CHAPTER **4**

EXAMPLES OF RESEARCH APPLICATIONS

This chapter contains examples of procedures for applying the research findings. A series of examples illustrate how bus capacities and speed can be estimated. In these examples, bus and car volumes are assumed as the flow rates based on the peak 15 min.

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

4.1.1 Description

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

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

4.1.2 Solution

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

4.1.2.1 Compute Bus Berth Capacity

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

4.1.2.2 Estimate Bus Speeds

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

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

4.2.1 Description

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

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

4.2.2 Solution

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

4.2.2.1 Compute Bus Berth Capacity

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

$$C_b = \frac{g/C\,(3600)}{t_c + (g/C)D + Z_a C_V D}$$

where:

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

Thus,

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

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

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

$$f_R = 1 - L_B\left(\frac{v_R}{c_R}\right) = 1 - 1(0.123) = 0.877$$

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

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

4.2.2.2 Estimate Bus Speeds

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

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

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

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

4.3 EXAMPLE 3: TYPE 2 BUS LANE WITH SKIP STOPS

4.3.1 Description

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

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

4.3.2 Solution

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

4.3.2.1 Compute Bus Berth Capacity

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

Bus Lane Capacity (CAP) = $C_b\, N_b f_R$

where:

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

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

Bus Lane Capacity (CAP) = $f_k\,(\mathrm{CAP}_A + \mathrm{CAP}_B)$

where f_K = capacity adjustment for skip-stop operations.

The basic capacities, C_b, are obtained from Table 2-5, Part B, assuming a 25 percent failure rate:

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

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

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

$$f_R = 1 - L_B \frac{v_R}{c_R} = 1 - L_B(0.36)$$

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

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

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

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

$$\text{Bus Lane Capacity (CAP)} = f_K\,(\text{CAP}_A + \text{CAP}_B) = (0.71)(82 + 97) = 127 \text{ buses}$$

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

- Stop A $= \dfrac{50}{(82)(0.71)} = 0.86\%$

- Stop B $= \dfrac{50}{(77)(0.71)} = 0.73\%$

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

4.3.2.2 Estimate Bus Speeds

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

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

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

$$\text{BUS SPEED} = V_0 f_S f_b$$

where:

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

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

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

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

4.4.1 Description

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

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

4.4.2 Solution

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

4.4.2.1 Compute Bus Berth Capacity

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

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

4.4.2.2 Estimate Bus Speeds

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

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

4.5 EXAMPLE 5: ESTIMATE ARTERIAL BUS LANE SPEEDS

4.5.1 Description

Buses operating in a curb bus lane along an urban arterial roadway stop every ¼ mi with 15-sec average dwell times. Within the CBD, buses stop every block (⅛ mi) with a 40-sec dwell time. Approximately 30 buses use the lane in the peak hour. Two bus berths are provided at each bus stop in the CBD, and one berth is provided at stops elsewhere.

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

4.5.2 Solution

The solution represents a straightforward application of Table 3-3. Because bus volumes are low relative to berth capacities, adjustments for bus-bus interference are not necessary. Using Table 3-3, for four stops per mile and interpolating between the dwell time values for 10 and 20 sec (13.2 mph and 15.5 mph), the average speed of buses along the arterial is estimated at 14.3 mph (4.2 min/mi). From the level of service criteria presented in Table 3-1, this speed corresponds to LOS A for the urban arterial bus lane. Similarly, from Table 3-3, it is determined that buses passing through the CBD would have an average speed of 5.3 mph (11.3 min/mi). From Table 3-1, this speed corresponds to LOS C. Thus, the LOS drops from A to C when proceeding through the CBD. The total trip time (one-way) is estimated to be (9 mi x 4.2 min/mile) + (1 mi × 11.33 min/mi) = 49.1 min. The average overall speed is 12.2 mph.

4.6 ADDITIONAL APPLICATIONS

The procedures can be applied to assess the following:

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

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

CHAPTER **5**

INTERPRETATION, APPRAISAL, AND IMPLICATIONS

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

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

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

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

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

5.1 SPEED AS A FLOW LEVEL OF SERVICE CRITERIA

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

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

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

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

5.2 EFFECTS OF ADJACENT LANES

Bus speeds are determined by how frequently bus stops are placed, how long buses dwell at each stop, traffic conditions along the route, and whether buses can pass and overtake one another. The primary benefit of having the adjacent lane available for buses is the ability to adopt skip-stop service patterns with alternate groups of buses stopping at alternate stops. In this manner, stops for each route can be spread further apart, thus increasing average bus speeds. Designation of dual bus lanes and the prohibition of right turns for a two-block skip-stop pattern can virtually double average bus speeds and nearly double route capacities. However, if buses must share the adjacent lane with other traffic, speed and capacity gains are less whenever the adjacent lane operates at or near its capacity. In addition, the availability of the adjacent lane enables buses to pass errant, stalled, or delayed vehicles without crossing barriers or going into an opposing traffic stream.

Such bus service and stopping patterns, however, must be tempered by the existing route structure, block spacings, and passenger demand. Overconcentration of passenger boardings tend to increase dwell times, thereby potentially reducing anticipated gains in speed and capacity. Thus, in practice, opportunities for skip stops may be limited. From a bus speed perspective, lengthening the distance between stops throughout the urban area may prove beneficial.

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

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

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

5.3 POTENTIAL MODIFICATIONS TO THE HCM

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

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

5.3.1 Overview of Suggested Changes

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

5.3.2 Specific Modifications to Chapter 12

The following modifications to Chapter 12 should be considered.

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

$$C_b = \frac{(g/C)3600\,R}{t_c + (g/C)D} \tag{5-1}$$

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

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

$$C_b = \frac{(g/C)3600}{t_c + (g/C)D + Z_a S_D} \tag{5-2}$$

where:

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

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

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

Level of Service	Approximate Probability of Queues Forming Behind Bus Stop	
	1985 HCM	Suggested Modification
A	1	1
B	2.5	2.5
C	10	75
D	20	15
E (Capacity)	30	25
E (Perfect Conditions Capacity)	50	50

3. *Revise the Effects of Spreading Stops* (presented on p. 12-30 of the HCM). Three conditions should be addressed and pertinent values indicated.
   a. *Where buses have complete use of the adjacent lane.* The current wording suggests a doubling of capacity if stops are spread across two alternating bus stops. The research indicates that a doubling would only occur if the bus arrivals were platooned in

advance and there was little or no traffic in the adjacent lanes and no change in dwell times. Thus, some downward adjustments may be needed to account for arrivals that are purely random and, more typically, partially platooned.

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

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

4. *Incorporate the Effects of Right Turns*. It also may be desirable to include reductive factors for the effect of right turns on bus flow in Chapter 12.
5. *Expand/Modify Problems*. If the revised capacity and/or level of service criteria are adopted, they may require changes in pp. 12–19 through 12–28 of the HCM as well as changes in many of the problems on pp. 12–39 through 12–47.
6. *Include Bus Speeds*. A section on bus lane speeds and speed-based levels of service should be added to Chapter 9 and/or Chapter 12. The additions should include (1) bus-speed-related level of service criteria and (2) basic tables showing bus speed values for Table 3-3 and relevant adjustment factors.
7. *Include Detailed Travel Time Equations*. The dwell range window concept appears to help in understanding the effects of the traffic signal system on bus speeds under typical bus lane conditions. This material may be applicable to Chapters 9 and 11 as well as to Chapter 12 and could be included in an appendix to either chapter.

5.3.3 Specific Modifications to Chapter 9

The following modification to Chapter 9 should be considered:

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

5.4 SERVICE PLANNING GUIDELINES

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

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

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

5.5 RESEARCH POSSIBILITIES

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

Traffic signals account for several minutes per mile delay to buses in exclusive lanes. Some of this delay might be reduced if the signals were timed to minimize total person delay, rather than vehicle delay. Further research on the interaction between buses and traffic signals is desirable. Simulation could be used to analyze the effects of bus advances and extension (or preemption) on bus and auto travel times. The objective is to minimize total person delay, while maintaining the integrity of overall signal system coordination.

APPENDIX A
LITERATURE REVIEW

A review was made of the available literature pertaining to bus flows, bus capacities, bus travel times, and their interactions. This information provides an important resource for traffic and transit professionals.

A.1 BUS FLOW AND CAPACITY

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

A.1.1 Observed Flows and Capacities

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

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

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

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

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

A.1.2 Capacity Formulas

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

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

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

These earlier formulas were modified in the 1985 HCM to include the effects of the effective green time per cycle ratio and the variability of bus arrivals at stops, two factors that

TABLE A-1 Observed peak-hour bus passenger volumes on urban arterial roadways in the United States and Canada, 1972–1990

City and Location	Buses/Hour In Peak Direction	Passengers/Hour In Peak Direction	Passengers /Bus
Bus-Only Streets:			
Portland, OR (Mall) - 5th Avenue (dual lanes)*	167	8,300	50
Portland, OR (Mall) - 4th Avenue (dual lanes)*	175	8,500	50
Chicago - State Street Transitway-south bound	130	7,200	60
Chicago - State Street Transitway-north bound	155	8,600	60
City Streets,Some Bypassing Possible:			
New York-Madison Avenue (dual lanes)*	200-220	10,000	50
Ottawa-Carleton Transport	200	10,000	50
New York-Hillside Avenue*	170	8,500	50
Washington, D.C.-14th Street Bridge (before Metro)*	160	8,000	50
Washington, D.C.-K Street N.W. (before Metro)	130	6,500	42
San Francisco-Market Street (before BART and MUNI)*	155	9,900	58
Philadelphia-Market Street*	143	8,300	58
City Streets, One Lane:			
Chicago-Michigan Ave.	116	3,580	31
Chicago-Washington St.	90	3,800	42
Rochester-Main St.	80	4,000	50
Atlanta-Peachtree St.	67	2,807	42

* Buses use more than one lane.

SOURCE: H.S. Levinson, California Department of Transportation, New York City Department of Transportation, Urban Mass Transit Administration, Texas Transportation Institute. Reported in (6)

affect capacity. The general equation for computing the number of vehicles that may be accommodated per effective berth at a bus stop was as follows:

$$C_v = \frac{(g/C)3600R}{(g/C)D + t_c} \quad \text{(A-1)}$$

where:

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

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

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

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

A.2 BUS TRAVEL TIMES

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

A.2.1 Transit Agency Perspective

Transit agencies establish bus schedules that reflect the frequency and duration of stops and street traffic conditions along each bus route (*13*). The schedules are varied to reflect differing conditions throughout the day. Performance is monitored to determine how well buses adhere to the established schedules. Buses generally should operate on time between 80 and 90 percent of the time. “On time” usually is defined as between 1 min early and 3 to 5 min late; specific requirements are keyed to the type of bus route (local,

TABLE A-2 Suggested HCM bus flow service volumes for planning purposes (*1*)

LEVEL OF SERVICE	DESCRIPTION	BUSES/LANE/HOUR	MIDVALUE
ARTERIAL STREETS			
A	Free Flow	25 or less	15
B	Stable Flow, Unconstrained	26 to 45	35
C	Stable Flow, Interference	46 to 75	60
D	Stable Flow, Some Platooning	76 to 105	90
E	Unstable Flow, Queuing	106 to 135	120
F	Forced Flow, Poor Operation	over 135[a]	150[a]
MAIN CBD STREET			
A	Free Flow	20 or less	15
B	Stable Flow Unconstrained	21 to 40	30
C	Stable Flow, Interference	41 to 60	50
D	Stable Flow, Some Platooning	61 to 80	70
E	Unstable Flow, Queuing	81 to 100	90
F	Forced Flow, Poor Operation	over 100[a]	110[a]

[a] Results in more than one-lane operation.

express, or feeder) and service frequency. However, specific speed-related level of service criteria, such as those set forth in the HCM for arterial streets, have not been used.

A.2.2 Travel Time Analysis

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

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

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

TABLE A-3 Suggested bus passenger service volumes for planning purposes (hourly flow rates based on 50 seats per bus) (*1*)

LEVEL OF SERVICE (STREET)	BUSES PER HOUR PER LANE	LEVEL OF SERVICE (PASSENGERS/SEAT)				
		A 0.00-0.50	B 0.51-0.75	C 0.76	D 1.01-1.25	E 1.26-1.50
URBAN ARTERIAL STREETS (PASSENGERS)						
A	25 or less	625	940	1,250	1,560	1,875
B	26 to 45	1,125	1,690	2,250	2,810	3,375
C	46 to 80	2,000	3,000	5,000	5,000	6,000
D	81 to 105	2,625	3,940	6,560	6,560	7,875
E	106 to 135	3,375	5,060	8,440	8,440	10,125
CBD STREETS (PASSENGERS)						
A	20 or less	500	750	1,000	1,250	1,500
B	21 to 40	1,000	1,500	2,000	2,500	3,000
C	41 to 60	1,500	2,250	3,000	3,750	4,500
D	61 to 80	2,000	3,000	4,000	5,000	6,000
E	81 to 100	2,500	3,750	5,000	6,250	7,500

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

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

Type of Operation	AM Maximum	AM Desired[(1)]	PM Maximum	PM Desired[(1)]
Dual bus lanes	200	180	180	150
Single bus lane with passing opportunities	120	90	90	80
Single bus lane with no passing opportunities	80	70	70	60
Buses in curb lane with mixed traffic	70	60	60	50

(1) 90% of maximum

TABLE A-5 Estimated peak-hour transit travel times by components (*15*)

Components	Travel Time (Minutes/Mile)[(a)] CBD	City	Suburbs
Moving	5.50 ± 1.00	3.90 ± 0.30	3.00 ± 1.02
Passenger Stops	3.00 ± 1.00	1.20 ± 0.30	0.50 ± 0.10
Traffic Delay	3.00 ± 1.00	0.90 ± 0.30	0.70 ± 0.12
TOTAL	11.50 ± 3.00	6.00 ± 0.30	4.20 ± 0.30

(a) Values presented after ± are standard deviations.

TABLE A-6 Bus travel times and speeds as a function of stop spacing and traffic congestion (*16*)

		Without Traffic Delays		Central Business District 3.0 min/m delay		Central City 0.9 min/m delay		Suburban 0.7 min/m delay	
Time Per Stop (sec)	Stops per Mile	Travel Time (min/m)	Speed (mph)	Travel Time (min/m)	Speed (mph)	Travel Time (min/m)	Speed (mph)	Travel Time (min/m)	Speed (mph)
10	2	2.40	25.0	5.40	11.1	33.30	18.2	3.10	19.4
	4	3.27	18.3	6.27	9.6	4.17	14.4	3.97	15.1
	6	4.30	14.0	7.30	8.2	5.20	11.5	5.00	12.0
	8	5.33	11.3	8.33	7.2	6.23	9.6	6.03	10.0
	10	7.00	8.6	10.00	6.0	7.90	7.6	7.70	7.8
20	2	2.73	22.0	5.73	10.5	3.63	16.5	3.43	17.5
	4	3.93	15.3	6.93	8.8	4.83	12.4	4.63	13.0
	6	5.30	11.3	8.30	7.2	6.20	9.7	6.00	10.0
	8	6.67	9.0	9.97	6.0	7.57	7.9	7.37	8.1
	10	8.67	6.9	11.67	5.1	9.57	6.3	9.37	6.4
30	2	3.07	19.5	6.07	9.9	3.97	15.1	3.77	15.9
	4	4.60	13.0	7.60	7.9	5.50	10.9	5.30	11.3
	6	6.30	4.5	9.30	6.5	7.20	8.3	7.00	8.6
	8	8.00	7.5	11.00	5.5	8.90	6.7	8.70	6.9
	10	10.33	5.8	13.33	4.5	11.23	5.3	11.03	5.5

A.2.3 Bus Volume Impacts

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

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

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

A.2.4 Bus Lane Impacts

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

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

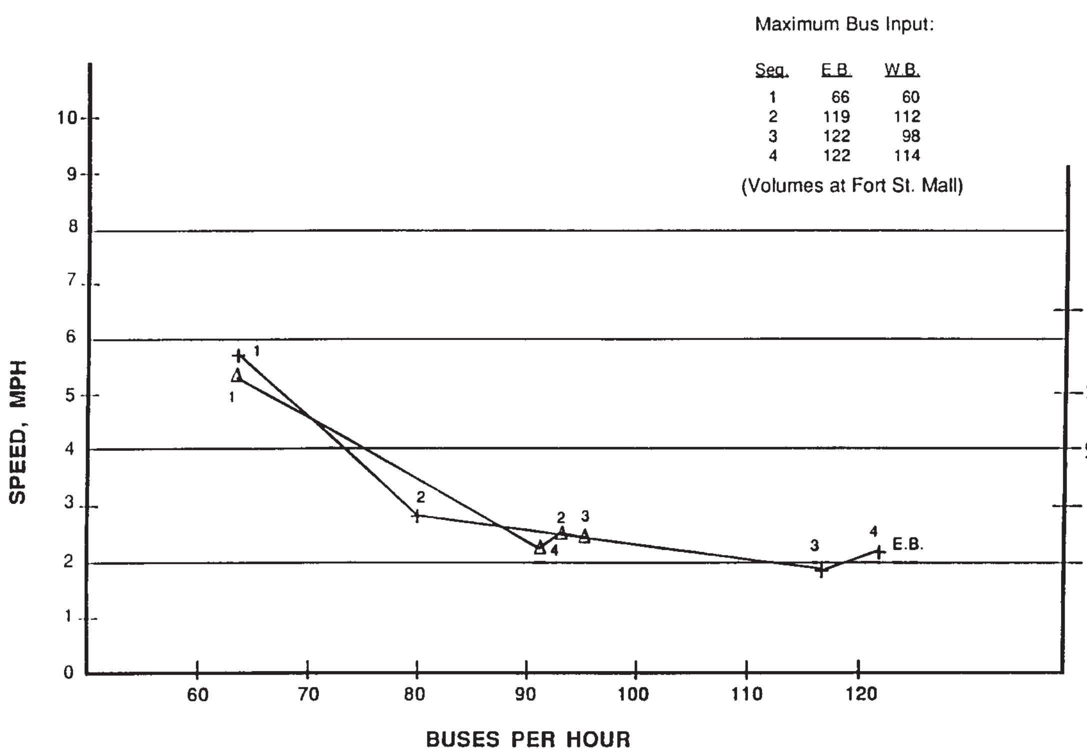


Figure A-1. Bus speeds—Hotel Street demonstration, Honolulu, 1978.

TABLE A-7 Bus travel times by component, Fifth and Sixth Avenues, New York City (*18*)

	Fifth Avenue A.M. Peak Period 86th St. to 34th St.		Sixth Avenue P.M. Peak Period 4th St.. to 59th St.	
Bus Volume Per Hour	220		150	
Bus Passing Opportunities	Difficult		Possible	
Travel Time Component	Minutes/Mile	% of Total	Minutes/Mile	% of Total
Running Time	8.1	53.9	6.0	51.1
Passenger Service	1.4	9.5	3.5	30.2
Traffic Signals	3.0	20.0	2.0	15.9
Right Turns/ Traffic Congestion(1)	0.3	1.7	0.0	0.0
Buses	2.2	14.9	0.2	0.8
Total Travel Time	15.0	100.0	11.7	100.0
Bus Speed, mph	4.0		5.1	

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

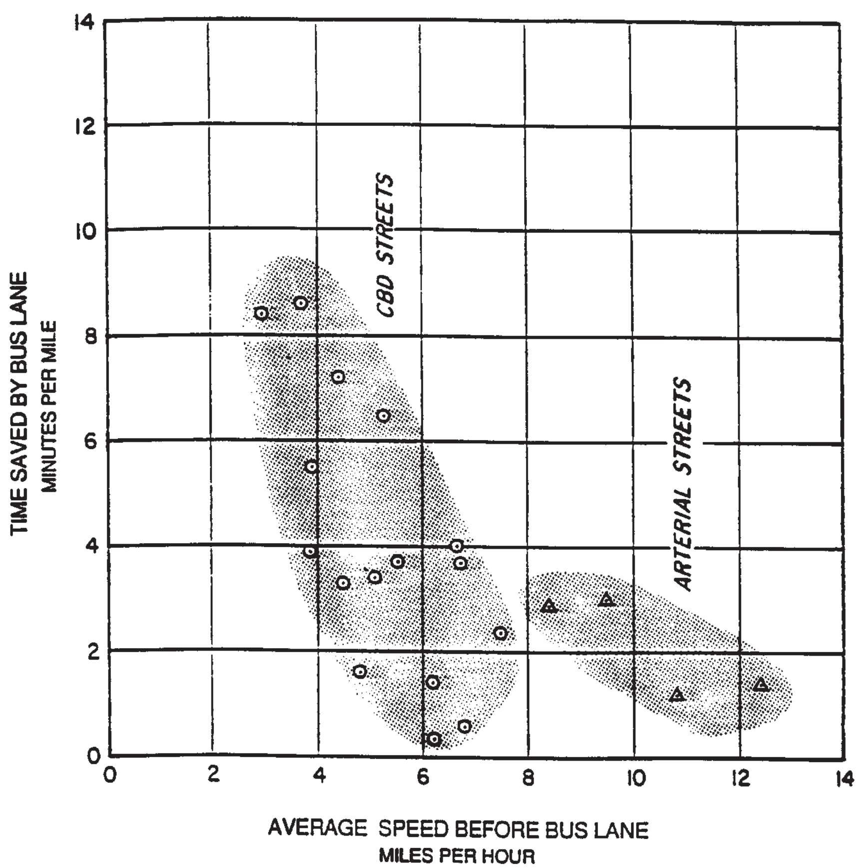


Figure A-2. Time savings—central business district and arterial on-street priority treatments (15).

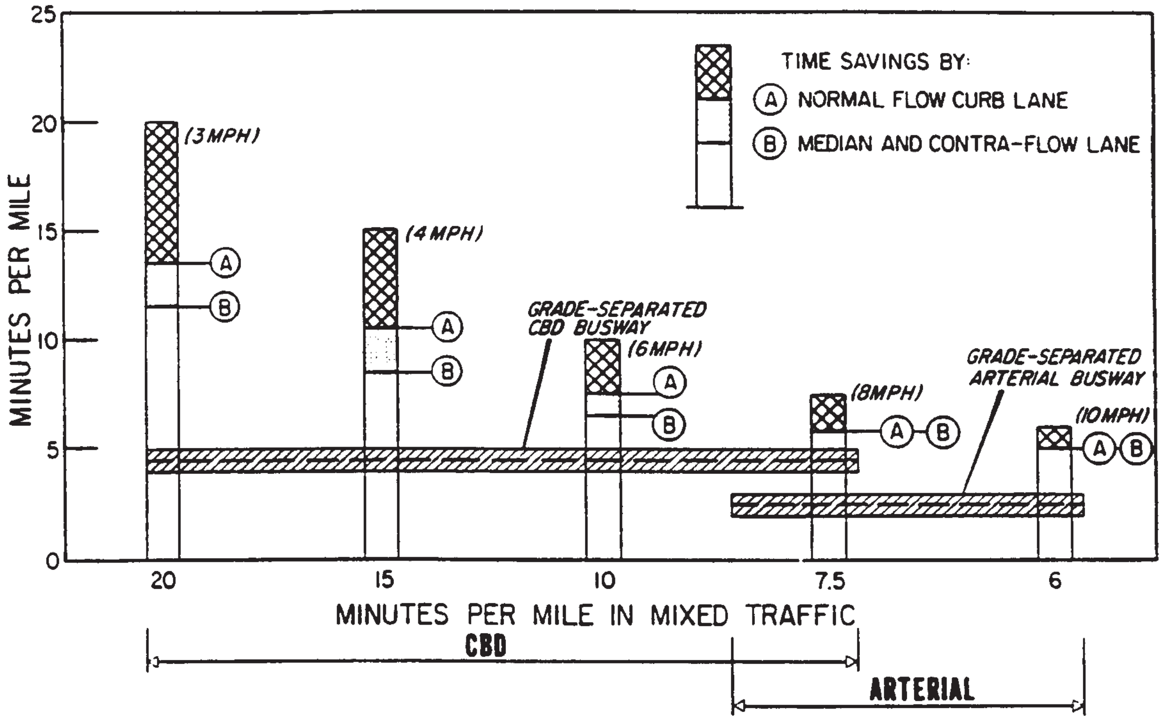


Figure A-3. Typical time savings—bus rapid transit options (19).

between 2:00 and 7:00 p.m., during which time right turns are prohibited along Madison Avenue. Figure A-4 illustrates current lane arrangements.

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

A.3 SIMULATION STUDIES

Various simulation studies have been reported in the literature during the past several decades (*22–28*). These studies have been used to depict bus operations and to assess the impacts of various changes in traffic and bus operations. The more promising simulations include those associated with NETSIM, a microscopic simulation model whose ongoing development is being sponsored by FHWA. The simulation of downtown Ottawa, Ontario, Canada, bus lane operations with BLOSSIM (*21*) revealed that bus flow rates of 150 to 170 buses per hour can be achieved, depending on the strat-

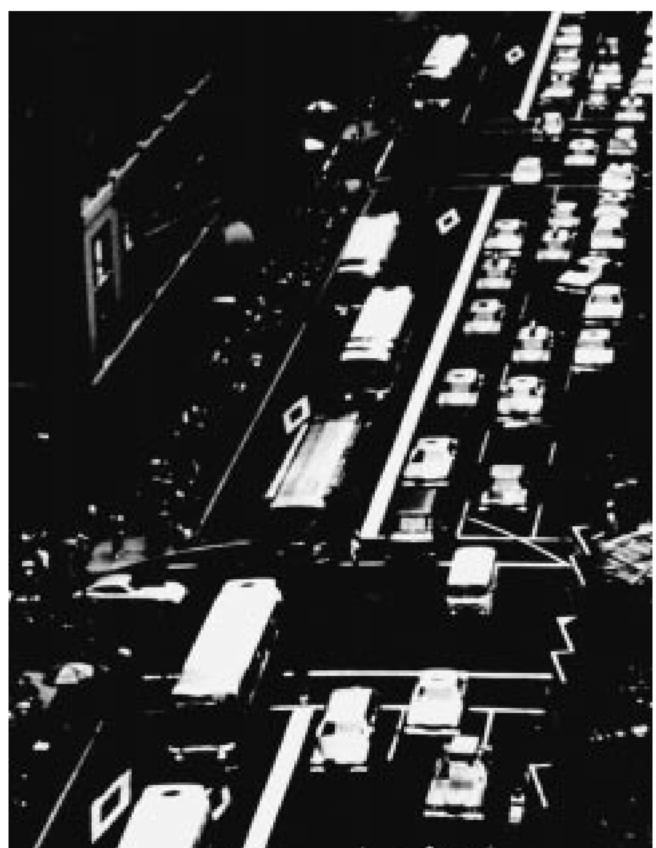


Figure A-4. Madison Avenue dual bus lanes (20).

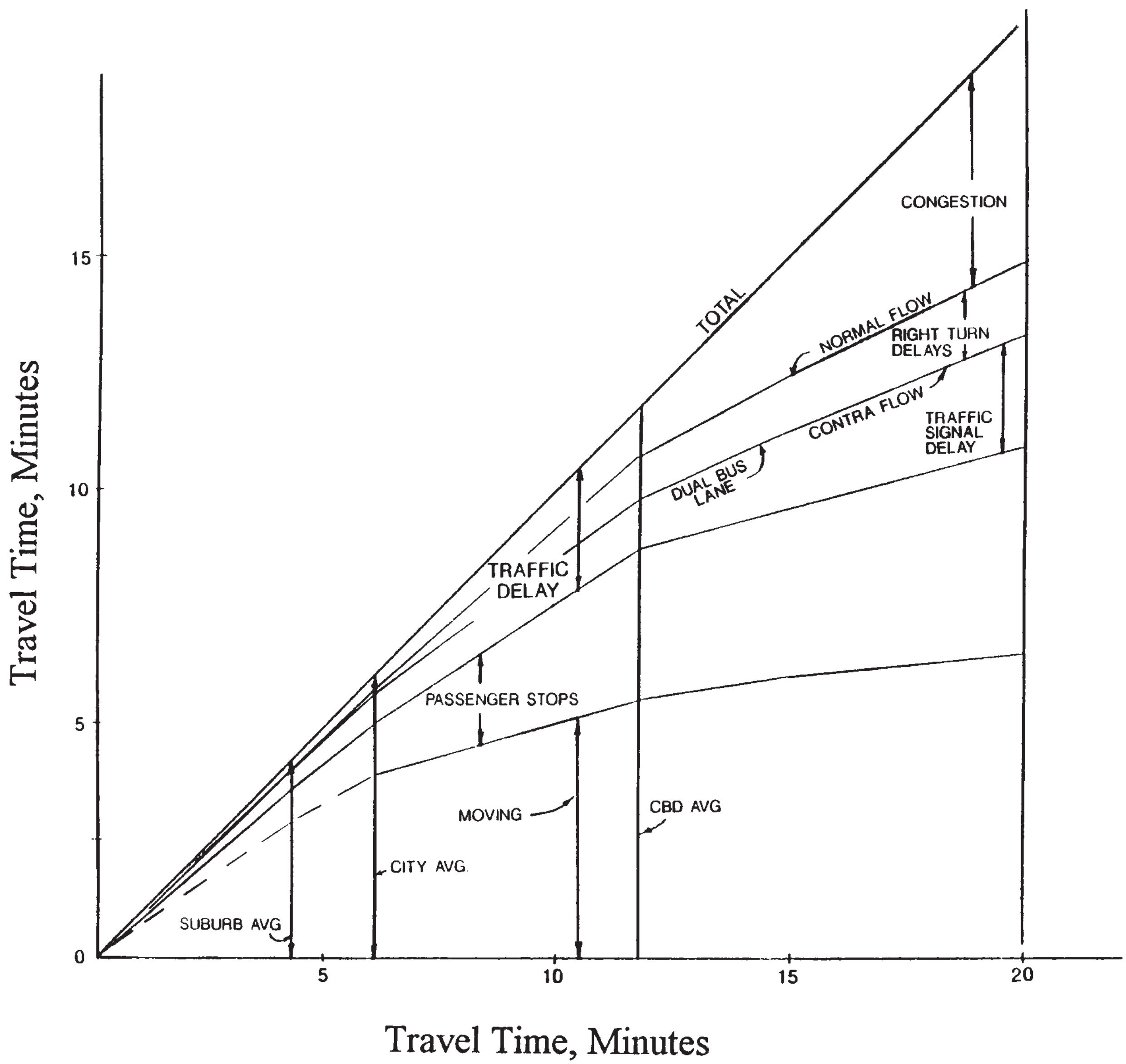
egy selected. Multiple-door channels on articulated buses, widespread use of passes, and the provision of right-turn lanes on the outside of bus lanes, with the availability of the adjacent lane for passing purposes, enable these flow rates to be achieved in what are essentially downtown bus lanes.

A.4 IMPLICATIONS

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

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

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



Source: (Estimated from Tables A-5, A-6, and Figure A-3.)

Figure A-5. Bus lane travel times by time component.

- Right-turn delays; and
- Traffic congestion/interference delays.

Two points are significant:

1. As indicated in previous analyses, the time saved by the installation of bus lanes is a function of how much congestion exists *before* the lanes are installed.
2. The contraflow curve is probably similar to the dual bus lane in performance. Note that it shows a difference up to 2 min under congested operations.

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

APPENDIX B

DWELL RANGE WINDOW APPROACH TO ESTIMATE SPEED

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

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

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

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

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

B.1 DWELL RANGE WINDOW CONCEPT

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

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

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

B.2 BUS SPEED COMPUTATION PROCEDURES

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

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

The basic bus speed equation is as follows:

$$\text{BUS SPEED} = \frac{d}{(C + o)} \tag{B-1}$$

where:

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

The basic bus speed is characteristic of the progression of a bus along an arterial that dwells into the red phase of the signal and then proceeds on the green phase (Type 1 operation).

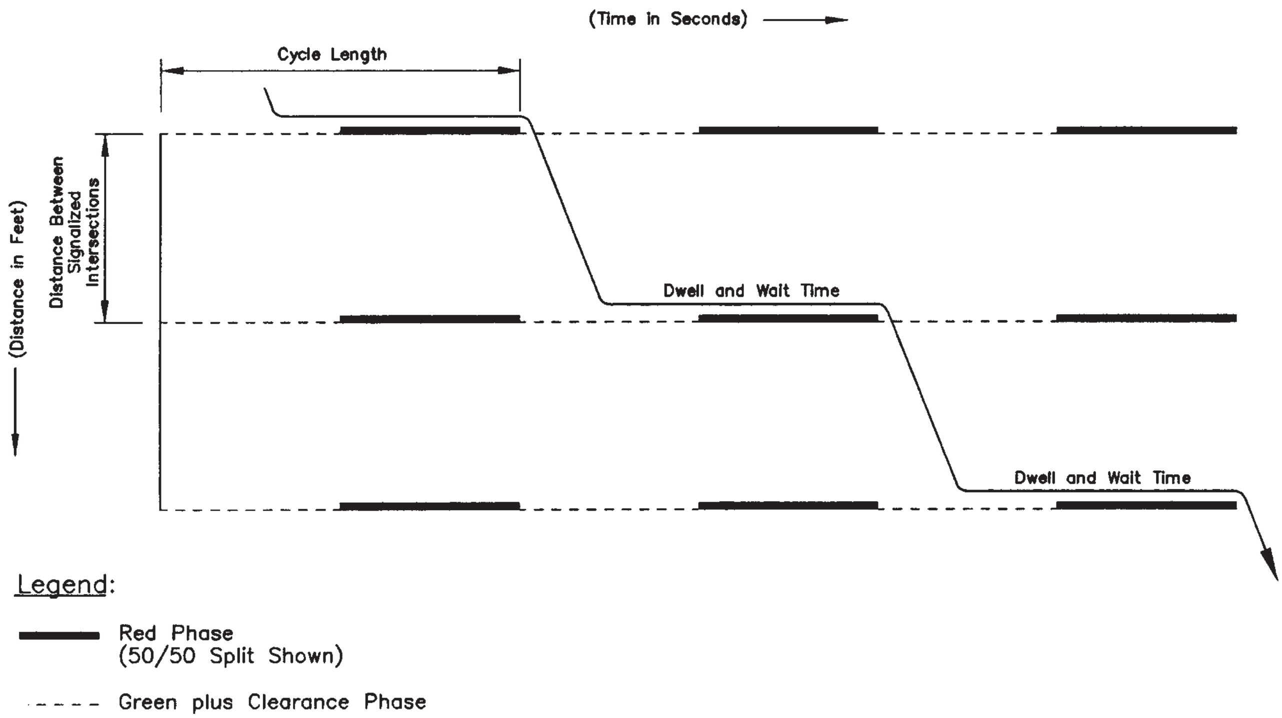


Figure B-1. Bus operations within the dwell range window.

This computed bus speed is applicable for bus dwell times that fall within the dwell range window defined by the following equations:

$$D_U = C + o - t \qquad \text{(B-2a)}$$

$$D_L = g + o - t \qquad \text{(B-2b)}$$

where:

- D_U = maximum dwell time for buses to serve bus stop on red phase, in seconds;
- D_L = minimum dwell time above which buses serve bus stop on red phase, in seconds;
- C = signal cycle length, in seconds;
- o = signal cycle offset to next signal, in seconds;
- g = effective green per cycle (green plus clearance time amber, plus all red time less start-up lost time, in seconds per cycle); and
- t = time to travel between bus stops, in seconds.

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

For $d \geq \left(\frac{V_c^2}{2_{a_1}}\right) + \left(\frac{V_c^2}{2_{a_2}}\right)$:

$$t = \left(\frac{V_c}{2_{a_1}}\right) + \left(\frac{d}{V_c}\right) + \left(\frac{V_c}{2_{a_2}}\right) + LT \qquad \text{(B-3a)}$$

For $d < \left(\frac{V_c^2}{2_{a_1}}\right) + \left(\frac{V_c^2}{2_{a_2}}\right)$:

$$t = \left(\frac{d}{a_1}\right)^{1/2} + \left(\frac{d}{a_2}\right)^{1/2} + LT \qquad \text{(B-3b)}$$

where:

- t = travel time between bus stops, in seconds
- V_c = cruise speed, in feet per second
- d = distance between stops, in feet
- a_1 = acceleration rate, in feet per second^2
- a_2 = deceleration rate, in feet per second^2
- LT = startup lost time, in seconds.

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

Stops Per Mile	Total Travel Time Less Dwell (sec)	Time Between Stops, t (sec)
2	124	62
4	156	39
6	198	33
8	240	30
10	320	32

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

Computation of the dwell range window indicates the allowable variation in dwell time that will maintain the “serve passengers on the red and proceed on the green” progression

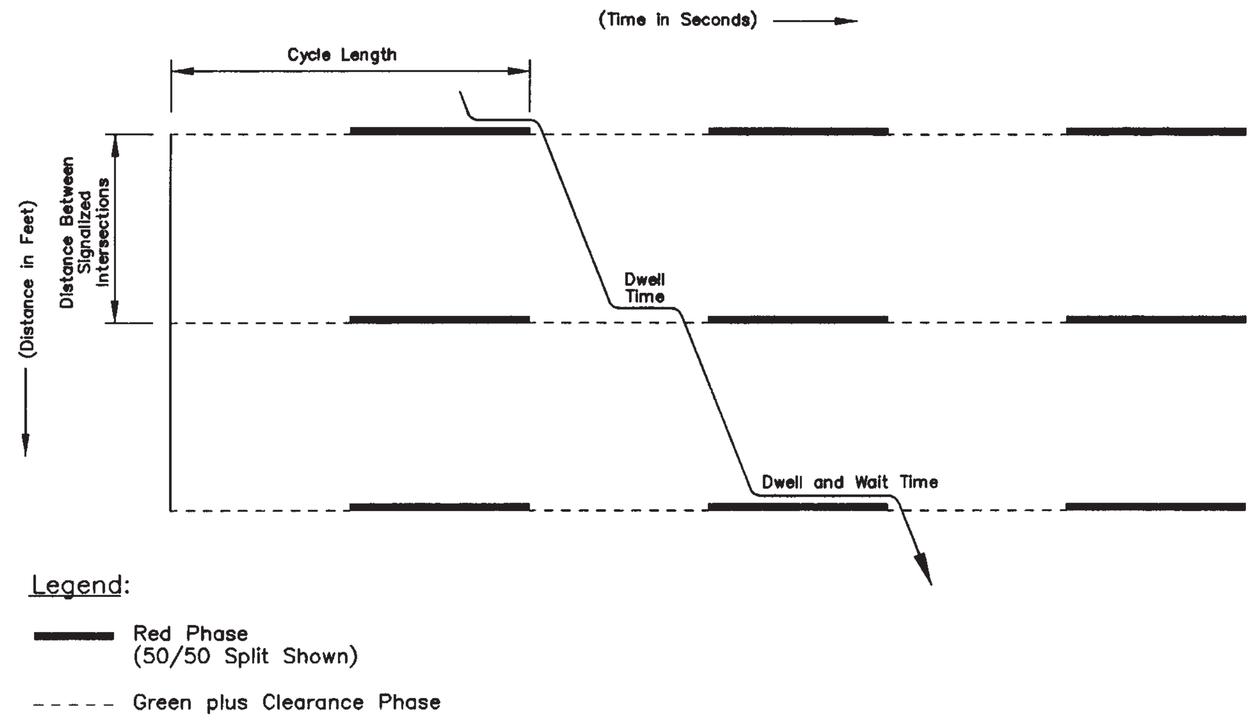


Figure B-2. Bus operations with dwell times less than the lower extent of the dwell range window (D_L).

for buses along the arterial. Transit agencies responding to the survey indicated that the predictability of bus speeds through bus lanes is nearly as important as the actual speed itself. Bus speed adjustment factors were developed for application to bus operations outside the dwell range window.

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

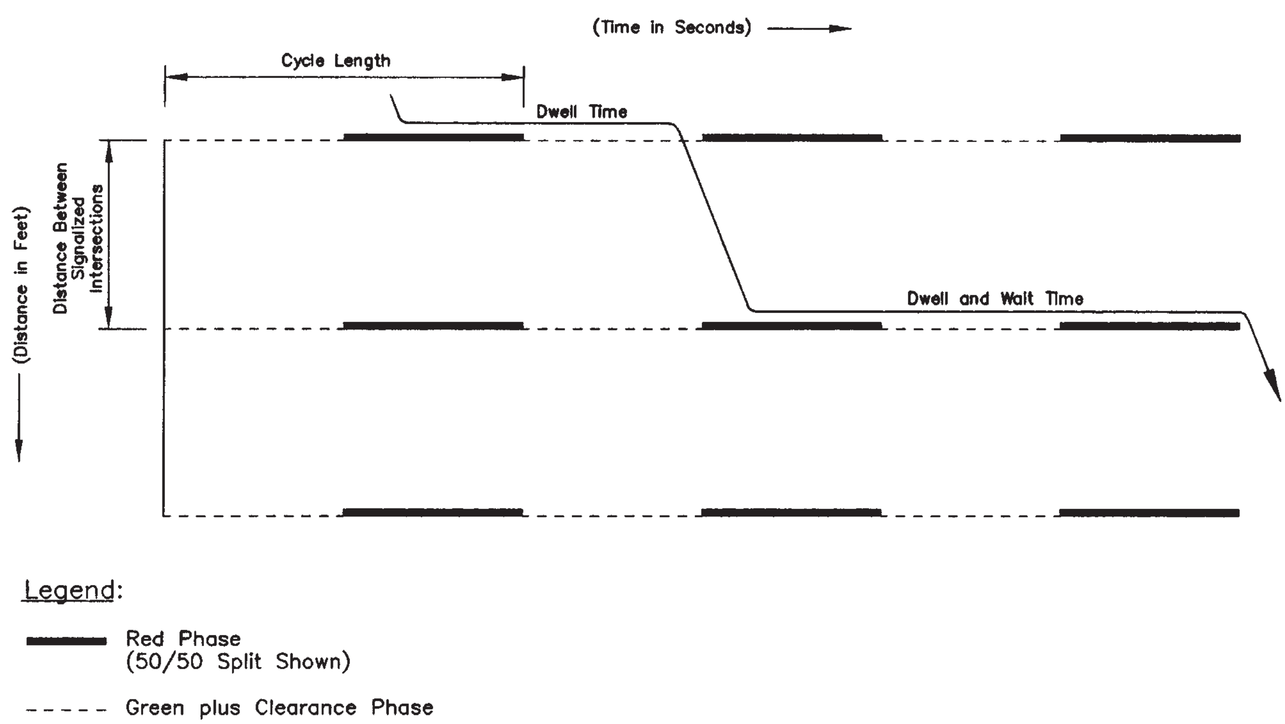


Figure B-3. Bus operations with dwell times greater than the upper extent of the dwell range window (D_U).

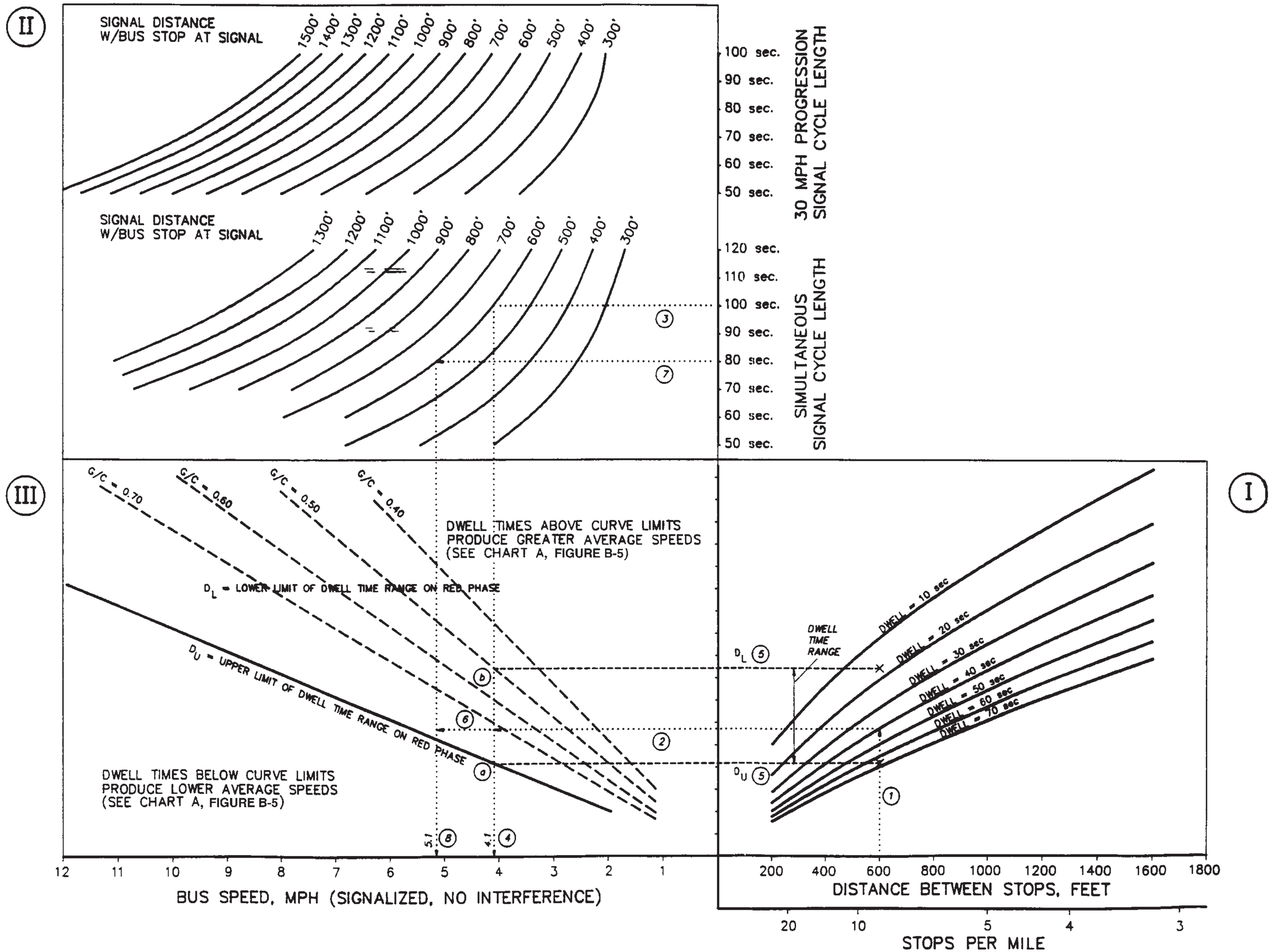


Figure B-4. Refined basic bus speed relationships.

B.2.2 Step 2: Compute Dwell Range Adjustment Factor

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

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

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

$$f_D = 2 \tag{B-4a}$$

where f_D = dwell range adjustment factor.

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

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

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

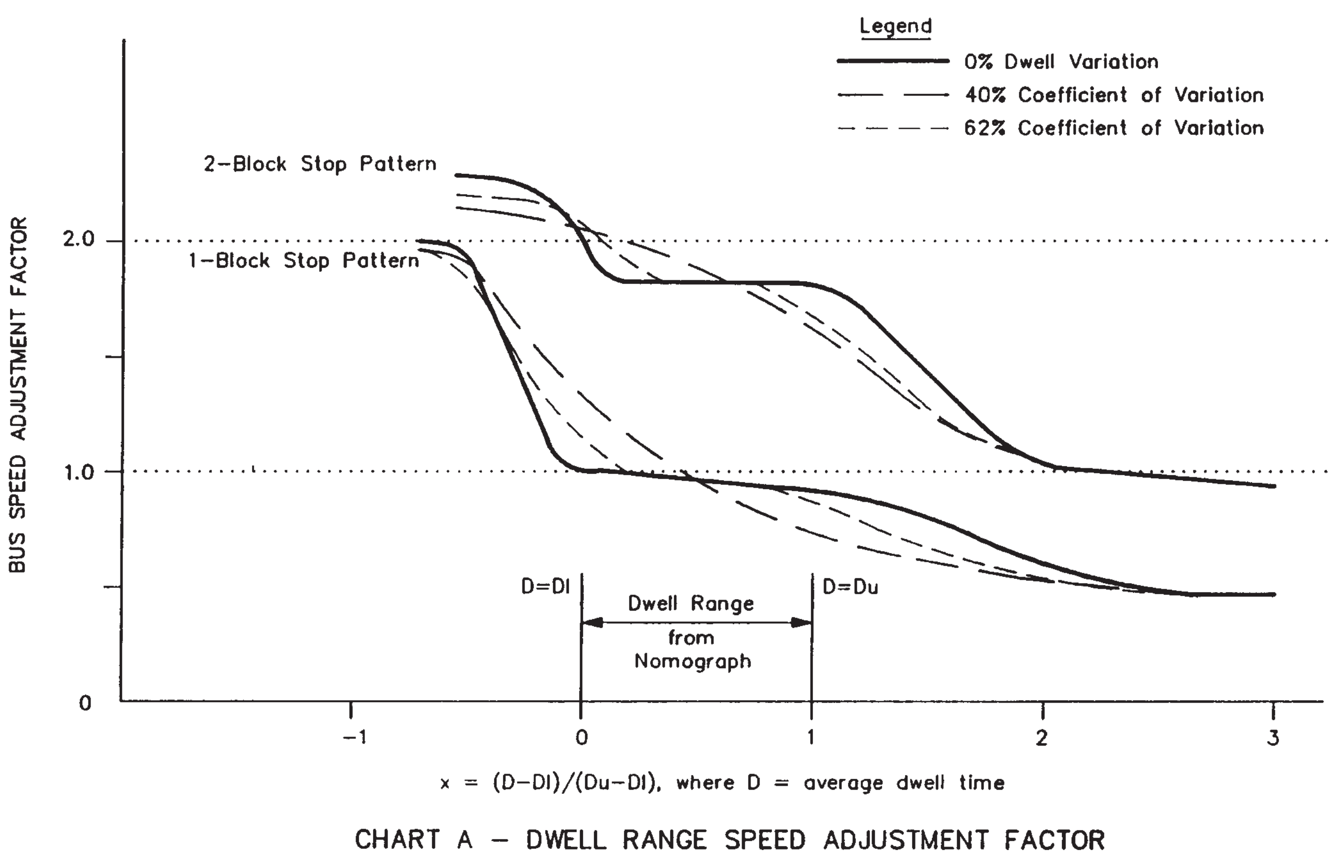


Figure B-5. Bus speed adjustment for dwell range, dwell variation, and stop pattern.

ing subsequent bus service at the stop. The following equations were developed as speed adjustments for the condition $D > D_U$ represented in Figure B-5.

$$\text{For } D_U \le D \le (D_U + g): \quad f_D = 1 - a\frac{(D - D_u)^b}{(g)} \qquad \text{(B-4b)}$$

$$\text{For } (D_u + g) \le D < (C + D_U): \quad f_D = 0.5 \qquad \text{(B-4c)}$$

where:

f_D = dwell range adjustment factor
D_U = dwell range upper limit, in seconds
D = average dwell time, in seconds
C = cycle length
g = green + clearance time + all red per cycle
a = 0.5
b = 1.5.

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

B.2.2.3 Step 3: Compute Dwell Variation Adjustment Factor

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

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

$$\text{For } D < D_L: \quad fv = 1 - \frac{D_v}{2}\left(\frac{D}{D_L}\right) \qquad \text{(B-5a)}$$

$$\text{For } D_L < D < D_R: \quad fv = 1 + \frac{D_v}{2}\frac{(D_R - D)}{(D_R - D_L)} \qquad \text{(B-5b)}$$

$$\text{For } D_R < D < D_U: \quad fv = 1 - \frac{D_v}{2}\frac{(D - D_R)}{(D_R - D_L)} \qquad \text{(B-5c)}$$

$$\text{For } D < D_U: \quad fv = 1 - \frac{D_v}{2}\left(\frac{D_U}{D}\right) \qquad \text{(B-5d)}$$

where:

f_V = dwell variation adjustment factor
D_V = coefficient of variation of average dwell time, percent/100
D_L = dwell range lower limit, in seconds
D_U = dwell range upper limit, in seconds
D_R = midpoint of the dwell range window, in seconds = $\tfrac{1}{2}(D_L + D_U)$
D = average dwell time, in seconds.

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

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

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

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

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

B.3 COMPARISON OF GENERAL AND DETAILED APPROACHES

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

B.3.1 Case 1

The average dwell time is 30 sec with a 20 percent coefficient of variation (D_v). The signals operate on a 70-sec cycle

TABLE B-1 Comparative analysis of simulated bus speeds for differing dwell time variations

CONDITION		$\frac{D - D_L}{Du - D}$	NO COEFFICIENT OF DWELL VARIATION Speed (mph) (Case 1)	NO COEFFICIENT OF DWELL VARIATION Ratio Sim. Spd/ Comp. Speed	11% COEFFICIENT OF DWELL VARIATION Speed (mph) (Case 4)	11% COEFFICIENT OF DWELL VARIATION Ratio Sim. Spd/ Comp. Speed	33% COEFFICIENT OF DWELL VARIATION Speed (mph) (Case 5)	33% COEFFICIENT OF DWELL VARIATION Ratio Sim. Spd/ Comp. Speed	50% COEFFICIENT OF DWELL VARIATION Speed (mph) (Case 21)	50% COEFFICIENT OF DWELL VARIATION Ratio Sim. Spd/ Comp. Speed
C = 100	D=10	-0.38	5.6	2.8	5.3	2.7	5.2	2.6	--	--
L = 300	D=20	-0.18	3.6	1.8	3.4	1.7	3.2	1.6	--	--
D = 29	D=30	0.02	2.2	1.1	2.3	1.2	2.5	1.3	--	--
Du = 79	D=40	0.22	2.2	1.1	2.2	1.1	2.4	1.2	--	--
Base Spd = 2.0	D=50	0.42	2.2	1.1	2.2	1.1	2.2	1.1	--	--
	D=60	0.62	2.2	1.1	2.1	1.1	2.0	1.0	--	--
C = 100	D=10	-0.32	6.3	2.3	6.2	2.3	5.7	2.1	--	--
L = 400	D=20	-0.12	3.9	1.4	4.0	1.5	3.7	1.4	--	--
D = 26	D=30	0.08	3.0	1.1	3.1	1.1	3.3	1.2	--	--
Du = 76	D=40	0.28	3.0	1.1	3.0	1.1	3.2	1.2	--	--
Base Spd = 2.7	D=50	0.48	3.0	1.1	3.0	1.1	2.8	1.0	--	--
	D=60	0.68	2.9	1.1	2.9	1.1	2.4	0.9	--	--
C = 90	D=10	-0.31	7.5	3.3	6.7	2.9	5.5	2.4	5.3	2.3
L = 300	D=20	-0.09	3.0	1.3	2.8	1.2	2.9	1.3	3.0	1.3
D = 24	D=30	0.13	2.3	1.0	2.3	1.0	2.6	1.1	2.8	1.2
Du = 69	D=40	0.35	2.3	1.0	2.3	1.0	2.5	1.1	2.7	1.2
Base Spd = 2.3	D=50	0.57	2.3	1.0	2.3	1.0	2.4	1.0	2.4	1.0
	D=60	0.80	2.3	1.0	2.3	1.0	2.0	0.9	1.6	0.7
C = 90	D=10	-0.24	5.9	2.0	5.6	1.9	5.9	2.0	5.5	1.8
L = 400	D=20	-0.02	3.2	1.1	3.3	1.1	3.6	1.2	3.8	1.3
D = 21	D=30	0.20	3.2	1.1	3.2	1.1	3.3	1.1	3.6	1.2
Du = 66	D=40	0.42	3.2	1.1	3.2	1.1	3.3	1.1	3.4	1.1
Base Spd = 3.0	D=50	0.64	3.2	1.1	3.2	1.1	2.9	1.0	3.1	1.0
	D=60	0.86	3.1	1.0	3.1	1.0	2.7	0.9	2.2	0.7
C = 80	D=10	-0.23	5.2	2.0	5.1	2.0	4.5	1.7	4.3	1.7
L = 300	D=20	0.03	2.8	1.1	2.9	1.1	3.1	1.2	3.3	1.3
D = 19	D=30	0.28	2.8	1.1	2.8	1.1	2.9	1.1	3.2	1.2
Du = 59	D=40	0.53	2.7	1.0	2.7	1.0	2.8	1.1	2.7	1.0
Base Spd = 2.6	D=50	0.78	2.7	1.0	2.7	1.0	2.3	0.9	2.2	0.8
	D=60	1.03	2.5	1.0	2.4	0.9	1.6	0.6	--	
C = 70	D=10	-0.11	4.7	1.6	4.3	1.5	4.1	1.4	4.1	1.4
L = 300	D=20	0.17	3.2	1.1	3.2	1.1	3.4	1.2	3.6	1.2
D = 14	D=30	0.46	3.2	1.1	3.1	1.1	3.2	1.1	3.3	1.1
Du = 49	D=40	0.74	3.1	1.1	3.1	1.1	2.9	0.9	3.0	1.0
Base Spd = 2.9	D=50	1.02	3.0	1.0	2.9	1.0	2.4	0.8	2.3	0.8
	D=60	1.31	2.5	0.9	2.3	0.8	1.5	0.5	--	
C = 60	D=10	0.03	3.8	1.1	3.8	1.1	3.8	1.1	4.4	1.3
L = 300	D=20	0.37	3.7	1.1	3.7	1.1	3.7	1.1	4.1	1.2
D = 9	D=30	0.70	3.7	1.1	3.7	1.1	3.5	1.0	3.8	1.1
Du = 39	D=40	1.03	3.6	1.1	3.4	1.0	3.0	0.9	2.7	0.8
Base Spd = 3.4	D=50	1.37	2.8	0.8	2.7	0.8	2.4	0.7	2.3	0.7
	D=60	1.70	1.7	0.5	1.9	0.6	2.0	0.6	--	
C = 50	D=10	0.24	4.4	1.1	4.4	1.1	4.5	1.1	4.5	1.1
L = 300	D=20	0.64	4.4	1.1	4.4	1.1	4.3	1.0	4.4	1.1
D = 4	D=30	1.04	4.3	1.0	4.2	1.0	3.8	0.9	3.4	0.8
Du = 29	D=40	1.44	3.2	0.8	3.2	0.8	2.8	0.7	2.6	0.6
Base Spd = 4.1	D=50	1.84	2.1	0.5	2.2	0.5	2.4	0.6	2.4	0.6
	D=60	2.24	2.0	0.5	1.9	0.5	2.0	0.5	--	

in a simultaneous pattern (i.e., 0-sec offset) with 40 sec of green, clearance, and all red time.

B.3.1.1 General Approach

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

B.3.1.2 Detailed Approach

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

$$\text{BUS SPEED} = \frac{d}{(c + o)} = \frac{500}{70} = 7.1\,ft/\text{sec} = 4.9\ mph$$

This speed applies to the dwell range window as defined by applying Equations B-2a and B-2b.

$$D_U = C + 0 - t = 70 + 0 - t = 70 - t$$

$$D_L = 40 + 0 - t = 40 + 0 - t + 40 - t$$

The value of t is obtained by applying Equation B-3a, assuming $V_C = 25$ mph:

$$t = \frac{V_c}{2a_1} + \frac{d}{V_c} + \frac{V_c}{2a_2} + LT = \frac{(25)(5280)}{(3600)(2)(4)} + \frac{(500)(3600)}{(25)(5280)} + \frac{(25)(5280)}{(3600)(2)(4)} + 2 = 25$$

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

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

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

B.3.2 Case 2

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

B.3.2.1 General Approach

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

B.3.2.2 Detailed Approach

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

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

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

$$D_U = C + o - t = 80 + 0 - 25 = 55 \text{ sec}$$

$$D_L = g + o - t = 40 + 0 - 25 = 15 \text{ sec}$$

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

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

$$f_v = 1 + \frac{(0.2)}{(2)}\frac{(35 - 30)}{(35 - 15)} = 1.03$$

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

B.3.3 Case 3

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

B.3.3.1 General Approach

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

	Travel Time (min/mi) With Right-Turn Delays	Without Right-Turn Delays
40-sec dwell	14.00	13.20
50-sec dwell	15.67	14.87
Interpolation for 45 sec	14.84	14.04
Speed (mph) @ 45-sec dwell	4.0	4.3

B.3.3.2 Detailed Approach

The detailed approach is similar to Case 1. Equation B-1 gives a speed of 4.9 mph. Equations B-2a and B-2b give a dwell range window of where $D_U = 45$ sec and $D_L = 15$ sec. The actual dwell time (45 sec) is at the upper limit of the dwell range.

The 20 percent dwell coefficient of variation calls for estimating the dwell variation factor, f_v. The midpoint of the dwell range (D_R) is 30 sec. Because $D_R < D$, Equation B-5c should be used:

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

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

B.3.4 Case 4

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

$$\text{BUS SPEED} = \left(\frac{d}{C + o}\right) f_D\, f_v\, f_s\, f_b$$

where:

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

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

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

B.3.4.1 Description

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

The following traffic signal improvements are proposed:

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

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

B.3.4.2 Solution: Existing Conditions

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

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

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

where:

C_b = berth capacity, buses per berth per hour
g/C = green per cycle = 0.5
t_C = clearance time = 15 sec
D = average dwell time = 35 sec
C_V = coefficient of variation = 0.6
Z_a = 0.675 for 25 percent failure at LOS E.

The capacity at LOS E is completed as follows:

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

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

$$\text{Bus Lane Capacity} = f_K\,(CAP_1 + CAP_2)$$

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

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

$$\text{BUS SPEED} = \frac{(400)(2)}{(70+0)} = 11.4\ ft/\text{sec} = 7.8\ mph$$

$$t = \frac{(36.75)}{(2)(4)} + \frac{(400)(2)}{(36.75)} + \frac{(36.75)}{(2)(4)} + 2 = 33\ sec$$

$D_U = 70 + 0 - 33 = 47$ sec

$D_L = 35 + 0 - 33 = 2$ sec

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

The midpoint of the dwell range, D_R, is (47 + 2)/2 or 24.5 sec. Because the dwell time, $D = 35$ sec, exceeds the dwell range midpoint, Equation B-5c is used to obtain f_V:

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

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

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

The adjusted speed, therefore, becomes:

$$\begin{aligned}\text{BUS SPEED} &= \left(\frac{d}{c+o}\right) f_D\, f_v\, f_s\, f_b \\ &= (7.8)(1.0)(0.86)(0.63)(0.86) = 4.0\ mph\end{aligned}$$

B.3.4.3 Solution: Proposed Conditions

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

Compute Proposed Bus Berth Capacity. The bus berth capacity for a g/C ratio of 0.56 at LOS E (25 percent failure) is as follows:

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

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

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

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

$D_U = 80 + 0 - 33 = 47$ sec

$D_L = 45 - 0 - 33 = 12$ sec

The dwell range midpoint, D_R, becomes (47 + 12)½ = 29.5 sec. Equation B-5c is applied to estimate, f_v, the dwell variation factor

$$f_v = 1 - \frac{(0.6)}{(2)}\frac{(35-29.5)}{(29.5-12)} = 0.90$$

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

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

The adjusted bus speed becomes the following:

BUS SPEED = (7.8)(1.0)(0.90)(0.67)(0.89) = 4.4 mph

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

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S. DOT	U.S. Department of Transportation