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TCRP Report 26

Operational Analysis of Bus Lanes on Arterials

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Report 26

Operational Analysis of Bus Lanes on Arterials

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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.

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The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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FOREWORD

*By Staff
Transportation Research
Board*

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.

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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.

	HCM	Simulation
2 berths to 1 berth	1.75	1.83
3 berths to 1 berth	2.25	2.43

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.

	HCM Table 12-17 (%)	Suggested Revision (%)
LOS A \leq	1	1
LOS B \leq	2.5	2.5
LOS C \leq	10	7.5
LOS D \leq	20	15
LOS E \leq	30	25

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:

Adjacent Lane v/c Ratio	Adjustment Factor
0.0	0.88
0.5	0.84
0.8	0.71
1.0	0.58

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

TABLE S-1 Suggested speed-related level of service criteria for buses on arterial roads and streets

LEVEL OF SERVICE	HCM CRITERIA FOR ARTERIAL CLASS III (25-35 MPH FREE FLOW SPEED)		CBD STREETS (> 7 STOPS/MI)		URBAN ARTERIALS (4 TO 7 STOPS/MI)		SUBURBAN ARTERIALS (1 TO 3 STOPS/MI)	
	min/mi	mi/hr	min/mi	mi/hr	min/mi	mi/hr	min/mi	mi/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	≤7.6	≥7.9
E	≤8.57	≥7.0	≤18.0	≥3.3	≤12.4	≥4.7	≤10.0	≥6.0
F	>8.57	<7.0	>18.0	<3.3	>12.9	<4.7	>10.0	<6.0

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:

	Traffic Signal Delay Only		Traffic Signal Right-Turn Delay	
	Travel Time (min/mi)	Bus Speed (mph)	Travel Time (min/mi)	Bus Speed (mph)
6 stops/mi				
20-min dwell	6.50	9.2	7.30	8.2
40-min dwell	8.50	7.1	9.30	6.5
8 stops/mi				
20-min dwell	6.87	7.6	8.67	6.9
40-min dwell	10.52	5.7	11.33	5.3

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

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:

Bus Berth v/c Ratio	Speed Reduction Factor
< 0.5	1.00
0.8	0.81
0.9	0.70
1.0	0.55

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

STEP 1**Identify Basic Parameters:**

- Type of Bus Lane
- Bus Stop Pattern
- Existing Traffic Signal Timing (Cycle Lengths, Green Time, Offsets)
- Existing Dwell Times
- Bus and Traffic Volumes
- Number of Bus Berths

STEP 2**Estimate Bus Lane Capacities (Chapter 2):**

- 2-1 Develop Basic Capacity Estimates
 - Stop Capacity – Equation 3-10
 - Effective Berths (Table 2-3)
- 2-2 Apply Adjustment Factors
 - A. Adjacent Lane Availability, Stop Pattern (Equation 2-12 or Tables 2-14, 2-15)
 - B. Right Turn Impacts (Equation 2-13 or Table 2-17)
 - C. Compute Refined Capacity (Equation 2-14)
- 2-3 Compute Volume, Capacity Ratio For Bus Lane
- 2-4 Compute Level of Service (Table 2-9)

STEP 3**Estimate Bus Speeds* (Chapter 3):**

- 3-1 Estimate Basic Bus Speed (Table 3-3)
- 3-2 Apply Adjustment Factors
 - A. Adjacent Lane Availability/Stop Pattern (Table 3-5)
 - B. Bus Bus Interference (Table 3-3)
 - C. Estimate Refined Speeds
- 3-3 Estimate "Flow" Level of Service (Table 3-1)

* Speeds may be measured

Figure 1-1. Bus lane capacity and speed analysis steps.

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 of a bus berth under uninterrupted flow conditions stem from the basic equation:

$$C_b = \frac{3600}{h} \quad (2-1)$$

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:

$$C_b = \frac{3600}{t_c + D} \quad (2-2)$$

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:

$$C_b = \frac{3600}{t_c + D + ZS_D} \quad (2-3)$$

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.

$$C_b = \frac{3600R}{t_c + D} \quad (2-4)$$

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:

$$C_b = \frac{(g/C)3600R}{t_c + (g/C)D} \quad (2-5)$$

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:

$$C_B = \frac{(g/C)3600RN_b}{t_c + (g/C)D} \quad (2-6)$$

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:

Ratio to Single Berth	HCM Table 12-19	Simulation
1	1.00	1.00
2	1.75	1.83
3	2.25	2.43
4	2.45	NA
5	2.50	NA

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

TABLE 2-1 Bus volumes processed from TRAF-NETSIM simulation (400-ft block spacing, 80-sec cycle length, three bus berths, no dwell time variation)

<u>CONDITION</u>	<u>DWELL TIME</u>	<u>MAXIMUM NUMBER OF BUSES PROCESSED (1)</u>
Type I Bus Lane	10	210
Single Lane with No Passing	20	144
1 Block Stops	30	132
	40	132
	50	122
	60	108
Type II Bus Lane	10	220
Single Lane with Passing	20	216
2 Block Skip Stops	30	216
No traffic in adjacent lane	40	192
	50	184
	60	164
Type III Bus Lane	10	220
Dual Lane	20	220
2 Block Skip Stops	30	208
	40	200
	50	180
	60	176

- (1) Maximum number of buses processed as an indicator of capacity was considered to have been reached when average bus speed dropped by more than 20 percent and buses served becomes notably less than buses input. For Type I buses, the time when the capacity of the bus stop was exceeded, between 5 and 10 minutes per hour (10 to 15 %), also coincided with the point of apparent capacity. For Type II and III bus lanes, buses processed includes buses not stopping at the bus stop.

formula (shown in Equation 2-6). Figure 2-1 compares one-berth, two-berth, and three-berth capacities obtained from the formula and from simulation, assuming zero dwell time variation. Figure 2-2 compares three-berth capacities assuming 0 percent, 33 percent, and 59 percent dwell time variations in the simulation.

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 vari-

ability. 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:

$$\text{Unsignalized} \quad C_b = \frac{3600}{t_c} + (D + Z_a + S_D) \quad (2-7)$$

$$\text{Signalized} \quad C_b = \frac{(g/C)3600}{t_c + g/C(D) + Z_a S_D} \quad (2-8)$$

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_a = 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

TABLE 2-2 Comparative analysis of bus lane capacities for Type 1 bus lane with differing numbers of berths per stop

CONDITION	1 BERTH STOP	2 BERTH STOP	RATIO TO 1 BERTH	3 BERTH STOP	RATIO TO 1 BERTH
	BUS LANE	BUS LANE		BUS LANE	
	CAPACITY *	CAPACITY *		CAPACITY *	
	(Case 2b)	(Case 2a)		(Case 1)	
TYPE I BUS LANE:					
C=100, L=300, D=10	98	170	1.73	206	2.10
D=20	65	120	1.85	154	2.37
D=30	65	98	1.51	118	1.82
D=40	36	72	2.00	106	2.94
D=50	36	72	2.00	106	2.94
D=60	36	72	2.00	100	2.78
C=100, L=400, D=10	98	172	1.76	214	2.18
D=20	65	120	1.85	156	2.40
D=30	65	98	1.51	118	1.82
D=40	36	72	2.00	106	2.94
D=50	36	74	2.06	106	2.94
D=60	36	72	2.00	100	2.78
C=90, L=300, D=10	96	152	1.58	198	2.06
D=20	70	114	1.63	140	2.00
D=30	70	82	1.17	124	1.77
D=40	40	92	2.30	118	2.95
D=50	40	82	2.05	116	2.90
D=60	40	78	1.95	98	2.45
C=90, L=400, D=10	96	170	1.77	206	2.15
D=20	58	114	1.97	140	2.41
D=30	58	84	1.45	128	2.21
D=40	40	88	2.20	118	2.95
D=50	40	80	2.00	118	2.95
D=60	40	80	2.00	114	2.85
C=80, L=300, D=10	98	170	1.73	198	2.02
D=20	65	116	1.78	144	2.22
D=30	44	88	2.00	132	3.00
D=40	44	90	2.05	132	3.00
D=50	44	86	1.95	118	2.68
D=60	44	82	1.86	106	2.41
C=70, L=300, D=10	98	178	1.82	188	1.92
D=20	80	106	1.33	160	2.00
D=30	45	108	2.40	154	3.42
D=40	45	98	2.18	140	3.11
D=50	45	92	2.04	110	2.44
D=60	45	72	1.60	78	1.73
C=60, L=300, D=10	98	170	1.73	196	2.00
D=20	60	124	2.07	180	3.00
D=30	60	116	1.93	170	2.83
D=40	58	108	1.86	130	2.24
D=50	58	86	1.48	96	1.66
D=60	43	74	1.72	90	2.09
C=50, L=300, D=10	116	146	1.26	220	1.90
D=20	65	142	2.18	208	3.20
D=30	65	134	2.06	162	2.49
D=40	65	100	1.54	112	1.72
D=50	50	80	1.60	108	2.16
D=60	48	70	1.46	102	2.13
		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

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.

$$\text{Unsignalized } C_b = \frac{3600}{t_c + D + Z_a C_v D} \quad (2-9)$$

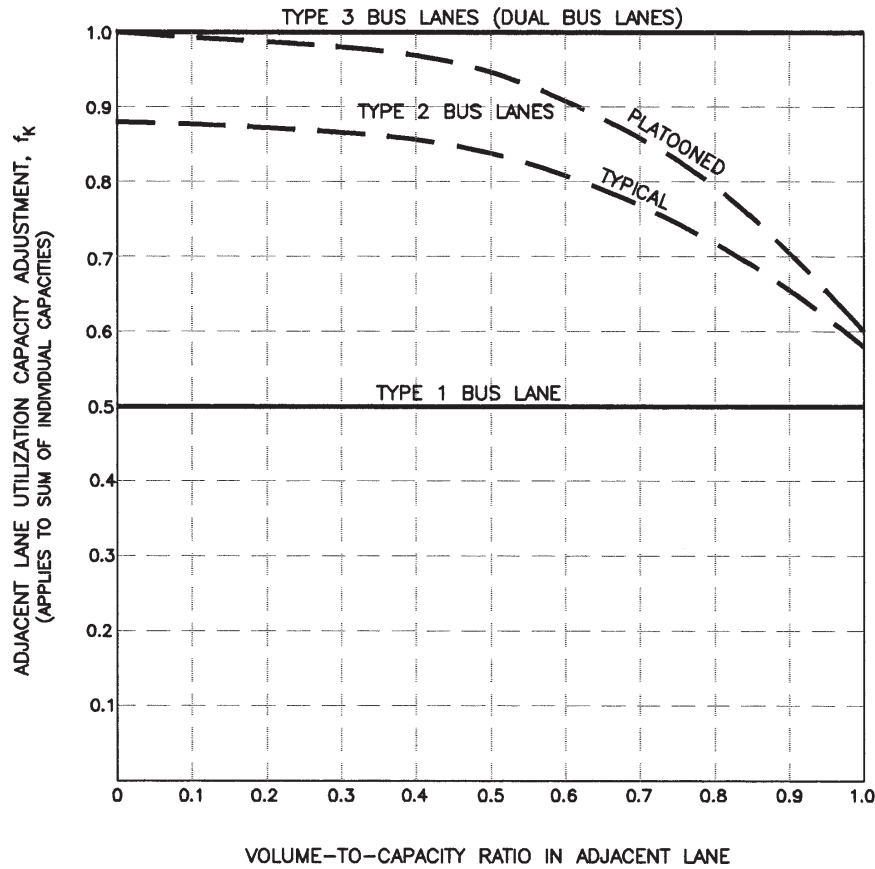


Figure 2-1. Capacity adjustment factors for availability of adjacent lane (alternate two-block stops).

$$\text{Signalized} \quad C_b = \frac{(g/C)3600}{t_c + (g/C)D + Z_a C_v D} \quad (2-10)$$

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.

2.3.1 Dwell Time Variations

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.

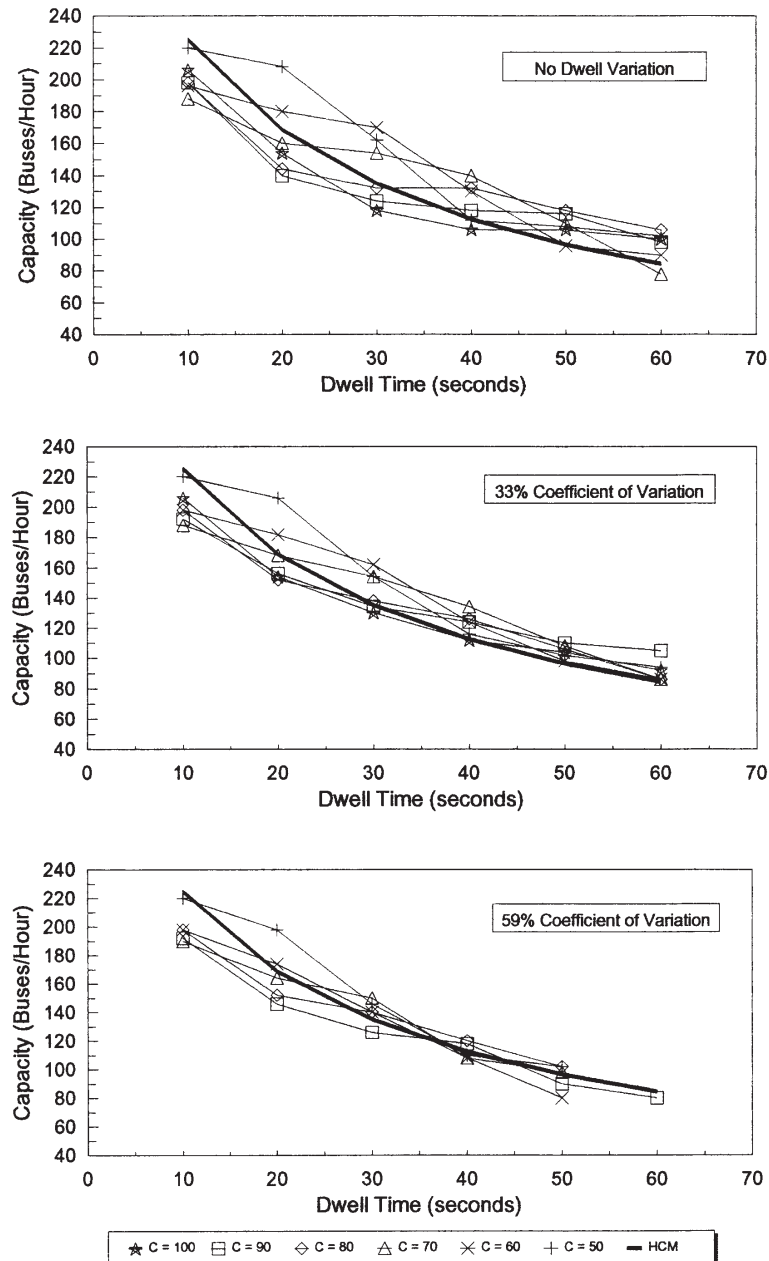


Figure 2-2. Simulated capacities and HCM-computed capacities for Type 1 bus lane (three bus berths per stop).

- 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

TABLE 2-3 Values of percent failure and associated one-tail normal variate, Z_a

FAILURE	Z
1.0%	2.330
2.5%	1.960
5.0%	1.645
7.5%	1.440
10.0%	1.280
15.0%	1.040
20.0%	0.840
25.0%	0.675
30.0%	0.525
50.0%	0.000

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 form-

ing 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.

TABLE 2-4 Observed dwell time variations—Houston, Texas

Peak Movement	Buses per Hour	Average Bus Speed	Dwell Time Sample		
			Average (Seconds)	Standard Deviation	Coefficient of Variation (%)
Milam, AM	100	4.48 mph	32.8	26.2	81.7
Travis, PM	100	4.86mph	26.0	18.9	72.9
NM Main, AM	68	3.62mph	18.4	11.0	59.8
SB Main, PM	70	4.61mph	25.6	27.4	100.7
Louisiana, PM	100	4.90mph	31.2	18.6	59.6

Source: WSA Field Studies, reported in the NCHRP 55-A Interim Report, May 1993.

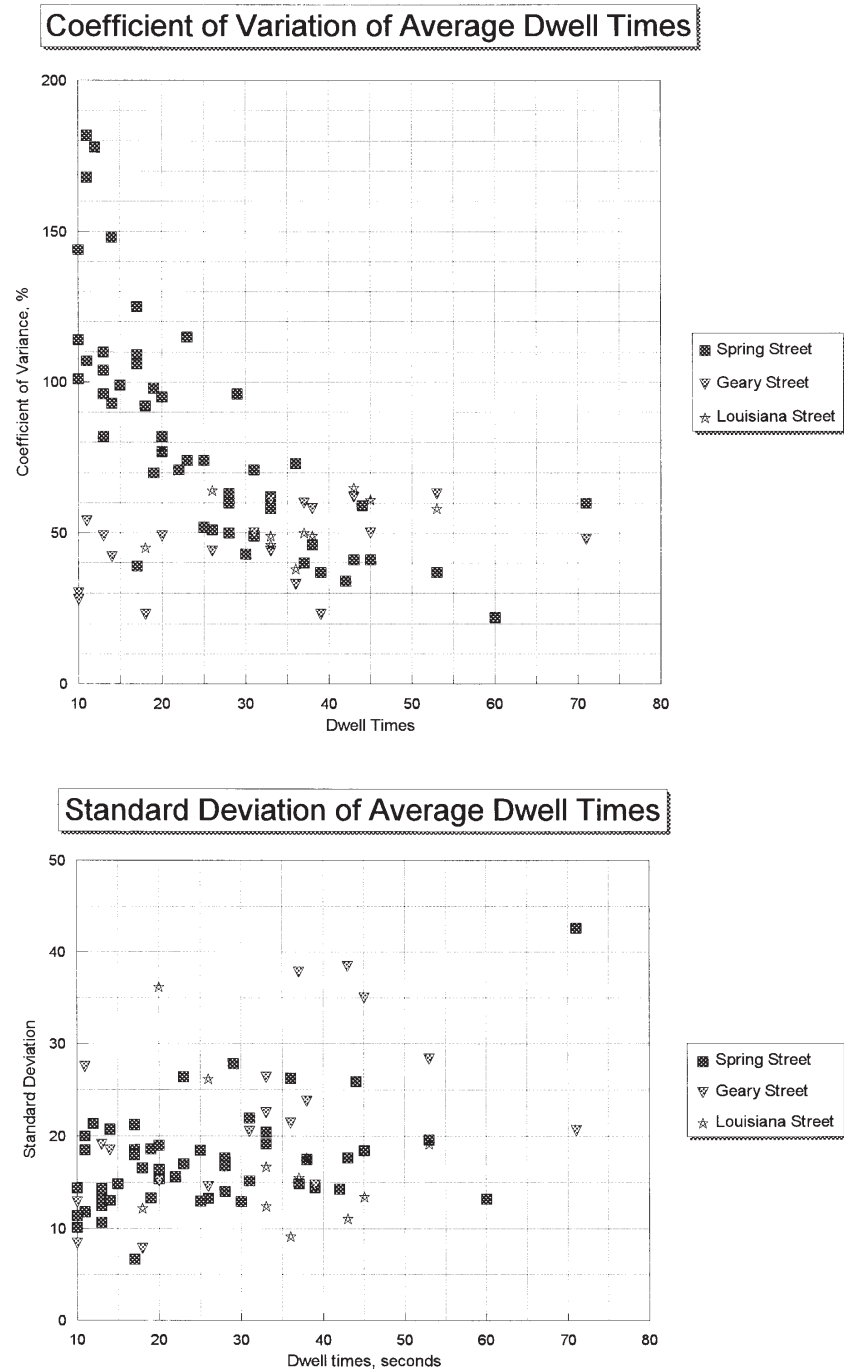


Figure 2-3. Observed bus dwell time variations.

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.

TABLE 2-5 Bus berth capacity, C_b (buses per berth per hour)

Failure Rate	A. UNINTERRUPTED FLOW					
	Average Dwell Time, Seconds					
	10	20	30	40	50	60
1.0%	92	57	41	32	27	23
2.5%	98	62	45	35	29	25
5.0%	103	66	48	38	31	27
7.5%	107	69	51	40	33	28
10%	110	71	56	45	37	32
15%	145	76	56	45	37	32
20%	120	78	60	48	40	34
25%	124	84	63	55	42	36
30%	128	87	66	53	45	38
50%	144	103	80	65	55	48
Failure Rate	B. SIGNALIZED WITH GREEN/CYCLE = 0.5					
	Average Dwell Time, Seconds					
	10	20	30	40	50	60
1.0%	53	34	25	20	16	14
2.5%	57	37	28	22	18	16
5.0%	60	40	30	24	20	17
7.5%	63	43	32	26	27	19
10%	65	45	34	27	23	20
15%	69	48	37	30	25	22
20%	72	51	40	33	28	24
25%	75	54	43	35	30	26
30%	78	58	46	38	32	28
50%	90	72	60	51	45	40

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

Dwell Time (Sec)	g/C = 0.5		g/C = 1.0	
	HCM	Table 2-5	HCM	Table 2-5
15	67	66	100	104
30	50	46	67	66
45	40	35	50	49
60	33	28	40	38
75	28	24	33	32
90	25	20	28	27
105	22	18	25	24
120	20	18??	22	21

- 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

TABLE 2-7 Comparison of berth capacities using HCM Table 12-18 and Equation 2-10 for various failure rates (C_v = coefficient of variation)

Failure Rate (Approximate Percent of Time Queues Form Behind Bus Stop)	HCM Table 12-18	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: $t_c = 15$ seconds
 $D = 60$ seconds
 $g/C = 0.5$

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 2-8 Possible modifications to HCM level of service criteria for bus berths

	Failure Rate	
	HCM Table 12-17	Suggested Revision
LOS A \leq	1.0%	1.0%
LOS B \leq	2.5%	2.5%
LOS C \leq	10%	7.5%
LOS D \leq	20%	15%
LOS E \leq	30%	25%

TABLE 2-9 Estimated bus v/c ratios as bus stop level of service criteria for capacity at LOS E and MAX LOS (assumes $C_v = 0.6$, $t_c = 5$ sec/clearance)

		A - Uninterrupted Flow - g/C = 1.0													
Suggested Level of Service	Approx. Percent of Failure	Average Dwell Time, Seconds												Suggested Indices (Rounded) (1)	
		10"		20"		30"		40"		50"		60"			
		Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max (1)	Ratio to E
A	1.0	0.64	0.74	0.55	0.68	0.51	0.65	0.49	0.64	0.49	0.63	0.48	0.63	.55	.65
B	2.5	0.68	0.79	0.60	0.73	0.56	0.71	0.54	0.69	0.53	0.60	0.52	0.69	.60	.70
C	7.5	0.74	0.86	0.67	0.82	0.64	0.81	0.62	0.79	0.60	0.78	0.58	0.77	.65	.80
D	15.0	0.80	0.93	0.74	0.89	0.70	0.89	0.69	0.89	0.67	0.88	0.67	0.88	.75	.90
E	25.0	0.86	1.00	0.82	1.00	0.79	1.00	0.78	1.00	0.76	1.00	0.75	1.00	.80	1.00
MAX	50.0	1.00		1.00		1.00		1.00		1.00		1.00		1.00	
		B - Interrupted Flow - g/C = 0.5													
Suggested Level of Service	Approx. Percent of Failure	Average Dwell Time, Seconds												Suggested Indices (Rounded)	
		10"		20"		30"		40"		50"		60"			
		Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E	Ratio to Max	Ratio to E
A	1.0	0.59	0.71	0.47	0.63	0.42	0.58	0.39	0.57	0.36	0.54	0.35	0.53	.45	.60
B	2.5	0.63	0.76	0.51	0.69	0.47	0.65	0.43	0.63	0.40	0.69	0.40	0.60	.50	.65
C	7.5	0.70	0.84	0.60	0.80	0.53	0.74	0.51	0.74	0.47	0.72	0.47	0.71	.55	.70
D	15.0	0.77	0.92	0.67	0.89	0.62	0.86	0.59	0.86	0.56	0.84	0.55	0.84	.65	.85
E	25.0	0.83	1.00	0.75	1.00	0.72	1.00	0.69	1.00	0.67	1.00	0.65	1.00	.72	1.00
Max	>	1.00		1.00		1.00		1.00		1.00		1.00		1.00	

(1) These are similar to the values for "R" in the HCM, Chapter 12.

TABLE 2-10 Observed bus use of adjacent traffic lanes in PM peak hour

Location:		Vehicles Per Hour			% in Adjacent Lane
		Curb Lane	Adjacent Lane	Total	
New York City Fifth Ave. (48th Street)	Buses	36	160	196	82
	Other vehicles	24	220	244	
	Total	60	380	440	
	Sixth Ave. (45th Street)				86
	Buses	14	84	98	
	Other vehicles	22	392	414	
Houston Louisiana St.⁽¹⁾	Total	36	476	522	29
	Buses	115	48	163	
	Other vehicles	165	315	645	
	Total	270	363	633	

(1) 45-minute expanded to one hour

SOURCE: WSA Field Studies in Houston
(11) New York City

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

1980 ESTIMATED VEHICLE DISTRIBUTION (INCLUDING BUSES)				
	Before Dual Lanes		After Dual Lanes	
	No. of Vehicles	%	No. of Vehicles	%
LANE 1	0	0.0	82	5.8
LANE 2	144	11.0	508	36.1
LANE 3	602	46.0	627	44.6
LANE 4	523	40.0	155 B	11.0
LANE 5	39	3.0	35 B	2.5
	1308	100.0	1407	100.0

ESTIMATED BUS DISTRIBUTION				
	Before Dual Lanes		After Dual Lanes	
	No. of Buses	%	No. of Buses	%
LANE 1	0	0.0	0	0.0
LANE 2	0	0.0	0	0.0
LANE 3	15*	7.5	0	0.0
LANE 4	146*	73.0	155	83.5
LANE 5	39	19.5	35	17.5
	200	100.0	200	100.0

B = buses

* = estimated

Note: Bus Lane in Lane 5 Before and Lane 4 After.

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

Local Buses			
	Before	After	Percent Change
Time	17.8	10.7	-39.9
Standard Deviation	4.6	1.9	-58.7
Coefficient of Variation	26%	18%	-30.8
Express Buses			
Time	17.8	8.9	-50%
Standard Deviation	6.3	2.8	-55%
Coefficient of Variation	35%	31%	-11.4%

TABLE 2-13 Summary of simulation bus volumes processed with varying adjacent lane volumes (400-ft block spacing, 80-sec cycle length, alternating two-block stop operations)

Dwell Time sec	Adjacent Lane Traffic Volume veh/hr	Adjacent Lane v/c Ratio	Max. Number of Buses Processed buses/hr	Index of Bus Capacity	Index to Type 1 Bus Capacity
20	0	0	240	1	1.52
20	100	0.14	238	0.99	1.51
20	200	0.29	240	1	1.52
20	300	0.43	240	1	1.52
20	400	0.57	232	0.97	1.47
20	500	0.71	206	0.86	1.30
20	600	0.86	198	0.82	1.25
20	700	1	186	0.77	1.18
20	Type 1, stop every block		158	0.66	1.00
40	0	0	180	1	1.45
40	100	0.14	178	0.99	1.44
40	200	0.29	162	0.9	1.31
40	300	0.43	162	0.9	1.31
40	400	0.57	162	0.9	1.31
40	500	0.71	158	0.88	1.27
40	600	0.86	154	0.86	1.24
40	700	1	154	0.86	1.24
40	Type 1, stop every block		124	0.67	1.00

- 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:

$$C_c = (C_1 + C_2 + \dots C_n)f_k \quad (2-11)$$

where:

$C_1, C_2, \dots C_n$ = capacities of the individual bus stops in the sequence

C_c = combined capacities

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

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

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-

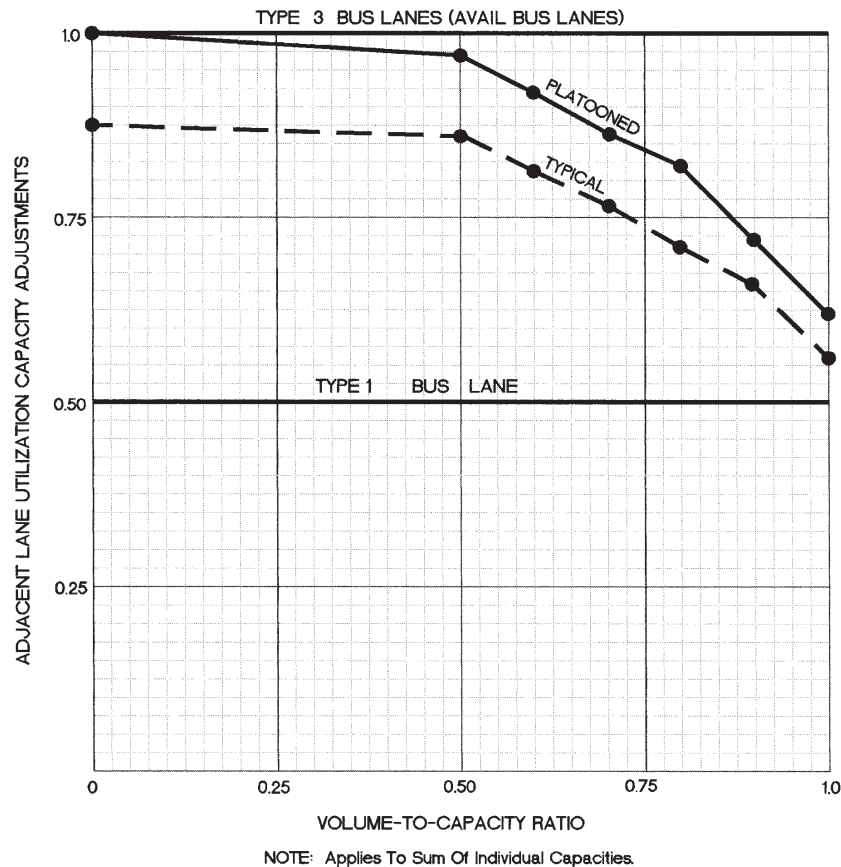


Figure 2-4. Capacity adjustment factors for available adjacent lane (alternate-block stops).

fic 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 (v_R/c_R).

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 impeditive 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, v_R/c_R 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, f_R , may be estimated from the following equation:

$$f_R = 1 - L_B \left(\frac{v_R}{c_R} \right) \quad (2-13)$$

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:

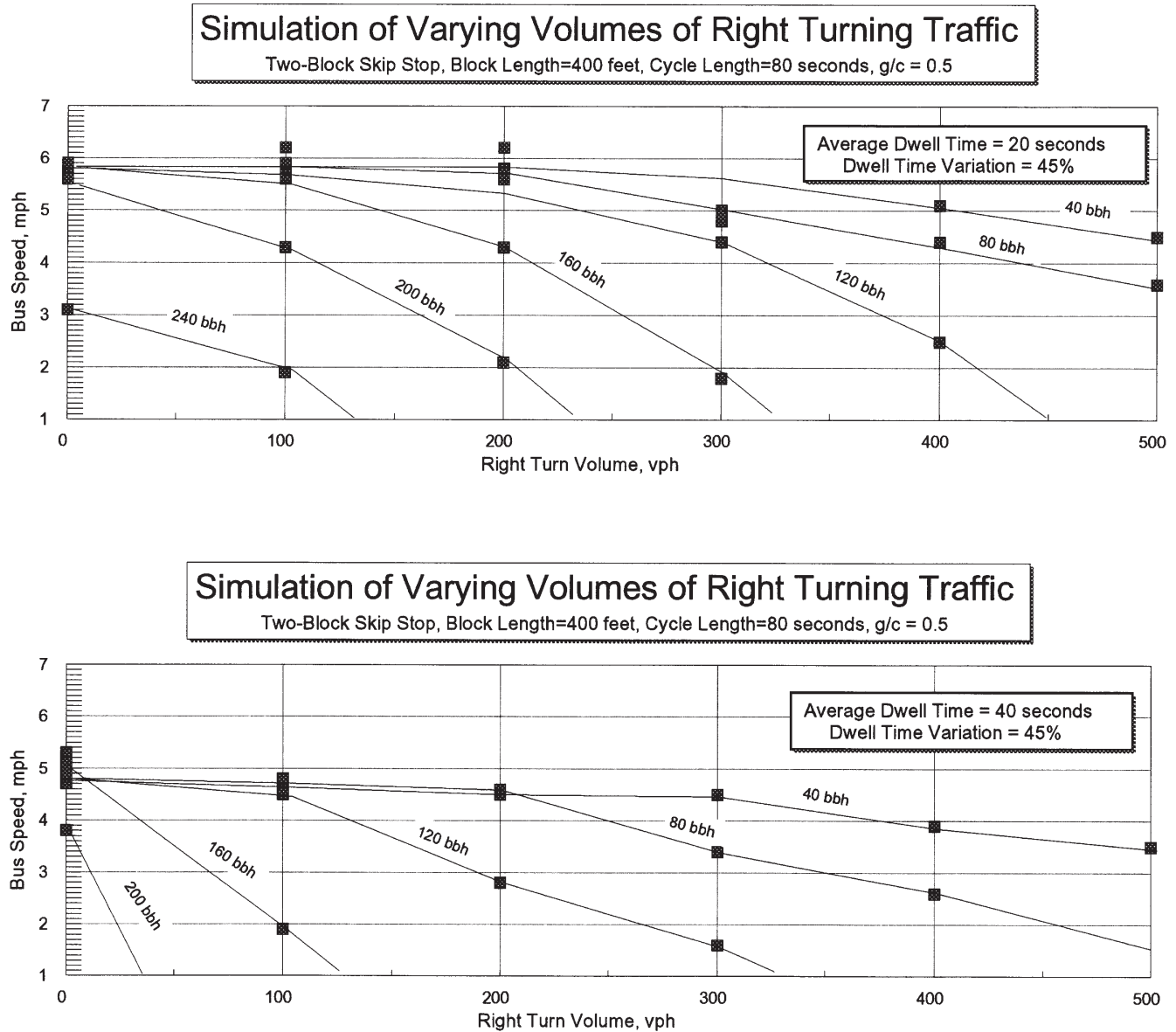


Figure 2-5. Simulations of varying volumes of right-turning traffic.

- 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)

$$CAP = C_b N_b f_R \quad (2-14a)$$

Adjusted Bus Lane Capacity (Skip Stop)

$$CAP = f_K (CAP_1 + CAP_2 + \dots + CAP_n) \quad (2-14b)$$

where:

- C_b = capacity of a bus berth (Equation 2-10)
- N_b = number of effective berths at bus stop (HCM Table 12-19)

TABLE 2-14 Effect of right turns on saturation flow

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

(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.

f_K = capacity adjustment factor for skip-stop operations (Equation 2-12)

f_R = capacity adjustment factor for right turns (Equation 2-13)

CAP_n = 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)

TABLE 2-15 Right-turn v/c ratio for 50 percent g/C ratio

Parallel Pedestrian Volume (Pedestrians/Hour)	Capacity With 50% Green ⁽¹⁾ g/c = 0.5	RIGHT TURN VOLUME TO CAPACITY RATIO			
		Right Turns per Hour			
		100	200	300	400
0	720	0.14	0.28	0.42	0.56
50	700	0.14	0.29	0.43	0.57
100	680	0.15	0.29	0.44	0.59
200	640	0.16	0.31	0.47	0.62
300	600	0.17	0.33	0.50	0.67
400	560	0.18	0.36	0.54	0.71
800	400	0.25	0.50	0.75	1.00
1200	240	0.42	0.83	*	*
1500	100	1.00	*	*	*

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

* Exceeds capacity

TABLE 2-16 Suggested bus stop location factors

Type of Bus Stop	Type of Bus Lane		
	Normal Flow Bus Lanes		Dual Bus Lanes
	Type 1	Type 2	Type 3
Near Side	1.0	0.9	n/a
Midblock	0.9	0.7	n/a
Far Side	0.8	0.5	n/a

Note: Not applicable for dual bus lanes or contra-flow bus lanes or median bus lanes

SOURCE: Estimated

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 impeding 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:

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

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:

$$N_p = \frac{N_s - 1}{N_s} v_b \left(\frac{v_b}{c_b} \right)^3 \quad (2-16)$$

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_b developed herein.

New York City

The three-block skip-stop pattern on Manhattan Avenue resulted in about three-quarters (± 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.

CHAPTER 3

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 operations. 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, min-

utes 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.

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	mi/hr	min/mi	mi/hr	min/mi	mi/hr	min/mi	mi/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	≤7.6	≥7.9
E	≤8.57	≥7.0	≤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

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, TRAF-NETSIM, 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 3-2 Variations in central business district peak-hour bus speeds in bus lanes

City	Location	Time	Ave. Speed (mph)	Standard Deviation	Coefficient of Variation (percent)
PM Peak Hour					
Houston	Milam St.	4:30-5:30PM	5.7	1.0	18%
	Travis St.	4:30-5:30PM	5.0	1.1	22%
	Main St. (SB)	4:45-5:45PM	5.1	1.2	24%
	Main St. (NB)	4:15-5:15PM	5.2	1.0	20%
	Louisiana St.	4:30-5:30PM	5.4	1.5	28%
Chicago	Madison St.	5:00-6:00PM	6.8	1.8	26%
Los Angeles	Spring St.	4:30-5:30PM	6.1	1.0	16%
New York City	Madison Ave. (Before Dual Bus Lanes)	5:00-6:00PM	2.4	N/A	26% ^a
	Madison Ave. (After Dual Bus Lanes)	5:00-6:00PM	4.8	N/A	18% ^a
San Francisco	Geary St.	5:00-6:00PM	4.3	1.1	25%
AM Peak Hour					
Houston	Milam St.	7:00-8:00AM	4.4	0.7	16%
	Main St. (SB)	7:15-8:15AM	5.5	1.1	20%
	Main St. (NB)	7:30-8:30AM	3.8	1.3	34%
	Louisiana St.	7:30-8:30AM	6.0	1.0	17%

^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 stop near-side at each block
- Bus routes distributed into two alternating two-block stop patterns.

TABLE 3-3 Bus travel times and speeds as a function of stop spacing, dwell time, and traffic signal and right-turn delays

		BUS LANES ONLY (without any traffic or signal delays)		SINGLE NORMAL FLOW BUS LANES (Includes signal and right turn delays)						DUAL OR CONTRA- FLOW BUS LANES (Includes signal delay)	
		(A)		(B)		(C)		(D)		(E)	
Dwell Time per Stop (sec.)	Stops Per Mile	Travel Time (min/mile)	Speed (mph)	Central Bus. District (Delay = 2.0 min./mile)		Central City (Delay = 0.6 min./mile)		Suburbs (Delay = 0.5 min./mile)		Central Bus. District (Delay = 1.2 min./mile)	
				Travel Time (min/mile)	Speed (mph)	Travel Time (min/mile)	Speed (mph)	Travel Time (min/mile)	Speed (mph)	Travel Time (min/mile)	Speed (mph)
10	2	2.40	25.0	4.40	13.6	3.00	20.0	2.90	20.7	3.60	16.3
	4	3.27	18.3	5.27	11.4	3.87	15.5	3.77	15.9	4.47	13.4
	6	4.30	14.0	6.37	9.4	4.90	12.2	4.80	12.5	5.50	10.4
	8	5.33	11.3	7.33	8.2	5.93	10.1	5.83	10.3	6.53	9.2
	10	7.00	8.6	9.00	6.7	7.60	7.8	7.50	7.1	8.20	7.3
20	2	2.73	22.0	4.23	12.7	3.33	18.0	3.23	18.6	3.93	15.3
	4	3.93	15.3	5.93	10.1	4.53	13.2	4.43	13.5	5.13	11.7
	6	5.30	11.3	7.30	8.2	5.90	10.2	5.80	10.3	6.50	9.2
	8	6.67	9.0	8.67	6.9	7.27	8.3	7.17	8.4	7.87	7.6
	10	8.67	6.9	10.67	5.6	9.27	6.5	9.17	6.5	9.87	6.1
30	2	3.07	19.5	5.07	11.8	3.67	16.3	3.57	16.8	4.27	14.0
	4	4.60	13.0	5.60	10.7	5.20	11.5	5.10	11.8	5.80	10.3
	6	6.30	9.5	8.30	7.2	6.80	8.4	6.70	9.0	7.50	8.0
	8	8.00	7.5	10.00	6.0	8.60	7.0	8.50	7.0	9.20	6.5
	10	10.33	5.8	12.33	4.9	10.93	5.5	10.83	5.5	11.53	5.2
40	2	3.40	17.6	5.40	11.1	4.00	15.0	3.90	15.4	4.60	13.0
	4	5.26	11.4	7.26	8.3	5.86	10.2	5.76	10.4	6.46	9.3
	6	7.30	8.2	9.30	6.5	7.90	7.6	7.80	7.7	8.50	7.1
	8	9.33	6.4	11.33	5.3	9.93	6.0	9.83	6.1	10.52	5.7
	10	12.00	5.0	14.00	4.3	12.60	4.8	12.50	4.8	13.20	4.5
50	2	3.74	16.0	5.74	10.5	4.34	13.8	4.24	14.2	4.94	12.1
	4	5.92	10.1	7.92	7.6	6.52	9.2	6.42	9.3	7.12	8.4
	6	8.30	7.2	10.30	5.8	8.90	6.7	8.80	6.8	9.50	6.3
	8	10.67	5.6	12.67	4.7	11.27	5.3	11.17	5.4	11.87	5.1
	10	13.67	4.4	15.67	3.8	14.27	4.2	14.17	4.2	14.87	4.0
60	2	4.07	14.7	6.07	9.9	4.67	12.8	4.57	13.1	5.27	11.4
	4	6.58	9.1	8.58	7.0	7.18	8.4	7.08	8.5	7.78	7.7
	6	9.30	6.5	11.30	5.3	9.90	6.1	9.80	6.1	10.50	5.7
	8	12.00	5.0	14.00	4.3	12.60	4.8	12.50	4.8	13.20	4.5
	10	15.33	3.9	17.33	3.5	15.93	3.8	15.83	3.8	16.53	3.6

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 3-4 Comparisons of initial bus speed relationships—Louisiana Street, Houston, Texas

Time Period	No. of Buses	Average Dwell Time	Average Observed Speed	Estimated Bus Speed		
				General Approach (Table 3-11)	Detailed Approach ⁽¹⁾	
					Basic Bus Speed for Dwell Window	Bus Speed Adjusted for Dwell Variation
4:00-4:15 PM	20	24 seconds	5.6 MPH	6.4 MPH	5.6 MPH	6.2 MPH
4:15-4:30 PM	21	21 seconds	6.0 MPH	6.5 MPH	5.6 MPH	6.5 MPH
4:30-4:45 PM	22	31 seconds	5.5 MPH	5.9 MPH	5.6 MPH	5.5 MPH
4:45-5:00 PM	25	31 seconds	4.6 MPH	5.9 MPH	5.6 MPH	5.6 MPH
5:00-5:15 PM	26	36 seconds	4.4 MPH	5.6 MPH	5.6 MPH	5.2 MPH
5:15-5:30 PM	25	29 seconds	5.1 MPH	6.1 MPH	5.6 MPH	4.9 MPH
5:30-6:00 PM	16	29 seconds	5.6 MPH	6.1 MPH	5.6 MPH	5.5 MPH

⁽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.

$$f_s = 1 - \left(\frac{d_1}{d_2} \right) \left(\frac{v}{c} \right)^2 \left(\frac{v_B}{c_B} \right) \quad (3-1)$$

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

TABLE 3-5 Suggested values of adjustment factor, f_s , for the effect of adjacent lane traffic on bus speeds for two-block skip-stop operations

Auto Volume-to-Capacity Ratio in Adjacent Lane	Bus Volume-To-Capacity Ratio			
	0.0	0.5	0.8	1.0
0.0	1.00	1.00	1.00	1.00
0.2	1.00	0.99	0.98	0.98
0.5	1.00	0.96	0.90	0.87
0.8	1.00	0.84	0.74	0.68
1.0	1.00	0.75	0.60	0.50

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 TRAF-NETSIM 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 3-6 Speed index values from TRAF-NETSIM simulation (400-ft block spacing; 80-sec cycle, 50 percent green time; 40-sec dwell time, 33 percent dwell time coefficient of variation)

Input Bus Volume	Type 1 1 Block Stops	Type 2 2 Block Skip-Stop
40	1.00	0.90
60	0.94	1.00
80	0.94	1.00
100	0.91	1.00
120	0.88	0.97
140	0.54	1.00
160		0.90
180		0.88
200		0.43
200		0.29

SOURCE: Simulations

Note: Speed Index represents ratio of speed to highest speed for the set of conditions.

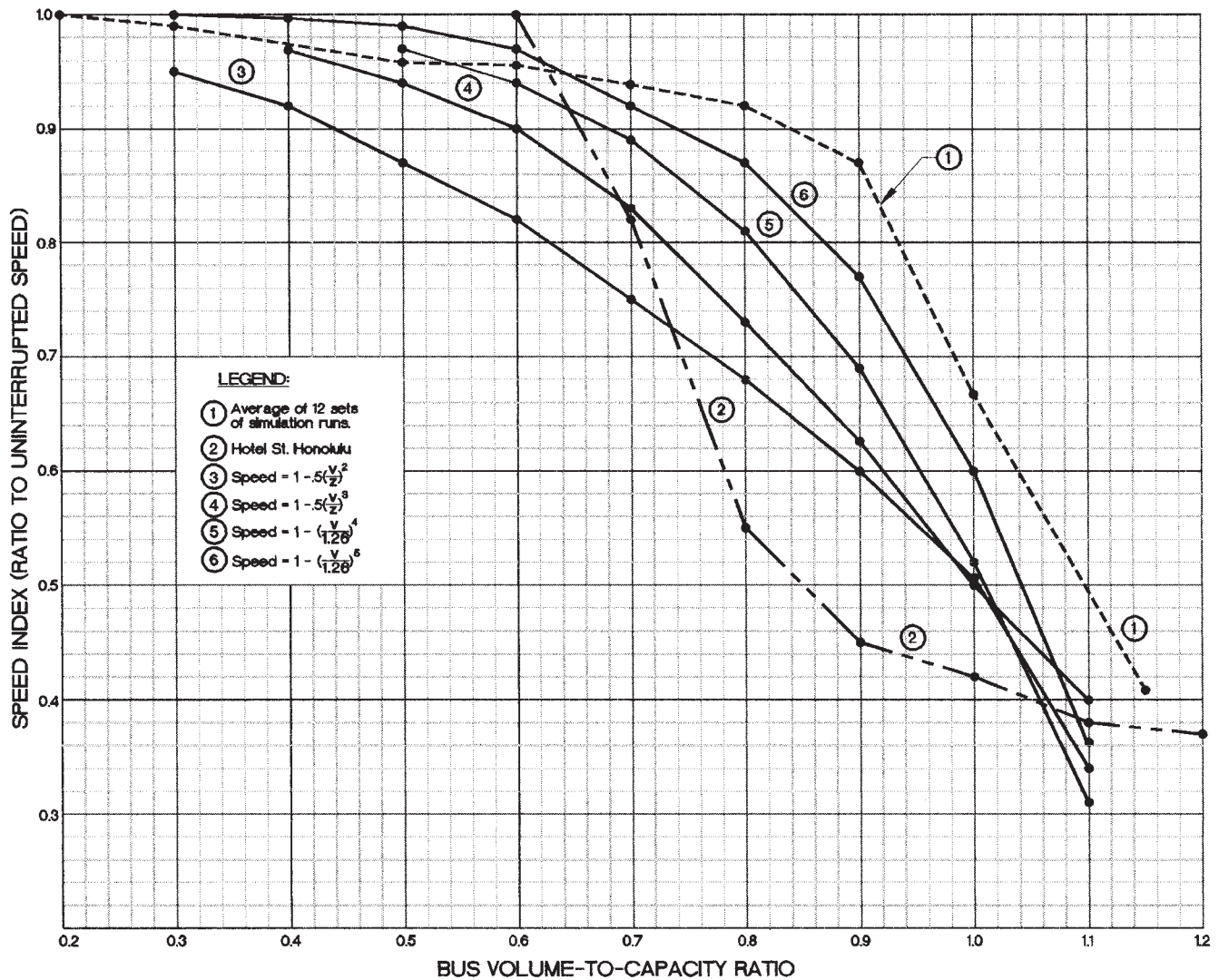


Figure 3-1. Estimated effects of increasing bus volumes on bus speeds.

TABLE 3-7 Suggested speed reduction factors for bus-bus interference, f_B

Bus Berth Volume-to Capacity Ratio	Index (Speed reduction factor)
< 0.5	1.00
0.5	0.97
0.6	0.94
0.7	0.89
0.8	0.81
0.9	0.69
1.0	0.52
1.1	0.35

Source: Compiled from computer simulations

Index represents normalized ratio of simulated speed for that condition to the highest speed condition (at 50% or less of capacity).

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 (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.

TABLE 3-8 Simulated right turns per hour for various speed reductions for skip-stop operations (400-ft block spacing; 80-sec cycle, 50 percent g/C; two-block skip stop; 45 percent dwell time variation)

	20-sec Dwell				40-sec Dwell			
Percent Speed Reduction	10	15	20	25	10	15	20	25
Buses Per Hour ^a	Right Turns Per Hour				Right Turns Per Hour			
40	330	390	450	500	280	340	400	450
80	300	340	380	420	200	230	250	260
120	220	250	280	300	110	130	140	160
150	156	190	210		20	30	10	50

^a Half of the buses would stop at each block

SOURCE: Simulations

3.3.4.1 General Approach

Bus speeds can be estimated by the following equation:

$$\text{BUS SPEED} = V_o f_s f_b \quad (3-2)$$

where:

V_o = speed from Table 3-3

f_b = bus-bus interference factor from Table 3-7

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:

$$\text{BUS SPEED} = \left(\frac{d}{C} + o \right) f_D f_V f_S f_b \quad (3-3)$$

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).

TABLE 3-9 Characteristics of bus lane sites analyzed

Item	Spring Street Los Angeles	Geary Street San Francisco	Louisiana Street Houston	Madison Street Chicago
Type of Bus Lane	Type 1 Contra Flow No Passing	Type 2 Normal Flow	Type 2 Normal Flow	Type 2 Normal Flow
Length of Bus Lane	0.86 mile	0.36 mile	0.25 mile	0.30 mile
Bus Stops	7	3	4	2
Bus Stops per mile	8	8	16	7
Observation Periods	3:00-7:00 PM	3:00-6:00 PM	4:00-6:00 PM	3:00-6:00 PM
Buses/Hour	40-60	16-20	84-102	26-48
Average Dwell Time per stop	18-45 seconds	41-58 seconds	21-36 seconds	13-37 seconds
Number of Traffic Signals	12	4	4	4
Average Bus Speeds	6.0-7.6 mph	3.9-5.1 mph	4.4-6.0 mph	6.2-7.8 mph

SOURCE: Field Studies

TABLE 3-10 Comparisons of predicted and observed speeds

Location	Measured (MPH)	Predicted (MPH)	
		General Approach Table 3.3	Detailed Approach Appendix B- Equation 3-6
Time Period: 4:00 - 4:30 P.M.			
Geary Street	5.5	5.0	6.0
Spring Street	6.1	6.5	5.3
Madison Street	7.8	6.8	n/a
Louisiana Street	5.8	5.7	5.6
Time Period: 4:30 - 5:00 P.M.			
Geary Street	4.8	4.5	5.0
Spring Street	6.6	6.3	6.1
Madison Street	6.5	5.9	n/a
Louisiana Street	5.0	4.5	4.4

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.