2\)

\( LT \) = startup lost time, in seconds.

The time, \( t \), also may be computed from the information in Column A of Table 3-3 in Chapter 3 by removing the time spent at bus stops. This leads to the following values, based on a 20 mph maximum cruise speed:

<table>
<thead>
<tr>
<th>Stops Per Mile</th>
<th>Total Travel Time Less Dwell (sec)</th>
<th>Time Between Stops, ( t ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>124</td>
<td>62</td>
</tr>
<tr>
<td>4</td>
<td>156</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>198</td>
<td>33</td>
</tr>
<tr>
<td>8</td>
<td>240</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>320</td>
<td>32</td>
</tr>
</tbody>
</table>

The dwell range window calculation is exact for near-side bus stops at the signalized intersection and approximate for midblock and far-side stops.

Computation of the dwell range window indicates the allowable variation in dwell time that will maintain the “serve passengers on the red and proceed on the green” progression.
for buses along the arterial. Transit agencies responding to the survey indicated that the predictability of bus speeds through bus lanes is nearly as important as the actual speed itself. Bus speed adjustment factors were developed for application to bus operations outside the dwell range window.

A nomograph was initially developed to represent the relationships described in the previous equations (Figure B-4). The nomograph was a useful tool for visualizing the relationships expressed in Equations B-1, B-2, and B-3 and for refining the dwell range window concept.

Legend:
- Red Phase (50/50 Split Shown)
- Green plus Clearance Phase

Figure B-2. Bus operations with dwell times less than the lower extent of the dwell range window ($D_L$).

Figure B-3. Bus operations with dwell times greater than the upper extent of the dwell range window ($D_U$).
Figure B-4. Refined basic bus speed relationships.
B.2.2 Step 2: Compute Dwell Range Adjustment Factor

The occurrence of bus stop dwell times that are less than or greater than the defined dwell range for a particular condition will affect the resulting average speed of buses in the bus lane. Multiple runs of TRAF-NETSIM on varying conditions were analyzed, which resulted in the relationships depicted in Figure B-5. These simulations incorporated zero dwell variation to isolate the dwell range relationship, as well as 40 percent and 62 percent dwell variations. Comparison of the simulations with the travel times obtained by the preceding equations resulted in the following adjustment factors, when bus speeds do not vary from the average (i.e., dwell variation = 0).

B.2.2.1 Step 2a: For $D < D_L$

Under these conditions, a sharp increase in bus speeds was evident when buses dwelled less than $D_L$, increasing to twice the speed calculated for that stopping spacing. The adjustment factor developed to represent this effect was as follows:

$$f_D = 2$$  \hspace{1cm} (B-4a)

where $f_D$ = dwell range adjustment factor.

B.2.2.2 Step 2b: For $D > D_U$

An equation was needed to represent the bus speed relationship when dwell times are greater than the upper limit of the dwell range ($D_U$). As depicted in the time-space diagram in Figure B-3, the condition $D > D_U$ causes buses to dwell into the green phase, delaying their travel to the next bus stop. Dwelling into the green phase may not initially affect the ability of the bus to reach the downstream bus stream within the signal cycle, unless dwell continues through the green phase into the next red phase. It is the additive effect of the $D > D_U$ condition that causes additional delays at the downtown bus stops. As bus volumes increase, the $D > D_U$ condition magnifies the bus-bus interference factor by delay-

Under most conditions, if a bus is able to serve its passengers and then proceed on the green, the bus most likely would be stopped at the next signal. For long cycle lengths and offsets and for short block spacings, it may be possible, although unlikely, for a bus to serve additional stops and continue to proceed on the green. The equation represents a reasonable estimation of the speed relationship in the range $D < D_L$. However, many factors affect the ability to attain these higher bus speeds under the $D < D_L$ condition.

Figure B-5. Bus speed adjustment for dwell range, dwell variation, and stop pattern.
ing subsequent bus service at the stop. The following equations were developed as speed adjustments for the condition $D > D_v$ represented in Figure B-5.

For $D_v \leq D \leq (D_v + g)$: 
\[ f_v = 1 - a \frac{(D - D_v)^{b}}{(g)} \]  
(B-4b)

For $(D_v + g) \leq D < (C + D_v)$: 
\[ f_v = 0.5 \]  
(B-4c)

where:

- $f_D = \text{dwell range adjustment factor}$
- $D_v = \text{dwell range upper limit, in seconds}$
- $D = \text{average dwell time, in seconds}$
- $C = \text{cycle length}$
- $g = \text{green + clearance time + all red per cycle}$
- $a = 0.5$
- $b = 1.5$.

These equations, as with Equation B-4a, are best-fit solutions to a complex set of considerations. The value $(D - D_v)$ represents the magnitude of dwelling into the green phase. When $D - D_v = g$, the bus is dwelling into the next red phase, and buses travel the distance between stops in two signal cycles, reducing the bus speed to 50 percent of that within the dwell range.

### B.2.2.3 Step 3: Compute Dwell Variation Adjustment Factor

Dwell time relationships are affected when dwell times vary for different buses at the same bus stop. Table B-1 presents the average bus speeds output from the simulation of a Type 1 bus lane with no dwell variation and with dwell coefficients of variation of 30 and 59 percent. For average dwell times near the middle of the dwell range, $(D_v + D_v)/2$, there is little or no effect on bus speeds. The dwell variation has its greatest effect for average dwell times near the extremes of the dwell range, $D_l$ and $D_u$. Thus, it is not the actual variation in dwell time that affects bus speeds, but how dwell variation results in dwell times beyond the dwell range window.

A set of adjustment factors were developed to represent the bus speed relationship as dwell time variations increase.

For $D < D_l$:
\[ f_v = 1 - \frac{D}{2} \left( \frac{D}{D_l} \right) \]  
(B-5a)

For $D_l < D < D_u$:
\[ f_v = 1 + \frac{D}{2} \left( \frac{D_u - D}{D_u - D_l} \right) \]  
(B-5b)

For $D_u < D < D_v$:
\[ f_v = 1 - \frac{D}{2} \left( \frac{D_v - D}{D_v - D_u} \right) \]  
(B-5c)

For $D < D_v$:
\[ f_v = 1 - \frac{D}{2} \left( \frac{D_v}{D} \right) \]  
(B-5d)

where:

- $f_v = \text{dwell variation adjustment factor}$
- $D_v = \text{coefficient of variation of average dwell time, percent/100}$
- $D_v = \text{dwell range lower limit, in seconds}$
- $D_u = \text{dwell range upper limit, in seconds}$
- $D_m = \text{midpoint of the dwell range window, in seconds = \sqrt[3]{(D_v + D_u)}}$
- $D = \text{average dwell time, in seconds}$.

In Equation B-5a, the greater the dwell variation, the more likely it is that there will be occurrences of dwell times greater than $D_l$. The closer the value of $D$ to $D_l$, the more likely it is that dwell variation will affect bus speeds.

In Equations B-5b and B-5c, the speed adjustments center about the midpoint of the dwell range, with the adjustment increasing from the midpoint depending on the magnitude of the variation. For low dwell variation, the impact on average speeds does not become significant until well beyond the midpoint of the dwell range and the necessary speed adjustment varies approximately as the square of the difference from the midpoint, increasing to a maximum value of approximately the decimal coefficient of variation of dwell time.

For high dwell variation, the speed adjustment varies approximately with the decimal coefficient of variation of dwell time and the speed adjustment approaches a straight line through the dwell range midpoint. The speed adjustment is positive for average dwell times approaching $D_u$, denoting the increased probability that dwell time will be less than $D_l$. Similarly, the speed adjustment is negative for average dwell times approaching $D_v$, denoting the increased probability that dwell time will be greater than $D_v$.

Equation B-5d decreases the effect of the dwell variation adjustment factor as the average dwell increases beyond $D_v$. Dwell variation impacts are of little importance because average dwells are much beyond the dwell range window.

Other adjustment factors to account for dwell variations, skip-stop bus patterns, right-turning vehicles, availability of the lane adjacent to the bus stop, and bus volumes and capacities, are described in Chapter 3. These factors are applicable to both the general and detailed procedures.

### B.3 COMPARISON OF GENERAL AND DETAILED APPROACHES

The following examples compare the results of the general and detailed approaches. They are based on a 500-ft block spacing (i.e., approximately 10 stops per mile) for a CBD curb bus lane, with bus stops every block.

#### B.3.1 Case 1

The average dwell time is 30 sec with a 20 percent coefficient of variation ($D_v$). The signals operate on a 70-sec cycle
TABLE B-1  Comparative analysis of simulated bus speeds for differing dwell time variations

<table>
<thead>
<tr>
<th>Condition</th>
<th>D = D_o - D</th>
<th>Dwell Variation</th>
<th>No Coefficient of Dwell Variation</th>
<th>11% Coefficient of Dwell Variation</th>
<th>33% Coefficient of Dwell Variation</th>
<th>66% Coefficient of Dwell Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D - D_o</td>
<td>Speed (mph)</td>
<td>Ratio Sim. Spd/ Comp. Speed</td>
<td>Speed (mph)</td>
<td>Ratio Sim. Spd/ Comp. Speed</td>
<td>Speed (mph)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Case 1)</td>
<td>(Case 4)</td>
<td>(Case 6)</td>
<td>(Case 21)</td>
</tr>
<tr>
<td>C = 100</td>
<td>-0.38</td>
<td>5.6</td>
<td>2.6</td>
<td>5.3</td>
<td>2.7</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.6</td>
<td>2.8</td>
<td>1.7</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Base Spd = 2.0</td>
<td>0.42</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>C = 100</td>
<td>-0.32</td>
<td>6.3</td>
<td>2.3</td>
<td>6.2</td>
<td>2.3</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
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<td></td>
<td></td>
<td></td>
<td>3.2</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Base Spd = 2.7</td>
<td>0.48</td>
<td>3.0</td>
<td>1.1</td>
<td>3.0</td>
<td>1.1</td>
<td>2.8</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>C = 90</td>
<td>-0.24</td>
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<td>2.0</td>
<td>5.6</td>
<td>1.9</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.6</td>
<td>1.9</td>
<td>5.9</td>
<td>1.9</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3.8</td>
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<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Base Spd = 3.0</td>
<td>0.64</td>
<td>3.2</td>
<td>1.1</td>
<td>3.2</td>
<td>1.1</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.1</td>
<td>2.9</td>
<td>1.0</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.7</td>
<td>2.7</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>C = 80</td>
<td>-0.23</td>
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<td>2.0</td>
<td>5.1</td>
<td>2.0</td>
<td>4.8</td>
</tr>
<tr>
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<td></td>
<td>5.1</td>
<td>2.0</td>
<td>4.8</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
<td>1.2</td>
<td>3.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Base Spd = 2.8</td>
<td>0.76</td>
<td>2.7</td>
<td>1.0</td>
<td>2.7</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>2.3</td>
<td>0.9</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>C = 40</td>
<td>0.24</td>
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<td>4.4</td>
<td>1.1</td>
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<td></td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Base Spd = 4.6</td>
<td>2.24</td>
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<td>0.8</td>
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<td>0.8</td>
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<td>2.0</td>
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</tr>
</tbody>
</table>
in a simultaneous pattern (i.e., 0-sec offset) with 40 sec of
green, clearance, and all red time.

**B.3.1.1 General Approach**

The general approach involves the use of Table 3-3. Column B is entered for a 30-sec dwell time with 10 stops per mile. The average speed is 4.9 mph. If there are no right-turn delays, Column E would be entered to find a 5.2 mph average speed.

**B.3.1.2 Detailed Approach**

The detailed approach assumes a 2-sec lost time and acceleration and deceleration rates of 4 ft/sec/sec. Equation B-1 is used to provide an initial estimate of bus speeds.

This speed applies to the dwell range window as defined by

\[
\begin{align*}
D_U &= C + 0 - t = 70 + 0 - t = 70 - t \\
D_L &= g + 0 - t = 40 + 0 - t = 40 - t \\
D_v &= 0.2
\end{align*}
\]

The value of \( t \) is obtained by applying Equation B-3a, assuming \( V_c = 25 \) mph:

\[
t = \frac{V_c}{2a} + \frac{d}{c + a} + \frac{V_c}{2a} + LT = \frac{(25)(5280)}{(3600)(2)(4)} + \frac{(500)(3600)}{(25)(5280)} + \frac{(25)(5280)}{(3600)(2)(4)} + 2 = 25
\]

Note that the values in Table 3-3, Column A, result in a 32-sec value, but are based on a 20 mph cruise speed. Substituting 25 sec for \( t \) in Equations B-2a and B-2b results in \( D_U = 45 \) sec and \( D_L = 15 \) sec. Thus, the dwell range window is 15 to 45 sec, compared with an average dwell time of 30 sec.

The 30-sec dwell time falls within the dwell range window; therefore, it is not necessary to compute the dwell range adjustment factor, \( f_D \). However, because of the 20 percent variation in average dwell times, the dwell variations and dwell range factor, \( f_v \), should be computed.

The average dwell time falls at the midpoint of the dwell range \( \frac{1}{2} (D_U + D_L) = 30 \) sec. Equations B-5b and B-5e result in \( f_v = 1 \); therefore, no adjustment is needed. Thus, there is no change in the average speed of 4.9 mph.

**B.3.2 Case 2**

This example is similar to Case 1, except that the cycle length is increased to 80 sec, with 40 sec of green plus clearance plus all red in the direction of bus flow.

**B.3.2.1 General Approach**

Table 3-3 gives the same speed as Case 1: 4.9 mph with right-turn delays included and 5.2 mph if there are no right turns.

**B.3.2.2 Detailed Approach**

The detailed approach again assumes a 2-sec lost time, 4 ft/sec/sec acceleration and deceleration rates, and a 25-sec cruise speed.

Equation B-1 provides an initial estimate of bus speeds. The increase in cycle length results in an initial estimate of bus speeds of 4.3 mph. (An increase in cycle length reduces the initial speed estimate.)

This speed applies to the dwell range window as defined by Equations B-2 and B-3. The value of \( t \) is 25 sec, similar to that for Case 1, because there is no change in block spacing and bus performance. Thus

\[
D_U = C + 0 - t = 80 + 0 - 25 = 55 \text{ sec} \\
D_L = g + 0 - t = 40 + 0 - 25 = 15 \text{ sec}
\]

The dwell window, therefore, is 15 to 55 sec, compared with a 30-sec average dwell. Again, no dwell range adjustment is needed. However, because of the 20 percent variation in dwell times \( D_v = 0.2 \) and the shifted dwell range window, the effects of dwell variation should be identified.

The midpoint of dwell range, \( D_{mD} \), is \( \frac{1}{2} \) \( (D_U + D_L) \) or 35 sec. This is greater than the average dwell time; therefore, Equation B-5b should be applied:

\[
f_v = 1 + \frac{(0.2)(35 - 30)}{(35 - 15)} = 1.03
\]

The adjusted bus speed, therefore, is 4.4 mph (i.e., \( 1.03 \times 4.3 \) mph). Again, this speed does not include the effects of right-turn delays.

**B.3.3 Case 3**

This case has the same characteristics as Case 1. However, the dwell time is increased to 45 sec, with a 20 percent dwell time variation.

**B.3.3.1 General Approach**

The average bus speeds are obtained from Table 3-3 by interpolation between the travel time rates.

<table>
<thead>
<tr>
<th>Travel Time (min/mi)</th>
<th>Without Right-Turn Delays</th>
<th>With Right-Turn Delays</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-sec dwell</td>
<td>14.00</td>
<td>13.20</td>
</tr>
<tr>
<td>50-sec dwell</td>
<td>15.67</td>
<td>14.87</td>
</tr>
<tr>
<td>Interpolation</td>
<td>14.84</td>
<td>14.04</td>
</tr>
<tr>
<td>for 45 sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed (mph)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ 45-sec dwell</td>
<td>4.0</td>
<td>4.3</td>
</tr>
</tbody>
</table>
B.3.3.2 Detailed Approach

The detailed approach is similar to Case 1. Equation B-1 gives a speed of 4.9 mph. Equations B-2a and B-2b give a dwell range window of where

\[ D_U = 45 \text{ sec} \quad \text{and} \quad D_L = 15 \text{ sec}. \]

The actual dwell time (45 sec) is at the upper limit of the dwell range. The 20 percent dwell coefficient of variation calls for estimating the dwell variation factor, \( f_v \). The midpoint of the dwell range \( (D_R) \) is 30 sec. Because \( D_R \), \( D_L \), Equation B-5c should be used:

\[ f_v = 1 - \frac{(0.2)(45 - 30)}{(2)(30 - 15)} = 0.9 \]

Thus, the adjusted speed is \((0.9)(4.9) = 4.4 \text{ mph}\). Further adjustments would be required to account for the effects of any right turns.

B.3.4 Case 4

In this case the detailed approach is used to estimate average bus speeds. This can be done by applying Equation 3-6 from Chapter 3:

\[
\text{BUS SPEED} = \left( \frac{d}{C + o} \right) f_D f_v f_s
\]

where:

\[ d = \text{distance between bus stops (at signalized intersections), in feet or meters} \]
\[ C = \text{cycle length, in seconds} \]
\[ o = \text{offset, in seconds} \]
\[ f_D = \text{dwell range window factor} \]
\[ f_v = \text{dwell time variation factor} \]
\[ f_s = \text{bus stop pattern factor for skip stops (Table 3-7)} \]
\[ f_b = \text{bus-bus interface factor (Table 3-3)}. \]

The first three factors are estimated from Equations B-1 through B-5. The other two factors are estimated as described in Chapter 3; however, they first require estimation of bus berth capacities and v/c ratios.

The equations in this appendix incorporate information on traffic signal timing, estimates of bus acceleration and deceleration rates and cruise speeds, and average dwell times and dwell time variations. This information may be used to minimize delay to bus passengers and as input for estimating and minimizing total person delay. A typical application involves changing the offsets, green time, and/or cycle lengths to improve bus and traffic flow. The following example illustrates how this detailed approach can be used.

B.3.4.1 Description

During the PM peak hour, 75 buses operate along a CBD arterial street bus lane and the three adjacent and general purpose lanes operate at capacity. The buses operate on a two-block alternating stop pattern, half of them stopping at each block. Average dwell time is 35 sec with a 60 percent coefficient of variation. The stops are located on the near side of each signalized intersection, 400 ft apart, and there are three berths at each stop. The traffic signals operate on a 70-sec cycle, with a 35-sec green plus amber plus all red phases and simulations offset in the direction of bus flow. Right turn–pedestrian conflicts are minimal.

The following traffic signal improvements are proposed:

- Increasing the cycle length from 70 sec to 80 sec (maintaining simultaneous offsets); and
- Adding an additional 10 sec per cycle to the green time for the bus lane street, resulting in a green plus amber plus all red of 45 sec (for a g/C of 56 percent).

It is desired to analyze how signal system changes will affect bus operations and determine what the transit agency can do to help improve conditions.

B.3.4.2 Solution: Existing Conditions

The solution involves first estimating existing capacity and then estimating existing bus speeds.

**Compute Existing Bus Berth Capacity.** The capacity of a bus berth can be estimated by applying Equation 2-10 from Chapter 2:

\[
C_b = \frac{(g/C)(3600)}{t_c + (g/C)D + Z_a C D}
\]

where:

\[ C_b = \text{berth capacity, buses per berth per hour} \]
\[ g/C = \text{green per cycle} = 0.5 \]
\[ t_c = \text{clearance time} = 15 \text{ sec} \]
\[ D = \text{average dwell time} = 35 \text{ sec} \]
\[ C_v = \text{coefficient of variation} = 0.6 \]
\[ Z_a = 0.675 \text{ for 25 percent failure at LOS E}. \]

The capacity at LOS E is completed as follows:

\[
C_b = \frac{(0.5)(3600)}{15 + (0.5)(35) + (0.675)(0.6)(35)} = 39 \text{ buses per berth per hour}
\]

(Note that interpolation on Table 2-5, Part B, in Chapter 2 also results in 39 buses per hour.) There are three berths at each stop, resulting in 2.25 effective berths. Therefore, the capacity of each stop is 88 buses. The combined capacity of the pair of stops is estimated as follows:

**Bus Lane Capacity** = \( f_K (CAP_1 + CAP_2) \)

The factor, \( f_K = 0.58 \), is obtained from Chapter 2, Table 2-15, for an adjacent lane v/c ratio of 1.0 and typical flow.
conditions. Thus, the combined capacity is $0.58(88 + 88) = 102$ buses. The bus v/c ratio is 75/102 or 74 percent.

**Estimate Existing Bus Speed.** The bus speed estimates are obtained by applying Equations B-1 through B-5 and then adjusting for use of the adjacent lane and the bus-bus interference. Equations B-1, B-2, and B-3, for an 800-ft distance between stops, give the following:

\[
D_U = \frac{(400)(2)}{(70 + 0)} = 7.8 \text{ mph}
\]

\[
t = \frac{(36.75)}{(2)(4)} + \frac{(400)(2)}{(36.75)} + \frac{(36.75)}{(2)(4)} + 2 = 33 \text{ sec}
\]

\[
D_v = 70 + 0 - 33 = 47 \text{ sec}
\]

\[
D_t = 35 + 0 - 33 = 2 \text{ sec}
\]

Because the dwell time falls within the dwell range window, there is no adjustment, \(f_D\), for dwell range. However, an adjustment, \(f_v\), for dwell variation is needed because of the 60 percent \(C_v\).

The midpoint of the dwell range, \(D_R\), is \((47 + 12)/2 = 29.5 \text{ sec}\). Equation B-5c is applied to estimate, \(f_v\), the dwell variation factor:

\[
f_v = 1 - \frac{(0.6)(35 - 24.5)}{(24.5 - 2)} = 0.86
\]

The bus-bus interference factor, \(f_b\), is obtained from Table 3-7 in Chapter 3. For a bus stop v/c ratio of 0.74, \(f_b\) is (by interpretation) determined to be 0.86.

The effects of traffic in the adjacent lane, \(f_s\), are estimated from Equation 3-2 or obtained directly from Table 3-5. For an adjacent lane v/c of 1.0 and a bus stop v/c ratio of 0.74, the factor, \(f_s\), (by interpretation) is 0.63.

The adjusted speed, therefore, becomes:

\[
\text{BUS SPEED} = \left(\frac{d}{c + a}\right)f_df_sf_bf_s = (7.8)(1.0)(0.86)(0.63)(0.86) = 4.0 \text{ mph}
\]

**B.3.4.3 Solution: Proposed Conditions**

The basic analyses steps are repeated for the proposed changes in traffic signal timing.

\[
C_b = \frac{(0.56)(3600)}{15 + (0.56)(35) + (0.675)(0.6)(35)} = 41 \text{ buses per berth per hour}
\]

The three berths at each stop translate into 2.25 effective berths. Thus, the capacity of each bus stop is 92 buses per hour. The combined capacity of the pair of stops is obtained by applying the factor, \(f_K\), to the sum of the capacities. For a v/c ratio of 1.0 with typical flow, \(f_K = 0.58\). Thus, the combined capacity of the bus lane is \((0.58)(2)(92) = 107 \text{ buses per hour}\). The bus v/c ratio is 75/107 or 70 percent.

**Estimate Bus Speed.** The bus speed estimate is obtained by applying Equations B-1 through B-3 and then making further adjustments.

The initial bus speed is 11.4 ft/sec = 7.8 mph. The upper and lower dwell windows are as follows:

\[
D_u = 80 + 0 - 33 = 47 \text{ sec}
\]

\[
D_t = 45 + 0 - 33 = 12 \text{ sec}
\]

The dwell range midpoint, \(D_R\), becomes \((47 + 12)/2 = 29.5 \text{ sec}\). Equation B-5c is applied to estimate, \(f_v\), the dwell variation factor:

\[
f_v = 1 - \frac{(0.6)(35 - 29.5)}{(29.5 - 12)} = 0.90
\]

The bus-bus interference factor, \(f_b\), is obtained from Table 3-7. The 70 percent bus-bus v/c ratio gives \(f_b = 0.89\).

The effect of traffic in the adjacent lane, \(f_s\), is obtained from Table 3-5 by interpolation (or by Equation 3-2). For an adjacent lane v/c of 1.0, \(f_s = 0.69\).

The adjusted bus speed becomes the following:

\[
\text{BUS SPEED} = (7.8)(1.0)(0.90)(0.67)(0.89) = 4.4 \text{ mph}
\]

The signal timing improvement gives automobiles approximately 10 percent more capacity and increases bus capacity about 5 percent. Bus speeds are increased by about 10 percent. However, the high volumes of adjacent lane traffic continues to inhibit the ability of buses to freely execute the skip-stop pattern and attain the associated higher speeds. Actions that reduce dwell times and dwell time variations may further improve both bus operating speed and capacity.
REFERENCES

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Abbreviations used without definitions in TRB publications:
- AASHO American Association of State Highway Officials
- AASHTO American Association of State Highway and Transportation Officials
- ASCE American Society of Civil Engineers
- ASME American Society of Mechanical Engineers
- ASTM American Society for Testing and Materials
- FAA Federal Aviation Administration
- FHWA Federal Highway Administration
- FRA Federal Railroad Administration
- FTA Federal Transit Administration
- IEEE Institute of Electrical and Electronics Engineers
- ITE Institute of Transportation Engineers
- NCHRP National Cooperative Highway Research Program
- NCTR National Cooperative Transit Research and Development Program
- NHTSA National Highway Traffic Safety Administration
- SAE Society of Automotive Engineers
- TCRP Transit Cooperative Research Program
- TRB Transportation Research Board
- U.S. DOT U.S. Department of Transportation