Transit Cooperative Research Program

Sponsored by the Federal Transit Administration

RESEARCH RESULTS DIGEST

September 2000—Number 38

Subject Area: VI Public Transit

Responsible Senior Program Officer: B. Ray Derr

Operational Analysis of Bus Lanes on Arterials: Application and Refinement

This TCRP digest provides the results of TCRP Project A-7A, "Field Evaluation of Bus Lanes on Arterials," conducted by Kevin R. St. Jacques, of Wilbur Smith Associates, in association with Herbert S. Levinson, Transportation Consultant.

TCRP Report 26, "Operational Analysis of Bus Lanes on Arterials," presented a new method of analyzing the operational performance of arterial bus lanes. This method was incorporated into *TCRP Web Document 6*, "Transit Capacity and Quality of Service Manual," and the Year 2000 edition of the "Highway Capacity Manual." This digest shows how the method was applied to six existing bus lane study sites and recommends refinements to the method. Readers will be better able to apply the *TCRP Report 26* method by seeing how its developers used it in the real world.

SUMMARY

This research analyzed the performance of buses along bus lanes on downtown streets. Additional field observations and measurements were used to test and refine the bus capacity and speed estimating procedures set forth in *TCRP Report 26*, "Operational Analyses of Bus Lanes on Arterials." Transit agencies helped to conduct the field studies.

Research Approach

New field data were collected for the following six bus lanes:

1. Fifth Avenue, Portland, Oregon—Dual bus lanes on bus-only street;
2. Sixth Avenue, Portland, Oregon—Dual bus lanes on bus-only street;
3. Second Avenue, New York City, New York—Curb bus lane;
4. Albert Street, Ottawa, Ontario—Curb bus lane;
5. Commerce Street, San Antonio, Texas—Curb bus lane; and
6. Market Street, San Antonio, Texas—Curb bus lane.

In addition, data on the bus speeds observed in bus lanes on Third Avenue and on Broadway in New York City were obtained from the local transit agency.

Physical conditions at each site (e.g., street widths, travel lanes, bus stops, and berths) and traffic signal timing were observed. Where possible, bus travel along the arterial was videotaped from one location between checkpoints. Usually, the evening peak-period was observed, and speeds were averaged for 15-min periods. The total time in the study section and the dwell time at each stop were collected for each bus.

Capacities and speeds were estimated in accordance with the procedures set forth in *TCRP Report 26*. These estimated speeds were then compared with those obtained from the field observations.

The research team focused on three basic questions:

1. Do the established procedures provide reasonable estimates of bus lane capacity?
2. Do the procedures produce realistic estimates of bus speeds and travel times?
3. What adjustments to existing parameters, procedures, and default values are desirable to better reflect actual operating conditions and observed speeds?

CONTENTS

Key Findings

The key findings and comparisons are given in Tables 1, 2, 3, and 4 and in Figure 1. These tables and this figure document the strengths and weaknesses of the various estimation techniques as demonstrated during observations of almost 900 buses.

Survey Results

Table 1 summarizes the results of the field surveys. The bus stop frequency ranged from 5 stops/mi to 10 stops/mi. Peak 15-min bus flowrates were as high as 164 buses/hr; and 15-min median dwell times ranged from 18 to 32 sec.

The coefficients of variation for bus dwell times for each 15-min period at each bus stop for each site were averaged. The resulting values for the critical bus stop were consistent with the 60-percent value suggested in *TCRP Report 26*. The critical bus stop has the lowest vehicular capacity (in buses/hr) as a result of either long dwell times or heavy interference by right-turning vehicles.

The 15-min bus speeds ranged from 2.6 mph to 12.8 mph. The high bus throughput and speeds along Albert Street in Ottawa resulted from fewer stops, lower dwell times, and traffic signals timed for bus flow.

Bus speeds varied considerably. Standard deviations of bus speeds were as high as 3.6 mph, with values of 1 to 2 mph common. Coefficients of variation of average bus speeds were as high as 45 percent, with most exceeding 20 percent. This variability resulted from the variations in dwell times and from the relatively short lengths of roadway sections observed (typically less than $^1/_2$ mi).

Capacity

The various capacity relationships and berth efficiency factors generally produced reasonable results, assuming a 25-percent failure rate. However, the complex bus operating patterns along Fifth and Sixth Avenues in Portland required using a much lower failure rate to reflect the implications of spill-back effects on bus lane capacity and bus speeds.

Bus Speed Comparisons

Observed bus speeds were compared with those estimated by the procedures set forth in *TCRP Report 26*. Most bus speed estimates fell within 20 percent of the observed speeds (approximately 1 standard deviation) and about one-half were within 10 percent of the observed speeds. However, estimated speeds often were higher than observed speeds along Fifth and Sixth Avenues in Portland and Second Avenue in New York. Estimated speeds often were lower than observed speeds along Albert Street in Ottawa.

Accordingly, bus speed estimates were recalculated by modifying certain assumptions as follows:

- Along Fifth and Sixth Avenues, the incremental traffic delay was increased from 1.2 to 2.0 min/mi to better

TABLE 1 Summary of observed bus performance

	Fifth Ave Portland	Sixth Ave Portland	Second Ave New York City	Albert St Ottawa	Commerce St San Antonio	Market St San Antonio
Type of Lane	Dual Bus Lane	Dual Bus Lane	Curb Bus Lane	Curb Bus Lane	Curb Bus Lane	Curb Bus Lane
Stops Per Mile	10	10	8	5	10	6
Hourly Bus Flow Rates by 15-Min Interval						
Range	76-164	88-112	16-52	100-164	56-100	8-108
Median	136	96	26	132	80	96
Dwell Times By 15-Min Interval (sec)						
Range	10-65	8-55	19-78	15-27	10-32	23-30
Median	29	32	29	18	22	26
Mean Coefficient of Variation	0.52	0.54	0.57	0.59	0.81	0.57
Bus Speeds Compiled by 15-Min Interval (mph)						
Range in Mean Speed	2.6-4.7	3.7-4.2	4.4-8.0	9.1-12.8	4.2-6.3	6.0-7.0
Range in Standard Deviation (mph)	0.5-1.5	0.9-1.5	0.2-2.7	1.3-3.6	0.6-1.5	1.0-2.3

account for the delays caused by intermediate traffic signals;

- Along Second Avenue, the incremental traffic delay was increased from 2.0 to 3.0 min/mi to account for blocking of the bus lanes;
- Along Albert Street, the incremental traffic delay was decreased from 1.2 to 0.6 min/mi to reflect the preferential traffic signal timing for buses; and
- A berth efficiency factor of 2.75 (rather than 2.50) was used to reflect the platooning effect of the upstream bus stop on Albert Street.

Table 2 shows how these adjustments reduced the absolute differences between observed and estimated speeds. In almost every case, the average differences were less than the standard deviations of observed speeds. About 43 percent of the individual 15-min periods had estimated speeds within 0.5 mph of observed speeds, and 82 percent had estimated speeds within 1.0 mph of observed speeds.

Figure 1 compares estimated and observed bus speeds. Nearly all speed estimates are within 20 percent and more than one-half are within 10 percent of the observed bus speeds. Still, speeds were consistently over- or underestimated for some sites.

Overall, the *TCRP Report 26* approaches appear to provide reasonable estimates of bus speeds. Under certain operating conditions, which may either favor or impede bus operations, adjustments in the traffic-delay time losses are desirable.

Implications

Several refinements to the parameters and default values suggested in *TCRP Report 26* emerged from this study:

1. Consideration should be given to increasing the efficiency of multiple, on-line berths and recognizing the increased efficiency of platooned operations. Further analyses and extrapolation of the TRAF-NETSIM simulation in *TCRP Report 26* suggest the factors shown in Table 3.

2. Single values of incremental traffic delay for various types and locations of bus lanes, as presented in Table 3-3 of *TCRP Report 26*, may not fully reflect specific operating conditions. Further latitude is suggested to better reflect the effects of (1) traffic signals set to favor buses, (2) traffic signals located between (as well as at) bus stops, and (3) bus lane blockage. Table 4 gives the suggested values.

This table, which replaces Table 3-3 in *TCRP Report 26*, contains the same information, but presents it so that the information is easier to adapt to various situations. Part A of the table presents the base travel time in minutes per mile for various stop frequencies and average dwell times. These base travel times represent optimal conditions—with no delay interference from signals, right turns, lane blockage, and so forth. These travel times are adjusted in Part B by

TABLE 2 Summary comparison of bus speeds

Site	Range in Observed Speeds 15-Min Intervals (mph)	Range in Standard Deviation of Speeds (mph)	Average Difference Between Observed and Estimated Speeds	
			Initial	Adjusted
Fifth Avenue, Portland	2.6-4.7	0.5-1.5	0.4	0.3
Sixth Avenue, Portland	3.7-4.2	0.9-1.5	1.0	0.8
Second Avenue, New York City	4.4-8.0	0.2-2.7	0.8	0.5
Albert Street, Ottawa	9.0-12.8	1.3-3.6	2.0	1.6
Commerce Street, San Antonio	4.2-6.3	0.6-1.5	0.5	N/A
Market Street, San Antonio	6.0-7.0	1.0-2.3	0.9	0.5

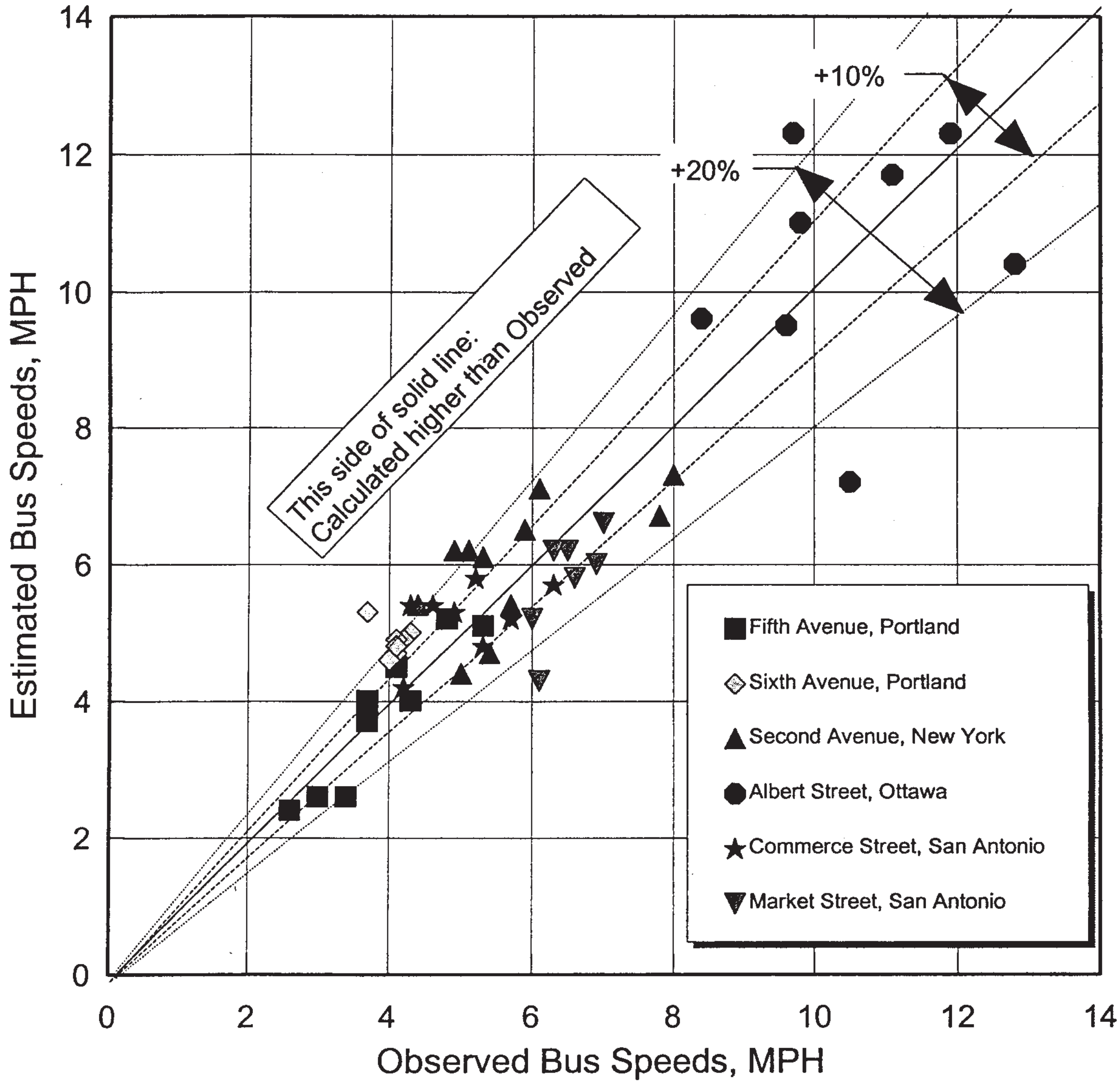


Figure 1. Estimated versus observed bus speeds (adjusted).

TABLE 3 Recommended effective bus berths for on-line bus stops

Number of Berths Provided	Effective Berths Factor, N_b	
	Random	Platooned
1	1.00	1.00
2	1.75	1.85
3	2.45	2.65
4	2.65	2.90
5	2.75	3.00

TABLE 4 Recommended bus travel times for various stop spacing, dwell times, and operating environments

A. Base Travel Time Rates/Minutes Per Mile

Average Dwell Time	Stops Per Mile								
Per Stop (sec.)	2	4	5	6	7	8	9	10	12
10	2.40	3.27	3.77	4.30	4.88	5.53	6.23	7.00	8.75
20	2.73	3.93	4.60	5.30	6.04	6.87	7.73	8.67	10.75
30	3.07	4.60	5.43	6.30	7.20	8.20	9.21	10.33	12.75
40	3.40	5.27	6.26	7.30	8.35	9.53	10.71	12.00	14.75
50	3.74	5.92	7.08	8.30	9.52	10.88	12.21	13.67	16.75
60	4.07	6.58	7.90	9.30	10.67	12.21	13.70	15.33	18.75

B. Additional Travel Time Losses/Minutes Per Mile

CENTRAL BUSINESS DISTRICT

	Bus Lane No Right Turns	Bus Lane With Right Turn Delays	Bus Lanes Blocked by Traffic	Mixed Traffic Flow
Typical	1.2	2.0	2.5-3.0	3.0
Signal Set For Buses	0.6	1.4	N/A	N/A
Signals More Frequent Than Bus Stops	1.7-2.2	2.5-3.0	3.0-4.0	3.5-4.0

ARTERIAL ROADS OUTSIDE OF CBD

	Bus Lane	Mixed Traffic
Typical	0.7	1.2
Range	0.5-1.0	0.8-1.6

Notes: Add values from Part A and Part B to obtain suggested estimate of total bus travel time.
Convert total travel time rate to estimated average speed by dividing into 60 to obtain mph.
Interpolation between shown values of dwell time is done on a straight line basis.

adding travel time delay for various operating environments. Part B is divided into two sections: central business district (CBD) and arterials outside of the CBD. In addition, the original information from Table 3-3 on CBD operation was modified as follows:

- When signals are set to favor bus operations, delay is reduced by 0.6 min/mi;
- When signals are more frequent than bus stops (e.g., buses skip blocks), delay is increased by 0.5 to 1.0 min/mi (depending on stop and signal spacing); and
- When lanes are blocked by traffic or no dedicated bus lane exists, delay is increased by 0.5 to 1.0 min/mi (depending on the amount of lane blockage).

INTRODUCTION

TCRP Project A-7 analyzed the operational performance of bus lanes on arterial streets. The research resulted in procedures for possible use in updating the transit and signalized arterial chapters of the "Highway Capacity Manual" (HCM)[1]. These procedures and their application are set forth in *TCRP Report 26*, "Operational Analysis of Bus Lanes on Arterials."[2]

Procedures and parameters for estimating capacity and speed were set forth for three types of bus lanes:

1. A curb bus lane where passing is impossible or prohib-

ited—the lane may operate in the same direction as other traffic or against the flow (Type 1);
2. A curb bus lane where buses can use the adjacent mixed-traffic lane for overtaking or "leap frogging" stopped buses (Type 2); and
3. Dual bus lanes where non-bus right turns are prohibited (Type 3).

This research (TCRP Project A-7A) was designed to test and validate the relationships set forth in *TCRP Report 26*. Additional field observations and measurements were obtained, results were assessed, and possible refinements to the relationships and parameters were identified. Information on bus performance was collected or assembled in three U.S. cities and one Canadian city. The research addressed several basic questions that relate to the procedures and default values set forth in *TCRP Report 26*:

- Are the estimates of bus berth and bus lane capacity realistic?
- How well do the bus speed (and travel time) estimates predict observed bus speeds?
- What changes in assumptions, default values, and procedures are desirable to produce more realistic estimates?

In addition to discussing what was learned in trying to answer these questions, this digest suggests areas where additional research is needed.

Research Approach

The research team interacted directly with the TCRP A-15 (Transit Capacity and Quality of Service) project team and with transit agencies at key milestones throughout the project. The data and results were shared with the four participating transit agencies: Tri-Metropolitan Area Transit (Tri-Met), Portland Oregon; New York City Transit, New York City; Ottawa-Charleton Transport Authority (O-C Transpo), Ottawa, Ontario; and VIA Transit, San Antonio, Texas.

Study Sites

Eight bus lane sites were analyzed as part of this research. Six locations were studied using field data collected by the research team:

- Fifth Avenue, Portland, Oregon–dual bus lanes on bus-only street;
- Sixth Avenue, Portland, Oregon–dual bus lanes on bus-only street;
- Second Avenue, New York City, New York–curb bus lane;
- Albert Street, Ottawa, Ontario, Canada–curb bus lane;
- Commerce Street, San Antonio, Texas–curb bus lane; and
- Market Street, San Antonio, Texas–curb bus lane.

Two locations in New York City were studied using average bus speed information provided by New York City:

- Third Avenue, New York City, and
- Broadway, New York City.

Field Surveys

Physical conditions at each survey site relative to street width, travel lanes, bus stops and berths, and traffic signal timing were observed. Where possible, bus performance and adjacent traffic movements were videotaped from one point between checkpoints. Using synchronized watches at the beginning and end of the study section and at each bus stop, the research team obtained travel time and dwell times. Bus speeds were then computed. Survey periods typically covered the evening peak from 4:00 p.m. to 5:30 p.m., with data also collected during the morning peak (San Antonio).

Data Summaries and Analyses

Travel times and speed information were averaged for each 15-min period. Average dwell times and speeds and their respective standard deviations and coefficients of variation were estimated. Capacities and speeds were estimated according to the procedures set forth in *TCRP Report 26*. Estimated speeds were then compared with those obtained from the field observations.

Overview of Procedures

Table 5 lists the procedures for estimating bus lane capacities and speeds and identifies the tables and equations from *TCRP Report 26* that should be used. A further discussion of these steps and procedures follows.

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 the following:

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.

TABLE 5 Bus lane capacity and speed analysis steps

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

Bus-berth capacities should be estimated first because the berth *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 15-min flowrates.

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 of *TCRP Report 26* 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 of *TCRP Report 26* will be necessary.

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

Estimating Bus-Berth Capacity and 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 such an estimate involves using the bus berth and bus stop capacity equations and tables set forth in Chapter 2 of *TCRP Report 26.* Basic bus lane capacity is the capacity of the critical bus stop, which is the product of the capacity of the bus berth multiplied by the number of effective bus berths at the stop. Equation 2-10 from *TCRP Report 26* estimates 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 of *TCRP Report 26.*

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.

Equations 2-14a and 2-14b of *TCRP Report 26* provide the adjusted bus lane capacity.

The levels of service at critical bus stops can be obtained by comparing the bus flowrates with the adjusted capacity and using the ratios in Table 2-9 of *TCRP Report 26.* Alternatively, the level of service (failure rate) can be set initially; basic capacity then can be estimated, adjustments can be applied, and the capacity can be compared with the bus flowrate.

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, analysis of 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 observed speeds to predict future conditions.

Bus speeds can be estimated from Table 3-3 of *TCRP Report 26.* For CBD bus lanes, Column E of this table generally should be used because the effects of right turns are reflected in the subsequent reductions. Next, the speeds should be adjusted downward to reflect bus-bus interference 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 of *TCRP Report 26*. 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 developed as part of the research for *TCRP Report 26* can be used to compare differences in bus operating conditions.

In the course of this research, errors in Table 3-3 became evident. Table 6 is a corrected version of Table 3-3.

ANALYSIS OF FINDINGS

This section compares observed bus speeds with the speeds estimated by using the procedures summarized in the preceding section. Location-specific procedures and illustrative calculations and tabulations of the detailed field surveys are available as *TCRP Web Document 15*.

Fifth and Sixth Avenues, Portland, Oregon

Fifth and Sixth avenues in Portland, Oregon, operate with dual (Type 3) bus lanes and have the same stopping patterns: four "nested" routes stop every two blocks, with two distinct bus stops per block. Each block has approximately 200 ft of curb face and can accommodate up to four stopped buses. Bus operations use two bus stops on each block with a maximum of two bus berths at each bus stop. For both avenues, a four-block segment was selected that included two complete skip-stop patterns for each of the four nested routes. The Fifth Avenue study section extended from S.W. Oak Street to S.W. Morrison Street; the Sixth Avenue study section extended from S.W. Taylor Street to S.W. Washington Street. The traffic signals along both avenues operate on a 60-sec cycle; offsets from block to block are approximately 16 sec. Figures 2 and 3 show the arrangements of the bus stops on Fifth and Sixth avenues, respectively.

Field Surveys and Data Summaries

Data were collected on Sixth Avenue on July 22, 1997, and on Fifth Avenue on July 23, 1997, with the assistance of the Tri-Metropolitan Transit Authority (Tri-Met). Tri-Met arranged for a team of data collection field personnel from a local agency to be available for hire, and it identified critical segments of the bus lanes.

Fifth Avenue. Bus flowrates on Fifth Avenue reached a peak of 156 buses/hr between 4:30 and 5:30 p.m. The peak 15-min flowrate (4:30-4:45 p.m.) was 164 buses/hr. Bus operations appeared to approach capacity during peak periods and when bus arrivals clustered. The 15-min average bus speeds during the study ranged from 2.6 to 5.3 mph (4.2 to 8.5 km/h); 15-min bus flowrates ranged from 104 to 164 buses/hr; and 15-min average dwell times ranged from 24 to 46 sec for the four bus stops in the skip-stop pattern.

Sixth Avenue. Bus flowrates on Sixth Avenue reached a peak of 104 buses/hr between 4:30 and 5:30 p.m. The peak 15-min flowrate was 112 buses/hr. The 15-min average bus speeds ranged from 3.7 to 4.3 mph (6.0 to 6.8 km/h); 15-min bus flowrates ranged from 88 to 116 buses/hr; 15-min average dwell times ranged from 23 to 35 sec for the four stops in the skip-stop pattern.

During the site reconnaissance, it was observed that Sixth Avenue generally operated at less than capacity during the peak periods. Tri-Met field supervisors indicated that this was primarily because of the route structure. Although similar bus volumes and routes use Sixth as on Fifth, Sixth Avenue has fewer and predominantly alighting passengers during the p.m. peak period and lower average dwell times.

Capacity and Speed Comparisons

Bus capacities and average bus speeds were estimated using the procedures set forth in *TCRP Report 26*. Key assumptions and considerations were as follows:

- A clearance time, t_c, between successive buses of 15 sec was used in the capacity equation.
- In estimating capacities for multiple stops along the streets, the lowest capacity at any one stop for each stop pattern was used.
- The base speed, V_o, was obtained from Column E in Table 6.
- The bus dwell times used to enter Table 6 were computed from an average of all bus stops in the study section during each period.

How to estimate the number of effective berths and how to select the appropriate failure rate were given careful consideration. The placement of two bus stop groups close to one another on the same block face is critical in estimating capacity. On Fifth and Sixth Avenues, there are only two bus berths at each stop and only room for four buses on each block face. Whenever a queue develops at a bus stop, the waiting bus blocks the departure of buses at the upstream bus stop. Therefore, the acceptable failure rate (i.e., the probability that queues will develop at the bus stop) is essentially zero for operations at capacity. Accordingly, a failure rate value of 1 percent was selected; this failure rate has an associated one-tail normal variate, Z_a, of 2.330.

An alternative assumption regarding the number of effective bus berths was also tested. In this alternative, each block face was considered as one 4-berth stop rather than

TABLE 6 Revised 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) Central Bus. District (Delay=2.0 min./mile)		(C) Central City (Delay=0.6 min./mile)		(D) Central Bus. District (Delay=0.5 min./mile)		(E) Central Bus. District (Delay=1.2 min./mile)	
Dwell Time per Stop (sec.)	Stops Per 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)	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	16.7
	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	6.30	9.5	4.90	12.2	4.80	12.5	5.50	10.9
	8	5.53	10.8	7.53	8.0	6.13	9.8	6.03	10.0	6.73	8.9
	10	7.00	8.6	9.00	6.7	7.60	7.9	7.50	8.0	8.20	7.3
20	2	2.73	22.0	4.73	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	6.87	8.7	8.87	6.8	7.47	8.0	7.37	8.1	8.07	7.4
	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	14.1
	4	4.60	13.0	6.60	9.1	5.20	11.5	5.10	11.8	5.80	10.3
	6	6.30	9.5	8.30	7.2	6.90	8.7	6.80	8.8	7.50	8.0
	8	8.20	7.3	10.20	5.9	8.80	6.8	8.70	6.9	9.40	6.4
	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	9.53	6.3	11.53	5.2	10.13	5.9	10.03	6.0	10.73	5.6
	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	10.88	5.5	12.88	4.7	11.48	5.2	11.38	5.3	12.08	5.0
	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	12.21	4.9	14.21	4.2	12.81	4.7	12.71	4.7	13.41	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 lanes where capacity analysis includes deductions for right-turn interferences.

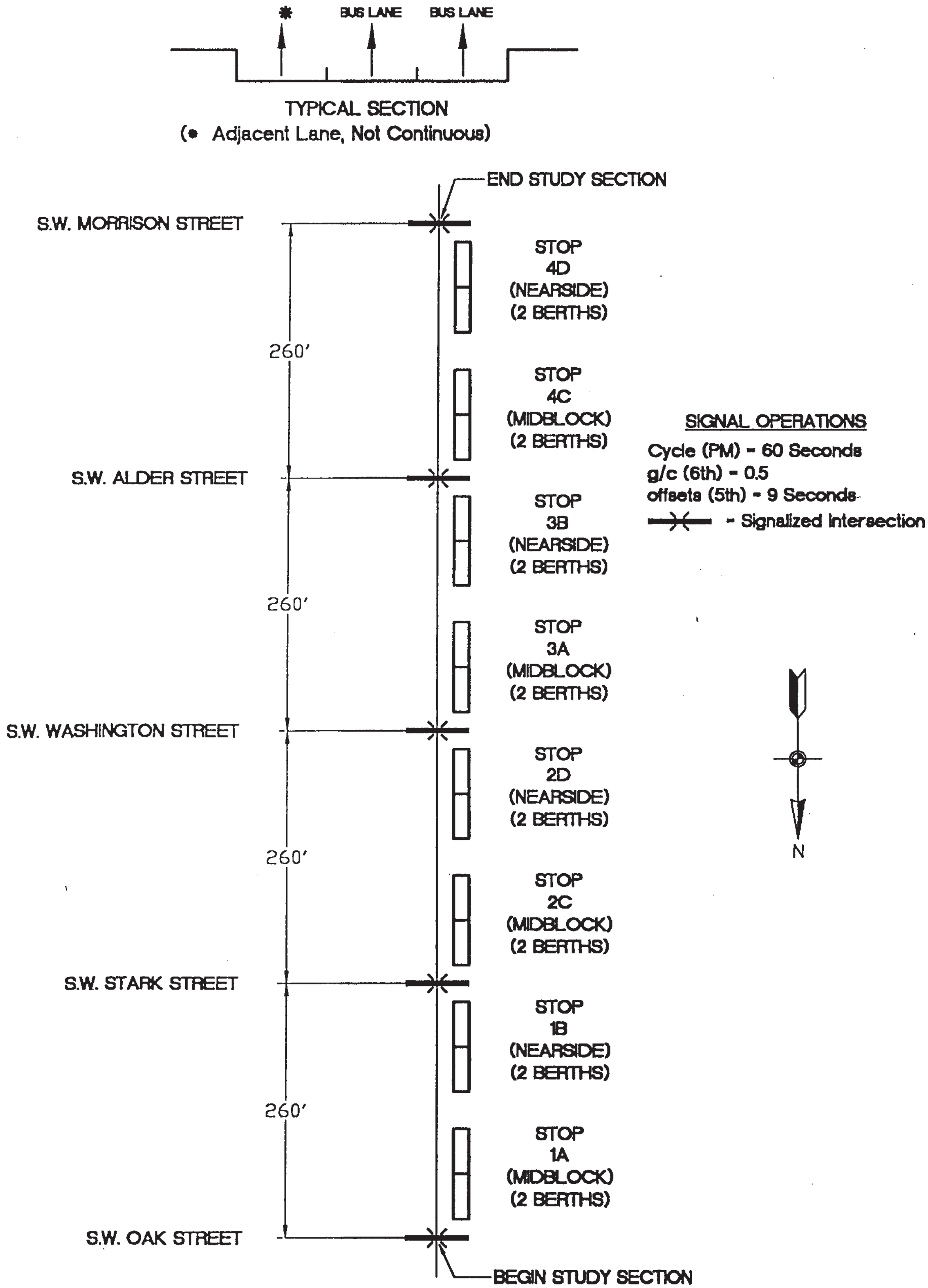


Figure 2. Fifth Avenue study area, Portland, Oregon.

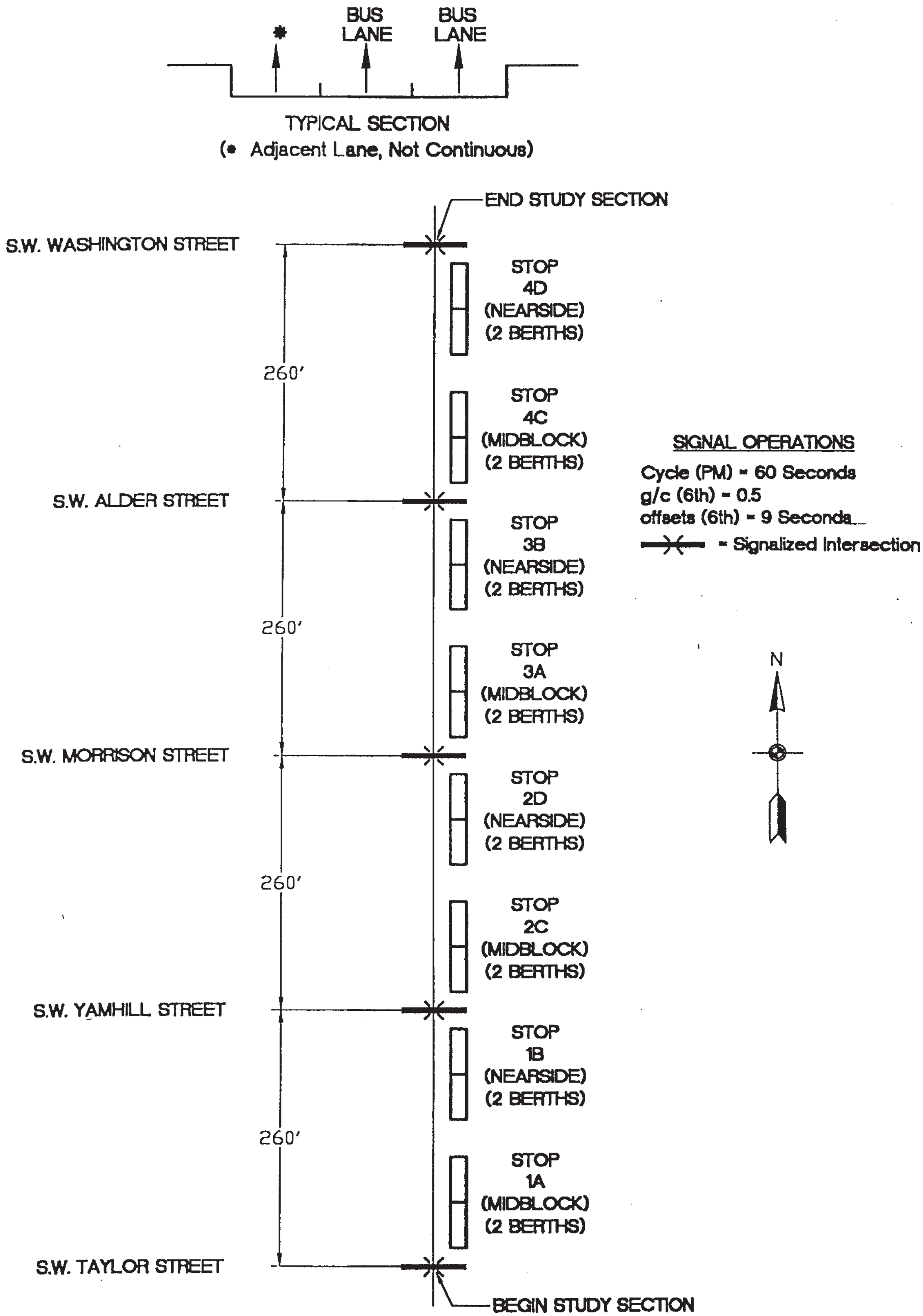


Figure 3. Sixth Avenue study area, Portland, Oregon.

two independent 2-berth stops. For this application, a failure rate of 25 percent ($Z = 0.675$) was used.

Fifth Avenue. The comparisons of observed and estimated bus flowrates and bus speeds, assuming two 2-berth stops per block and a 1-percent failure rate, are shown in Table 7. Field observations indicated that bus operations approach capacity beginning near 5:00 p.m. This phenomenon is reflected in the estimated bus *v/c* ratios in Table 7. As shown in Figure 4, the 15-min averages of the observed bus speeds are reasonably estimated using the relationships established in *TCRP Report 26*. The difference between estimated and observed average bus speeds ranged from zero to 0.8 mph. On average, the speeds estimated were approximately 0.2 mph higher than those observed. Capacities and estimated bus speeds (assuming a single 4-berth stop and a 25-percent failure rate) are shown in Table 8.

Table 9 compares estimated and observed bus speeds for both sets of bus-berth assumptions and failure rates. Both sets of calculations provide reasonable estimates of observed speeds and are generally within 1 standard deviation of the observed speeds. However, by assuming two 2-berth stops and a 1-percent acceptable failure rate, a slightly better estimation—an average error of 0.4 mph as compared with 0.7 mph for the 4-berth assumption—can be produced.

The frequency of traffic signals (i.e., every block) as compared with the frequency of bus stops (i.e., every other block) results in greater time loss (because of bus acceleration and deceleration) beyond that accounted for by the 1.2 min/mi signal delay. When this incremental delay is increased from 1.2 to 2.0 min/mi, as shown in Table 9, there is a slight reduction in the average error (from 0.4 to 0.3 mph).

Sixth Avenue. Table 10 and Figure 5 compare observed and estimated bus flowrates and speeds, assuming a 1-percent failure rate and two 2-berth stops, for Sixth Avenue. The estimated bus speeds are generally about 0.5 to 1.0 mph higher than the observed speeds. Bus dwell times were usually short. Many of the 15-min average dwell times were under 15 sec. Some buses were able to proceed through the traffic signals in their "dwell range window"; other buses incurred significant delay. For the relatively short segment of street analyzed, the traffic signal delay had a greater influence than expected.

Accordingly, further comparisons were made, assuming an incremental delay of 2.0 min/mi (rather than the 1.2 min/mi assumed in Table 6). Table 11 shows the resulting speed comparisons. This adjustment reduced the average difference between estimated and observed speeds from 1.0 mph to 0.8 mph.

Observations and Comments

The closely spaced skip-stop operations of four alternating bus route patterns in dual bus lanes was a good, albeit stringent, test of the bus capacity and speed estimating procedures. Overall, the relationships in *TCRP Report 26* estimated bus capacities and speeds in complex settings with reasonable accuracy. However, careful assumptions regarding the number of effective berths and the acceptable failure rates were essential. There was a generally good match between estimated and observed conditions. Estimated capacities were usually reached during periods that had significant congestion.

Estimated bus speeds for specific 15-min periods were generally within 1 standard deviation of the observed speeds. The standard deviations of the bus speeds for 15-min periods were as high as 1.5 mph.

Along Sixth Avenue, several periods with low dwell times had estimated speeds that exceeded observed speeds by 1.0 mph or more. This condition was attributed to buses getting caught at traffic signals between stops and incurring more than the 1.2 min/mi of delay suggested in Table 6. The differences between observed and estimated speeds were reduced when the incremental signal delay was increased to 2.0 min/mi to reflect the greater frequency of traffic signals.

Second Avenue, New York City, New York

Second Avenue is a wide multilane southbound street in Manhattan. New York City Transit and the New York City Department of Transportation indicated that the road operates at its capacity during evening peak hours and that traffic conditions delay buses. Traffic congestion is common on approaches to the Queensboro Bridge and at intersections with major crosstown arterials such as 42nd and 57th Streets.

Second Avenue is a Type 2 curb bus lane; buses can use the adjacent lane, as available, to leave the bus lane when necessary. Bus stops are generally on the near side of the intersection, approximately every two to three blocks (about 750 ft), and can store up to two stopped buses. Buses stop at each stop. A five-block segment was analyzed. This segment included two complete bus stop patterns. The study section extended from 56th Street to 51st Street, with a total length of approximately 1,320 ft. The traffic signals operate on a fixed-time 90-sec cycle with a green-plus-amber-plus-all-red time for Second Avenue of approximately 50 sec. The signals are timed for southbound progression with start-of-green offsets set at approximately 7 sec from block to block. Figure 6 shows the study area and the arrangements of the bus stops.

Field Surveys and Data Summaries

During an initial site reconnaissance, a vantage point was selected and, subsequently, arrangements were made to lease space for videotaping bus operations. Data were collected on Second Avenue on Tuesday, October 21, 1997. Bus flowrates on Second Avenue reached a peak of 40 buses/hr between 4:15 and 5:15 p.m. The peak 15-min flowrate was 52 buses/hr. Bus operations did not approach bus berth

TABLE 7 Observed bus flowrates and speeds versus estimated capacity and speeds (two 2-berth stops per block and 1% failure), Fifth Avenue, Portland, Oregon

Time Period (p.m.)	Average Dwell, seconds / Coefficient of Variation (Ratio) at each bus stop: 1A	1B	2C	2D	3A	3B	4C	4D	Flow Rate, bph	Average Speed mi/hr	Average Speed km/h	Avg Dwell Sec	Cap., bph	Bus v/c Ratio	Vo from Table 6	Adj Factor *fb*	Calculated Speed mi/hr	Calculated Speed km/h	Difference mi/hr (Calc-Obs)
3:15-3:30	48 / 0.28 *	65 / 0.35 *	26 / 0.37 *	46 / 0.05 *	n/a / n/a	16 / 1.13	n/a / n/a	24 / 0.79	76	4.3	6.9	38	170	0.45	4.6	1.00	4.6	7.3	0.3
3:30-3:45	31 / 0.49	41 / 0.18	28 / 0.37 *	30 / 0.00	33 / 0.69 *	19 / 0.73 *	22 / 0.23	45 / 0.77 *	108	4.1	6.6	31	144	0.75	5.1	0.84	4.3	6.8	0.2
3:45-4:00	27 / 0.63 *	32 / 0.64 *	10 / 1.81 *	25 / 0.73 *	18 / 0.49	29 / 0.59	24 / 0.21	26 / 0.56	104	4.7	8.5	24	149	0.70	5.7	0.88	5.0	7.9	0.3
4:00-4:15	18 / 0.56 *	42 / 0.44 *	26 / 0.30 *	34 / 0.53 *	14 / 0.28	14 / 0.53	28 / 0.11	24 / 0.45	136	3.7	6.0	25	175	0.78	5.7	0.94	5.5	8.7	0.9
4:15-4:30	30 / 0.43 *	26 / 0.52	16 / 0.30	28 / 0.43 *	17 / 0.45	20 / 0.81 *	19 / 0.45 *	26 / 0.45	108	4.6	7.7	23	186	0.82	5.7	0.78	4.4	7.0	0.8
4:30-4:45	28 / 0.60 *	39 / 0.38 *	31 / 0.72 *	18 / 0.2 *	16 / 0.29	15 / 0.53	24 / 0.24	14 / 0.29	164	3.4	5.5	23	179	0.92	5.8	0.65	3.8	5.9	0.4
4:45-5:00	29 / 0.64 *	30 / 0.42	16 / 0.34	24 / 0.30	25 / 0.31	30 / 0.64 *	18 / 0.34 *	25 / 0.40 *	152	3.6	5.9	25	186	0.82	5.7	0.78	4.4	7.0	0.8
5:00-5:15	43 / 0.13 *	29 / 0.41 *	36 / 0.87 *	30 / 0.48 *	20 / 0.28	16 / 0.88	29 / 0.48	32 / 0.31	160	2.6	4.2	29	162	0.99	5.3	0.52	2.8	4.4	0.2
5:15-5:30	28 / 0.60 *	28 / 0.56 *	17 / 0.51	41 / 0.90 *	19 / 0.20	19 / 0.69	27 / 0.53 *	35 / 0.38	148	3.0	4.5	27	139	1.06	5.5	0.40	2.2	3.5	-0.8

Notes:
1. g/C = 0.55
2. Capacity computed for the critical section of stop patterns A, B, C, and D using the highlighted values of D and Cv denoted by asterisk.
3. Average speed computed using the average of all observed dwell times during the time period.

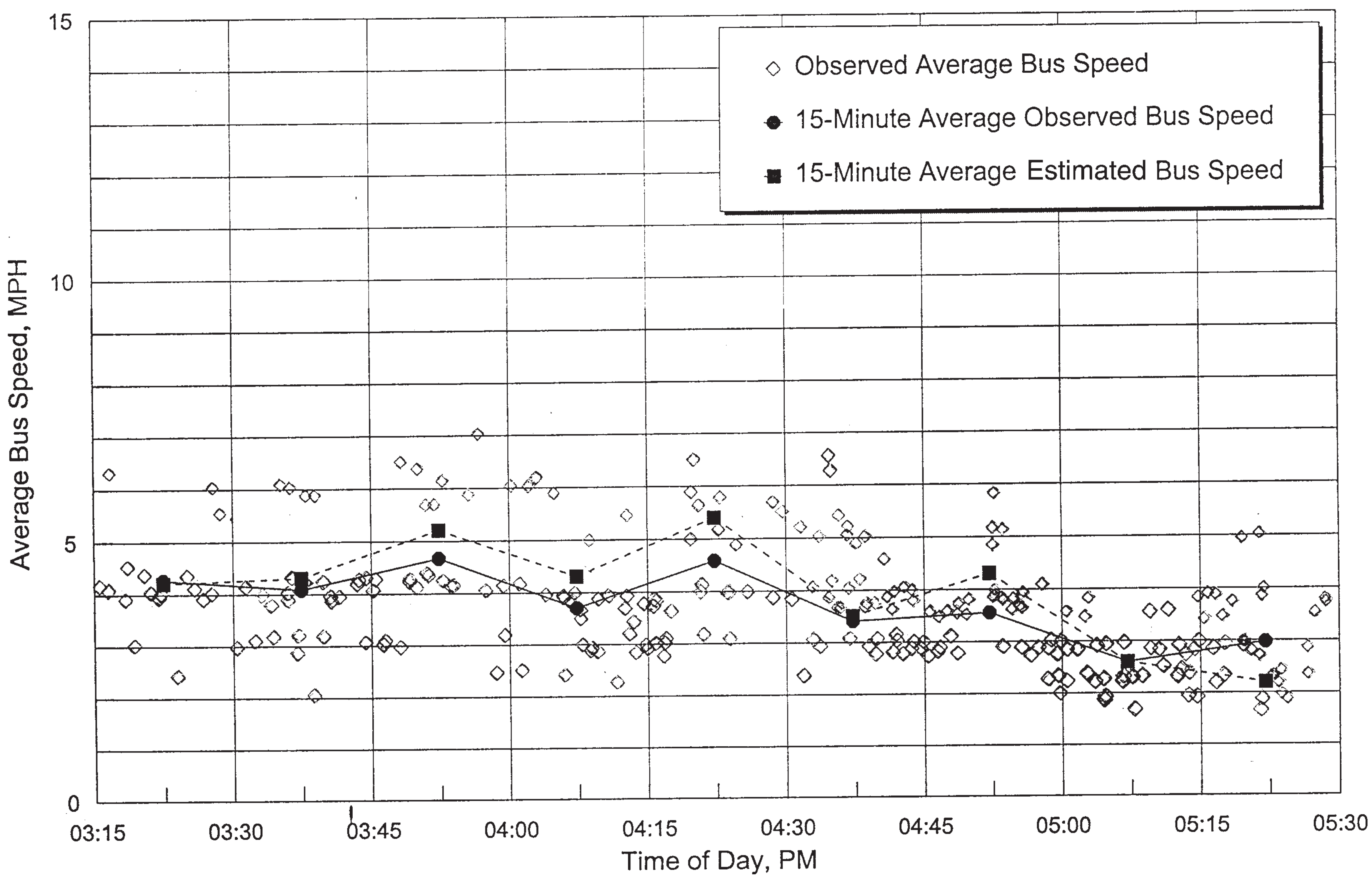


Figure 4. Observed versus estimated bus speeds, Fifth Avenue study area, Portland, Oregon.

TABLE 8 Observed bus flowrates and speeds versus estimated capacity and speeds (single 4-berth stops per block and 25% failure), Fifth Avenue, Portland, Oregon

Time Period (p.m.)	Average Dwell, seconds / Coefficient of Variation (Ratio) at Each Bus Stop								Flow Rate, bph	Average Speed		Avg Dwell Sec	Capacity bph	Bus v/c Ratio	Vo from Table 6	Adj Factor *fb*	Calculated Speed		Difference
	1A	1B	2C	2D	3A	3B	4C	4D		mi/hr	km/h						mi/hr	km/h	Mi/hr (Calc-Obs)
	48	65	26	46	n/a	16	n/a	24											
3:15-3:30	0.28	0.35	0.37	0.05	n/a	1.13	n/a	0.79	76	4.3	6.9	38	148	0.45	4.6	1.00	4.6	7.3	0.3
		*		*															
	31	41	28	30	33	19	22	45											
3:30-3:45	0.49	0.18	0.37	0.00	0.69	0.73	0.23	0.77	108	4.1	6.6	31	150	0.75	5.1	0.84	4.3	6.8	0.2
					*			*											
	27	32	10	25	18	29	24	26											
3:45-4:00	0.63	0.64	1.81	0.73	0.49	0.59	0.21	0.56	104	4.7	8.5	24	182	0.70	5.7	0.88	5.0	7.9	0.3
		*		*															
	18	42	26	34	14	14	28	24											
4:00-4:15	0.56	0.44	0.30	0.53	0.28	0.53	0.11	0.45	136	3.7	6.0	25	172	0.78	5.7	0.94	5.5	8.7	0.9
		*		*															
	30	26	16	28	17	20	19	26											
4:15-4:30	0.43	0.52	0.30	0.43	0.45	0.81	0.45	0.45	108	4.6	7.7	23	206	0.82	5.7	0.78	4.4	7.0	0.8
	*			*															
	28	39	31	18	16	15	24	14											
4:30-4:45	0.60	0.38	0.72	0.25	0.29	0.53	0.24	0.29	164	3.4	5.5	23	200	0.92	5.8	0.65	3.8	5.9	0.4
		*	*																
	29	30	16	24	25	30	18	25											
4:45-5:00	0.64	0.42	0.34	0.30	0.31	0.64	0.34	0.40	152	3.6	5.9	25	211	0.82	5.7	0.78	4.4	7.0	0.8
	*					*		*											
	43	29	36	30	20	16	29	32											
5:00-5:15	0.13	0.41	0.87	0.48	0.28	0.88	0.48	0.31	160	2.6	4.2	29	169	0.99	5.3	0.52	2.8	4.4	0.2
	*		*																
	28	28	17	41	19	19	27	35											
5:15-5:30	0.60	0.56	0.51	0.90	0.20	0.69	0.53	0.38	148	3.0	4.5	27	153	0.97	5.5	0.40	2.2	3.5	-0.8
	*	*		*			*												

Notes:

1. g/C = 0.50
2. Capacity computed for the critical section of stop patterns A/B and C/D using the highlighted values of D and Cv denoted by asterisk.
3. Average speed computed using the average of all observed dwell times during the time period

TABLE 9 Summary comparison of alternatives analyzed, Fifth Avenue, Portland, Oregon

Time Period (p.m.)	Bus Flow Rate[2] Buses/hr	Average Dwell, sec.	Observed Speed[1] (mph)		Estimated Speed (mph)		
			Average Speed	Standard Deviation	Table 7 (1% Failure)	(Adjusted) Table 7 (1% Failure) 2.0 min/mi Loss	Table 8 (4 Berth) (25% Failure Rate)
3:15-3:30	76	38	4.3	0.9	4.6	4.3	4.5
3:30-3:45	108	31	4.1	1.0	4.3	4.0	4.5
3:45-4:00	104	24	4.7	3.0	5.0	4.7	5.4
4:00-4:15	136	25	3.7	1.2	4.7	4.3	4.7
4:15-4:30	108	23	4.6	1.5	5.5	5.1	5.6
4:30-4:45	164	23	3.4	1.4	3.8	3.5	4.6
4:45-5:00	152	25	3.6	1.2	4.4	4.1	4.8
5:00-5:15	160	29	2.6	0.5	2.8	2.6	3.3*
5:15-5:30	148	27	3.0	0.8	2.2	2.1	3.1
Average Difference (Absolute) = ∑ [Estimated Minus Observed] /n					0.4	0.3	0.7

Notes: [1] Observations with valid speed measurements
[2] 15-min flowrate expressed as buses/hr
* Beyond ± 1 Standard Deviation

capacity at this peak flowrate, although some delays were incurred. These delays primarily were the result of stops at intermediate signals, right turns, and bus lane blockage. The bus lane was blocked for much of the observation period by stopped automobiles and trucks. Even when the bus lane was not blocked, buses used the adjacent lane, except when approaching the bus stop, to avoid delays caused by the right turns of other vehicles and any potential blockage. The bus stop was not blocked by automobiles or trucks loading at curbside. The 15-min average bus speeds during the study period ranged from 4.4 to 8.0 mph (7.1 to 12.9 km/h); 15-min bus flowrates varied from 20 to 52 buses/hr; 15-min average dwell times varied from 17 to 48 sec.

Capacity and Speed Comparisons

Bus capacity and average bus speeds were estimated using the procedures set forth in *TCRP Report 26.* A traffic delay of 2.0 min/mi was assumed–the suggested value for curb bus lanes with right-turn friction. Table 12 compares observed and estimated speeds.

The relationships in *TCRP Report 26* generally estimated bus speeds that were 10 to 30 percent higher than the observed bus speeds between 3:30 and 4:45 p.m. The lower observed speeds may be attributed to factors such as the following: (1) two-to-three signalized intersections between bus stops; (2) traffic interferences that block the bus lane (e.g., delivery vehicles and passenger pickup activities); and (3) buses maneuvering around blockages of the bus lane and into the adjacent general traffic lane.

A review of the videotape taken along the Second Avenue study area found that buses commonly use the adjacent lane, rather than the bus lane, to travel from bus stop to bus stop. The effect of the lane blockage was highly irregular—depending on when in the signal cycle the bus needed to enter the adjacent lane (availability of gaps) and how close the blockage was to the stop. When lane blockage occurred near the corner with a heavy right-turn movement, the right turns affected bus speeds significantly. Right-turn volumes (on every other street) were approximately 200 vehicles/hr.

Accordingly, adjustments appeared desirable in order to better predict the effects of lane blockage. Two possible approaches were examined:

- The bus travel times were based on those anticipated in mixed flow for a CBD environment. The delay value for **mixed-flow** bus operations in a CBD (presented in Table A-4 in Appendix A of *TCRP Report 26*) is 3.0 min/mi as compared with the 2.0 min delay/mi used in Table 6 of this digest for a **bus lane** in the CBD. Thus,

TABLE 10 Observed bus flowrates and speeds versus estimated capacity and speeds, Sixth Avenue, Portland, Oregon

Time Period	AverageDwell, seconds at each bus stop / Coefficient of Variation (Ratio) at each bus stop								Flow Rate, bph	Average Speed		Avg Dwell sec	CAPACITY, bph	Bus v/c Ratio	Vo from Table 6	Adj. Factor fb	Calculated Speed,		Difference mi/hr
	1A	1B	2C	2D	3A	3B	4C	4D		mi/hr	km/hr						mi/hr	km/hr	(Calc-Obs)
3:45-4:00 pm	n/a	55	32	13	n/a	45	24	26	88	3.9	6.8	33	100 (3 stops)	0.88	4.9	0.70	3.4	5.5	-0.5
	n/a	0.73	0.54	0.45	n/a	0.99	0.24	1.20											
			*			*		*											
4:00-4:15 pm	8	27	37	10	12	39	28	12	96	3.7	6.0	22	234	0.41	5.6	1.00	5.6	9.0	1.9
	0.33	0.37	0.34	0.42	0.36	0.42	0.46	0.48											
			*		*	*		*											
4:15-4:30 pm	n/a	44	33	12	26	34	42	22	88	4.1	6.6	30	216	0.41	5.1	1.00	5.1	8.2	1.0
	n/a	0.55	0.44	0.45	0.00	0.51	0.85	0.22											
					*	*	*	*											
4:30-4:45 pm	n/a	31	43	6	35	39	34	16	96	4.0	6.5	29	191	0.50	5.0	0.97	4.9	7.8	0.9
	n/a	0.42	0.39	0.42	0.00	0.87	0.07	0.62											
			*		*	*													
4:45-5:00 pm	n/a	33	47	12	n/a	37	29	10	100	4.2	6.8	28	140 (3 stops)	0.71	5.2	0.87	4.5	7.3	0.3
	n/a	0.81	0.23	0.46	n/a	0.35	0.26	0.65											
			*	*				*											
5:00-5:15 pm	9	34	48	16	6	34	30	17	104	4.1	6.5	24	229	0.45	5.5	1.00	5.5	8.9	1.4
	0.38	0.36	0.25	0.33	0.27	0.39	0.32	0.56											
	*		*			*		*											
5:15-5:30 pm	n/a	43	40	17	n/a	39	45	15	112	4.1	6.6	33	117 3 stops)	0.96	5.0	0.64	3.2	5.2	-0.9
	n/a	0.89	0.44	0.91	n/a	0.76	0.40	0.97											
		*		*			*												

Notes:

1. g/C = 0.55
2. Capacity computed for the critical section of stop patterns A, B, C, and D using the highlighted values of D and Cv.
3. Average speed computed using the average of all observed dwell times during the time period, excluding stops with no observed buses.

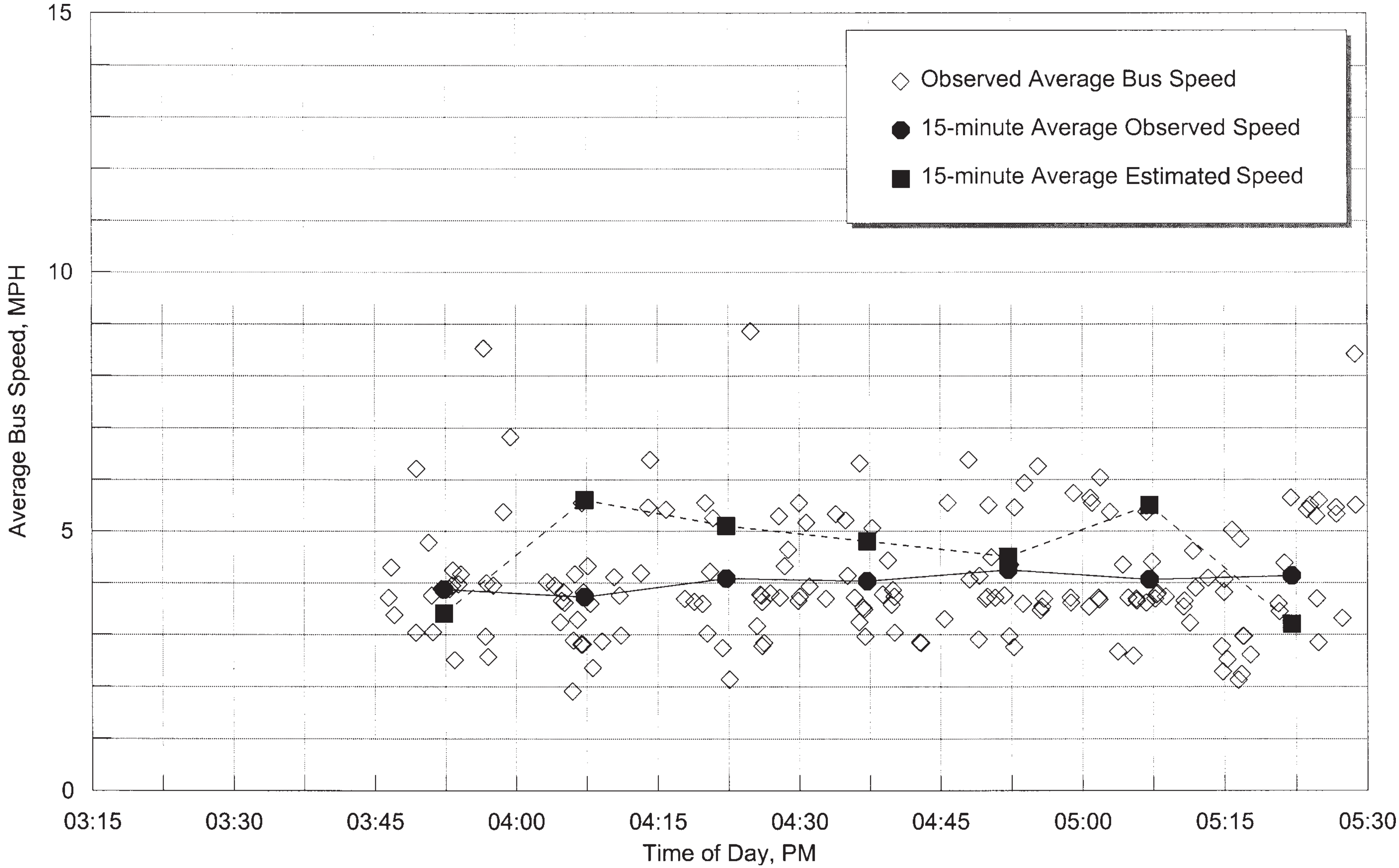


Figure 5. Observed versus estimated bus speeds, Sixth Avenue study area, Portland, Oregon.

TABLE 11 Summary comparison of alternatives analyzed, Sixth Avenue, Portland, Oregon

Time Period (p.m.)	Bus Flowrate Buses/hr [2]	Average Dwell (Sec)	Observed Average Speed[1]	Standard Deviation	Table 10 Estimated Speed (mph) 1% Failure	(Adjusted) Estimated Speed (mph)/1% Failure 2.0 Min/mi Time Loss
			mph	mph		
3:45-4:00	88	33	4.2	1.4	3.4	3.2
4:00-4:15	96	22	3.7	1.0	5.6*	5.2*
4:15-4:30	88	30	4.1	1.4	5.1	4.8
4:30-4:45	96	29	4.0	0.9	4.9	4.5
4:45-5:00	100	28	4.2	1.1	4.5	4.2
5:00-5:15	104	24	4.1	0.9	5.5	5.1
5:15-5:30	112	33	4.1	9.5	3.2	3.0
Average Difference (Absolute) = Σ [Estimated Minus Observed]/n					1.0	0.8

Notes:
1. Observed with valid speed measurements
2. 15-min flowrate, buses/hr
* Beyond 1 standard deviation of observed speeds.

without a bus lane, general traffic delays add about 1.0 min/mi to the CBD travel times. Table 13 presents the results of this analysis. The differences between observed and estimated speeds are generally reduced.

- A reductive factor for lane blockage could be added to the capacity and/or bus speed equations. One possible lane blockage factor could be a capacity reduction element that includes an additional term in the right-turn factor, such as the following:

$$f_R = 1\text{-}L_B\,(V_R/C_R) - (0.4)(B_L/60)(v/c)^*$$

Where: B_L = Number of minutes per hour that lane is blocked
v/c = Volume-to-capacity ratio in the lane adjacent to the bus lane

*This equation is a modified form of Equation 2-13 on page 27 of *TCRP Report 26*.

Table 14 gives the results of using this reductive factor for lane blockage.

Table 15 and Figure 7 compare the observed speeds with the estimated speeds for each of the three methods. Using the traffic delays of 3.0 min/mi associated with mixed traffic serves to make estimated speeds mirror observed speeds more closely.

Observations and Comments

There were relatively few observations made in most of the 15-min intervals. The daily fluctuations in traffic movements and lane blockage occurrences make the average speeds of buses on Second Avenue highly variable. Despite similar average dwell times, bus speeds could be slower or faster, depending on various potential delay sources (e.g., the location along the block that a certain vehicle blocked the bus lane, bunching of right-turn vehicles, the number of pedestrians crossing the street, queuing on the cross streets, and the order of arrival of buses in the traffic stream).

It seems appropriate to add a lane blockage factor to the speed prediction relationships. This can be accomplished by adding 1.0 min/mi to the traffic impedance value, thereby resulting in a total traffic delay of 3.0 min/mi–the same as for mixed traffic. However, the effects of bus lane blockage may vary widely, depending on other potential delay sources, and user discretion should be applied when such adjustments are used. Further study may be required to quantify the effects of bus lane blockage under various conditions.

Albert Street, Ottawa, Ontario

Albert Street is part of a one-way couplet (with Slater Street) that serves downtown Ottawa and connects to the busways on each side of downtown. A normal-flow Type 2 bus lane and two adjacent travel lanes are provided. Bus stops are located every two blocks, and all buses stop at each stop. The block spacing is approximately 567 ft (183 m), stop bar to stop bar; thus, the stop spacing is every 1,134 ft for a stop density of 4.7 stops/mi. At streets where right turns are allowed, a right-turn pullover lane is provided, and there are no bus stops on the near side.

Buses arrive somewhat randomly onto Albert Street, but create queues up to several buses long at the Metcalf Street near-side bus stop just upstream of the study section,

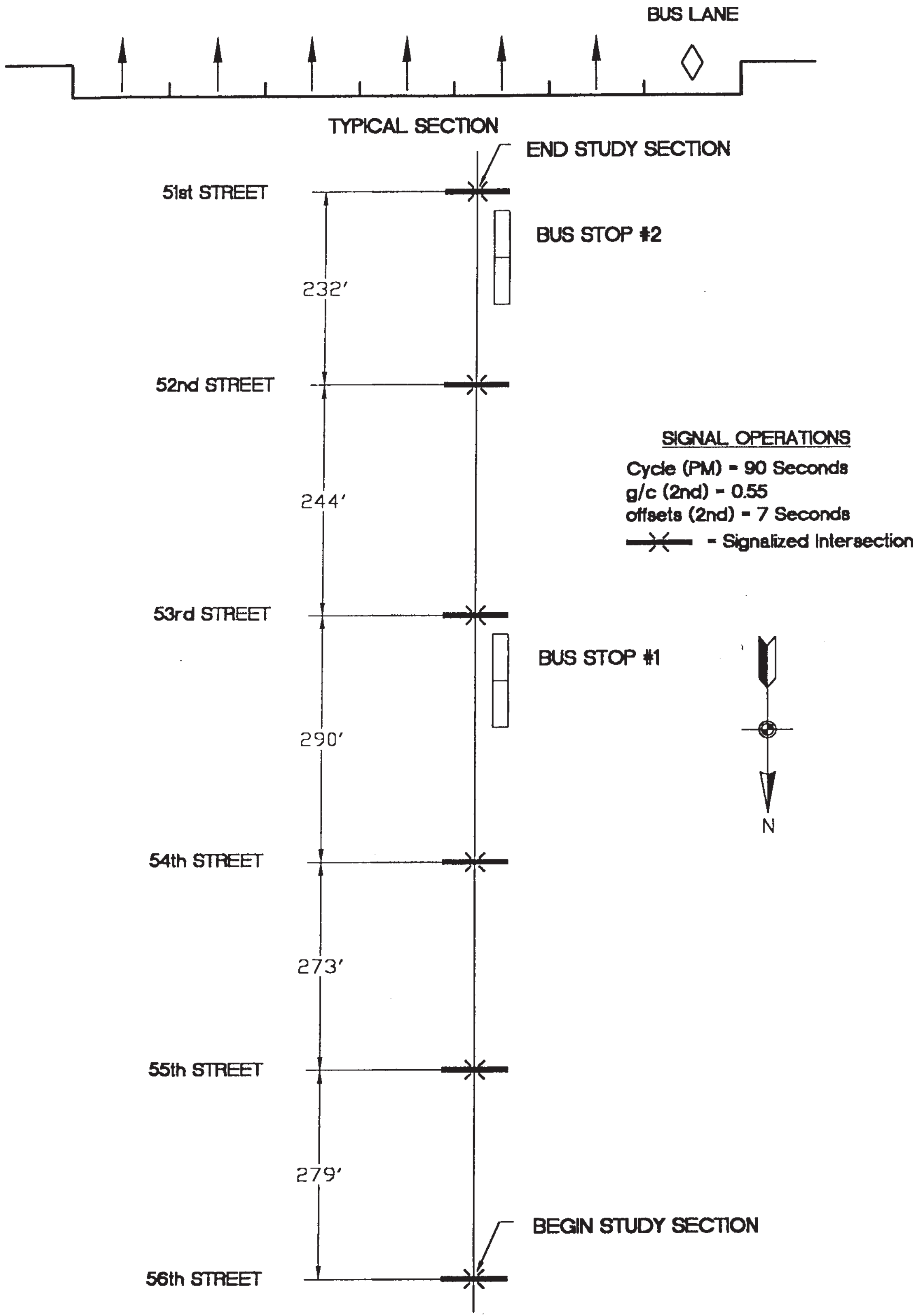


Figure 6. Second Avenue study area, New York City, New York.

TABLE 12 Observed bus flowrates and speeds versus estimated capacity and speeds, Second Avenue, New York City, New York

Time Period (p.m.)	Average Dwell, seconds / Coefficient of Variation		Flow Rate, bph	Average Speed mi/hr	Average Speed km/h	Average Dwell Sec	Capacity bph	Bus v/c Ratio	Vo from Table 6	Adj Factor *fb*	Calculated Speed mi/hr	Calculated Speed km/h
	STOP #A	STOP #B										
3:00-3:15	34	20	20	6.3	10.1	27.0	69	0.29	6.3	1.00	6.3	10.1
	0.41	0.05										
3:15-3:30	5	29	20	8.0	12.9	17.0	73	0.27	7.3	1.00	7.3	11.7
	1.14	0.50										
3:30-3:45	29	24	28	4.9	7.9	26.5	81	0.35	6.3	1.00	6.3	10.2
	0.22	0.54										
3:45-4:00	27	26	32	5.1	8.2	26.5	93	0.34	6.3	1.00	6.3	10.2
	0.04	0.15										
4:00-4:15	26	29	24	5.3	8.5	27.5	68	0.35	6.2	1.00	6.2	10.0
	0.00	0.66										
4:15-4:30	17	31	52	5.7	9.2	24.0	80	0.65	6.5	0.92	6.0	9.7
	0.76	0.24										
4:30-4:45	16	29	32	5.9	9.5	22.5	80	0.40	6.7	1.00	6.7	10.7
	0.37	0.32										
4:45-5:00	26	18	16	7.8	12.6	22.0	102	0.16	6.7	1.00	6.7	10.8
	0.00	0.00										
5:00-5:15	44	28	36	5.4	8.7	36.0	58	0.62	5.6	0.92	5.2	8.3
	0.42	0.08										
5:15-5:30	19	12	36	6.1	9.8	15.5	75	0.48	7.5	1.00	7.5	12.0
	1.12	0.27										
5:30-5:45	23	50	24	4.4	7.1	36.5	58	0.42	5.5	1.00	5.5	8.9
	0.33	0.27										
5:45-6:00	73	35	24	5.0	8.0	54.0	54	0.44	4.5	1.00	4.5	7.3
	0.00	0.54										

Notes:
1. g/C = 0.55 (g = green + amber + all red-lost time)
2. Capacity computed using the highlighted values of D and Cv
3. Average predicted speed computed using the critical dwell and CV for determining Vo
4. Right turn factor fR = 1 – LB* (vR/cR) = 1 – 0.7(0.2) = 0.86

TABLE 13 Observed bus flowrates and speeds versus estimated capacity and speeds, Second Avenue, New York City, New York (Add 1.0 min/mi of delay to travel time for bus lane blockage)

Time Period (p.m.)	Average Dwell, seconds / Coefficient of Variation		Flow Rate, bph	Average Speed		Avg Dwell Sec	Capacity bph	Bus v/c Ratio	Vo from Table 6	Adjusted Vo	Adj Factor fb	Calculated Speed	
	STOP #A	STOP #B		mi/hr	km/h							mi/hr	km/h
3:00-3:15	34 / 0.41	20 / 0.05	20	6.3	10.1	27.0	69	0.29	6.3	5.7	.00	5.7	9.1
3:15-3:30	5 / 1.14	29 / 0.50	20	8.0	12.9	17.0	73	0.27	7.3	6.5	1.00	6.5	10.5
3:30-3:45	29 / 0.22	24 / 0.54	28	4.9	7.9	26.5	81	0.35	6.3	5.7	1.00	5.7	9.2
3:45-4:00	27 / 0.04	26 / 0.15	32	5.1	8.2	26.5	93	0.34	6.3	5.7	1.00	5.7	9.2
4:00-4:15	26 / 0.00	29 / 0.66	24	5.3	8.5	27.5	68	0.35	6.2	5.6	1.00	5.6	9.1
4:15-4:30	17 / 0.76	31 / 0.24	52	5.7	9.2	24.0	80	0.65	6.5	5.9	0.92	5.4	8.8
4:30-4:45	16 / 0.37	29 / 0.32	32	5.9	9.5	22.5	80	0.40	6.7	6.0	1.00	6.0	9.7
4:45-5:00	26 / 0.00	18 / 0.00	16	7.8	12.6	22.0	102	0.16	6.7	6.0	1.00	6.0	9.7
5:00-5:15	44 / 0.42	28 / 0.08	36	5.4	8.7	36.0	58	0.62	5.6	5.1	0.92	4.7	7.6
5:15-5:30	19 / 1.12	12 / 0.27	36	6.1	9.8	15.5	75	0.48	7.5	6.7	1.00	6.7	10.7
5:30-5:45	23 / 0.33	50 / 0.27	24	4.4	7.1	36.5	58	0.42	5.5	5.1	1.00	5.1	8.2
5:45-6:00	73 / 0.00	35 / 0.54	24	5.0	8.0	54.0	54	0.44	4.5	4.2	1.00	4.2	6.8

Notes:

1. g/C = 0.55 (g = green + amber + all red-lost time)
2. Capacity computed using the highlighted values of D and Cv
3. Average predicted speed computed using the critical dwell and CV for determining Vo
4. Right turn factor fR = 1 – LB* (vR/cR) = 1 – 0.7(0.2) = 0.86

TABLE 14 Observed bus flowrates and speeds versus estimated capacity and speeds, Second Avenue, New York City, New York (Add reductive factors for bus lane blockage)

Time Period (p.m.)	Average Dwell, seconds Coefficient of Variation		Flow Rate, bph	Average Speed		Avg Dwell Sec	ORIGINAL CAPACITY bph	MODIFIED CAPACITY bph	Bus v/c Ratio	Vo from Table 6	Adj Factor fb	Calculated Speed	
				mi/hr	km/h							mi/hr	km/h
	STOP #A	STOP #B											
3:00-3:15	34 0.41	20 0.05	20	6.3	10.1	27.0	69	58	0.35	6.3	1.00	6.3	10.1
3:15-3:30	5 1.14	29 0.50	20	8.0	12.9	17.0	73	61	0.33	7.3	1.00	7.3	11.7
3:30-3:45	29 0.22	24 0.54	28	4.9	7.9	26.5	81	68	0.41	6.3	0.99	6.2	10.0
3:45-4:00	27 0.04	26 0.15	32	5.1	8.2	26.5	93	78	0.41	6.3	0.99	6.2	10.0
4:00-4:15	26 0.00	29 0.66	24	5.3	8.5	27.5	68	57	0.42	6.2	0.98	6.1	9.9
4:15-4:30	17 0.76	31 0.24	52	5.7	9.2	24.0	80	67	0.77	6.5	0.82	5.4	8.7
4:30-4:45	16 0.37	29 0.32	32	5.9	9.5	22.5	80	67	0.48	6.7	0.97	6.5	10.5
4:45-5:00	26 0.00	18 0.00	16	7.8	12.6	22.0	102	85	0.19	6.7	1.00	6.7	10.8
5:00-5:15	44 0.42	28 0.08	36	5.4	8.7	36.0	58	48	0.74	5.6	0.85	4.7	7.6
5:15-5:30	19 1.12	12 0.27	36	6.1	9.8	15.5	75	63	0.57	7.5	0.95	7.1	11.4
5:30-5:45	23 0.33	50 0.27	24	4.4	7.1	36.5	58	48	0.50	5.5	0.97	5.4	8.7
5:45-6:00	73 0.00	35 0.54	24	5.0	8.0	54.0	54	45	0.53	4.5	0.96	4.4	7.0

Notes:
1. g/C = 0.55 (g = green + amber + all red-lost time)
2. Capacity computed using the highlighted values of D and Cv
3. Average predicted speed computed using the critical dwell and CV for determining Vo
4. Right turn factor fR = 1 – LB* (vR/cR) = 1 – 0.7(0.2) = 0.86
5. Add reductive factor to the right lane factor applied to bus lane capacity calculation fR = 1-LB (vR/cR) – (0.25)(BL/60)(v/c) of ad lane=0.55; fR=0.55; fR=0.68

TABLE 15 Summary comparison of alternatives analyzed, Second Avenue, New York City, New York

Time Period	Number of Buses[1]	Observed Speed (mph)		Estimated Speed (mph)		
		Average Speed	Standard Deviation	Table 12 (Delay=2.0 min/mi)	Table 13 (Delay=3.0 min/mi) (Adjusted)	Table 14 (Delay=2.0 min/mi (Right Turn Delay Factor)
3:00-3:15	2	6.3	2.7	6.3	5.7	6.3
3:15-3:30	3	8.0	0.3	7.3*	6.5*	7.3*
3:30-3:45	4	4.9	1.1	6.3*	5.7	6.2
3:45-4:00	2	5.1	1.0	6.3*	5.7	6.2*
4:00-4:15	2	5.3	1.9	6.2	5.6	6.1
4:15-4:30	5	5.7	1.5	6.0	5.1	5.4
4:30-4:45	3	5.9	2.4	6.7	5.4	6.5
4:45-5:00	1	7.8	-	6.7	6.0	6.7
5:00-5:15	3	5.4	0.2	5.2	4.7*	4.7*
5:15-5:30	3	6.1	1.1	7.5*	6.7	7.1
5:30-5:45	3	4.4	0.2	5.5*	5.1*	5.4
5:45-6:00	2	5.0	0.2	4.5*	4.2*	4.4
Average Difference (absolute) [Estimated minus Observed]				0.8	0.5	0.8

Notes: [1]Observations with valid speed measurements in 15-min interval
*Beyond ± 1 standard deviation

which begins at Metcalf. Typically, no more than three buses are served during one cycle length at the Metcalf stop and these proceed in a platoon for the two blocks to the next stop; the remaining buses in the queue move to the front of the Metcalf stop. The signals are timed to facilitate the bus flow to the next stop; the 55-sec cycle compliments the relatively short dwell times, and the 17-sec offset to the downstream signal minimizes the bus stop time at the signal. This signal offset setting is somewhat less than optimal timing for automobile traffic progression, but very efficient for buses.

Each bus stop can accommodate as many as five buses, but bus-operating procedures discourage the fourth bus in line from proceeding past the stop without stopping at the first berth. The signals are timed so that the first set of three buses in platoon would typically leave the bus stop just as the next set of three buses in platoon arrive. The evening peak-period signal cycle is 55 sec (approximately 65 cycles/hr). It appeared that, if three buses could be processed each cycle, the capacity of the bus lane would be 195 buses/hr, and average bus speeds would be approximately 13 mph (including dwell times). Figure 8 shows the lane configuration along Albert Street.

Field Surveys and Data Summaries

Discussions were held with representatives of the Ottawa-Charleston Transport Authority (O-C Transpo) regarding O-C Transpo's bus transit priority treatments and, in particular, its Albert Street and Slater Street bus lanes. O-C Transpo has been investigating the relationships between signal operations and bus operations along these and other arterials for many years. The intersection of Albert and Metcalf was identified as one of the busier p.m. stops.

Data were collected on Albert Street from 3:30 to 5:30 p.m. on Thursday, October 23, 1997, by O-C Transpo. A two-block segment from Metcalf to Bank was selected that included one complete stop pattern.

Bus flowrates on Albert Street reached a peak of 139 buses/hr between 4:30 and 5:30 p.m. The peak 15-min flowrate was 164 buses/hr. Bus operations approached capacity at the stop upstream of the Metcalf intersection where bus arrivals clustered and queues of four to six buses occurred. The 15-min average bus speeds in the study section ranged from 8.4 to 12.8 mph (13.4 to 20.6 km/h); 15-min average dwell times ranged from 15 to 27 sec.

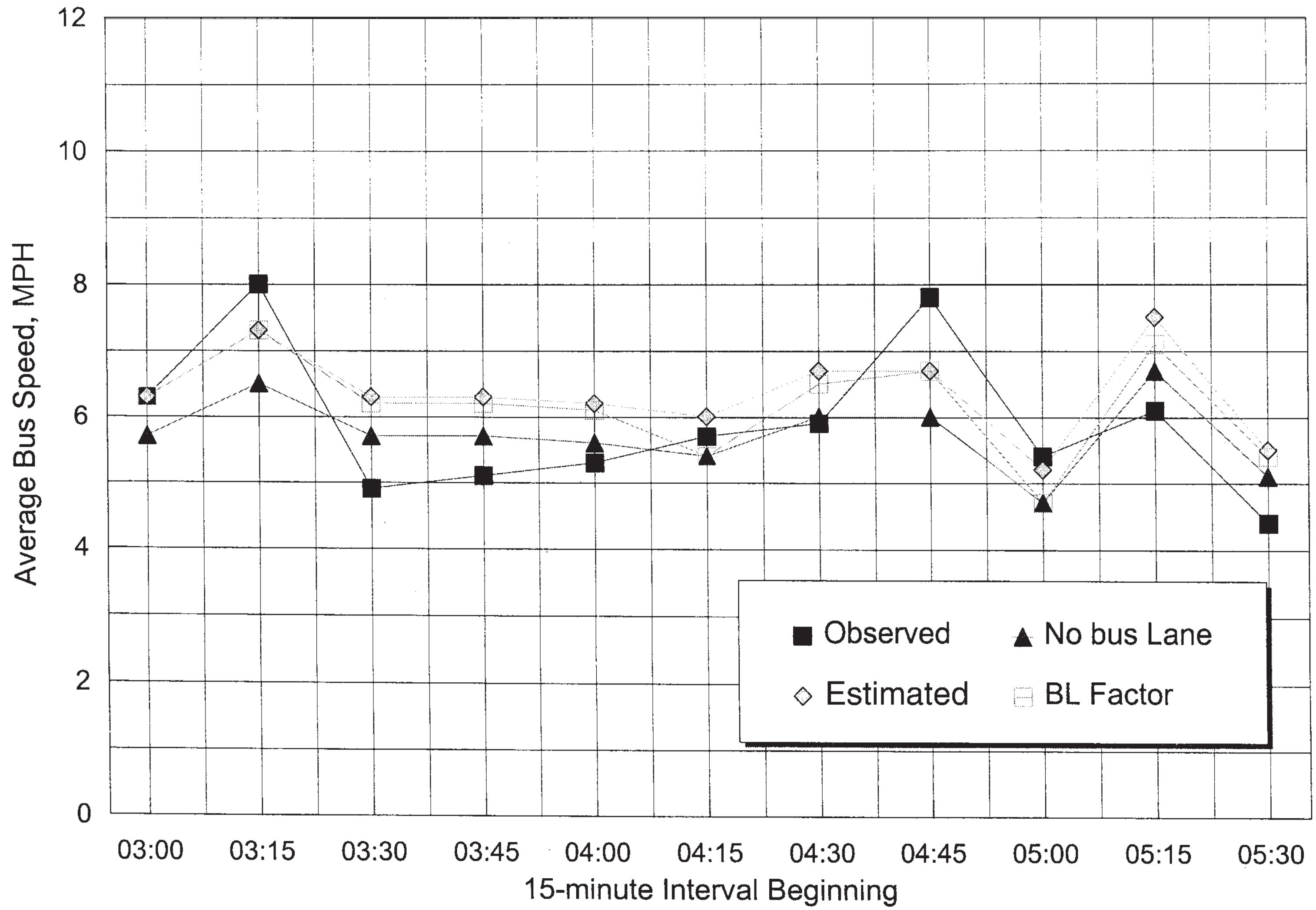


Figure 7. Observed versus estimated bus speeds, Second Avenue study area, New York City, New York.

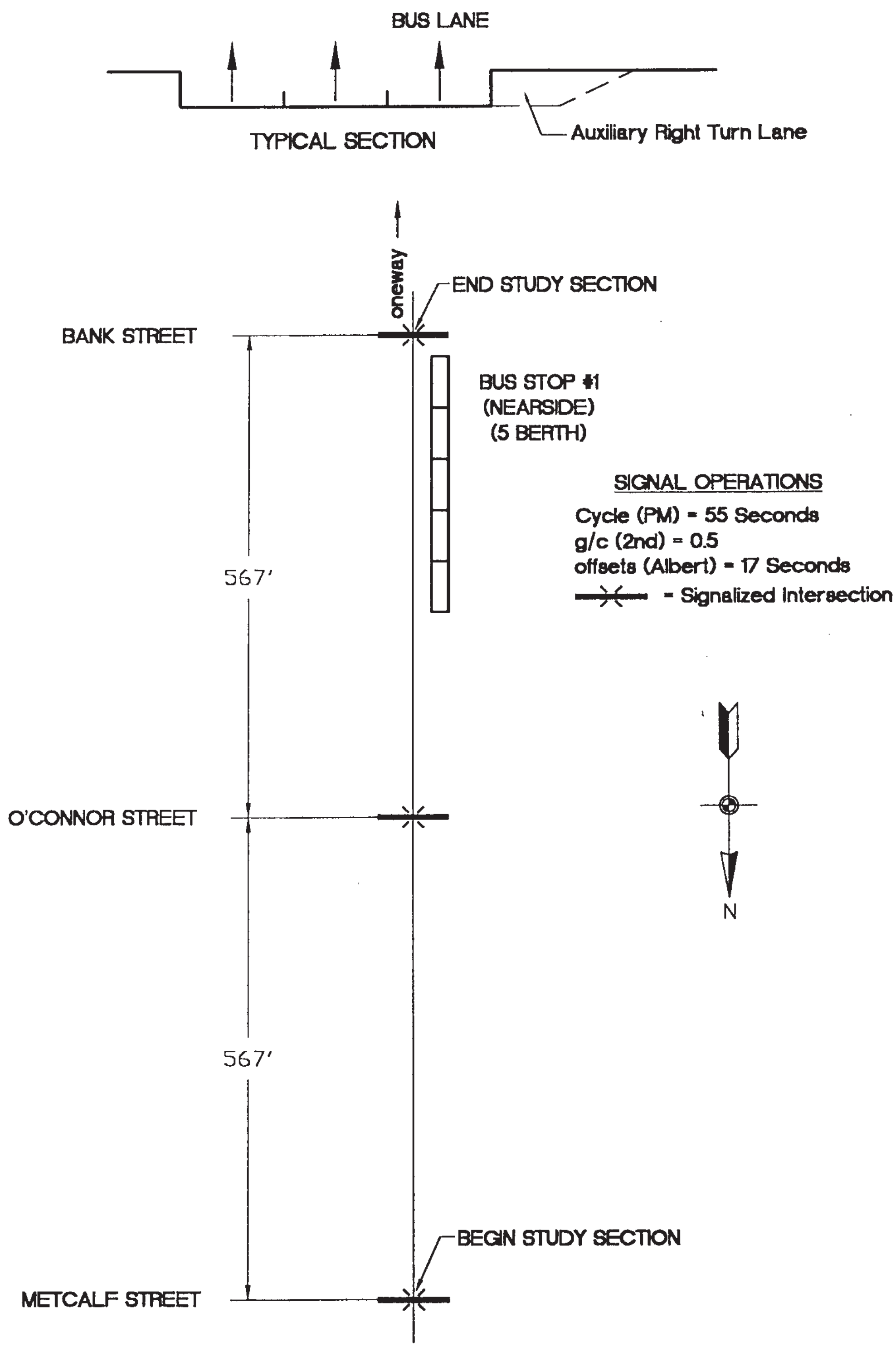


Figure 8. Albert Street study area, Ottawa, Ontario, Canada.

Capacity and Speed Comparisons

Bus capacities and average bus speeds were estimated using the procedures set forth in *TCRP Report 26.* Table 16 compares observed speeds with estimated speeds. A review of Table 16 indicates the following:

- The estimated bus speeds, **before** adjusting for any bus-bus congestion, are sometimes lower than the observed speeds. This phenomenon suggests that the initial assumption of 1.2 min/mi for traffic signal delay is excessive, given that the signals are timed progressively for buses.
- The platooning of the buses at the Metcalf stop makes efficient use of the available berths at stops downstream. The HCM effective berth value, N_b, of 2.5 appears to underestimate bus lane capacity. The field observations show that, typically, about 3 buses are processed per signal cycle, which would result in a maximum attainable flowrate of 195 buses/hr. However, peak flows of only 164 buses/hr were attained, primarily as a result of not always having three buses in the platoon. Thus, a higher value of N_b, perhaps approaching 3.00, is more appropriate for this condition.

Accordingly, two adjustments were made to the basic input parameters. First, signal delay was adjusted to 0.6 min/mi. At 4.7 stops/mi, this signal delay represents about 8 sec/stop, which is closer to the average delay observed in the field. Second, the number of effective berths for a three-berth, in-line bus stop was increased from 2.5 to 2.75. This value was suggested in previous simulation studies in *TCRP Report 26*. The comparison of observed and estimated bus speeds and capacities are shown in Table 17. The adjustments eliminate the consistent underestimates of speed; they reduce, but do not eliminate, the discrepancies between the observed and estimated speeds.

Table 18 and Figure 9 compare the observed and estimated bus speeds. The refinements result in an average difference of about 1.6 mph, slightly over 10 percent but within 1 standard deviation of observed average speeds.

TABLE 16 Observed bus flowrates and speeds versus estimated capacity and speeds, Albert Street, Ottawa, Ontario

Time Period (p.m.)	Average Dwell, Sec / Coefficient Of Variation	Flow Rate, Buses/hr	Average Speed		Average Dwell, sec. (Coef. Of Var'n)	Capacity,	Bus v/c Ratio	V_o from Table 6, mph (Col. E)	Adj Factor f_b	Estimated Speed	
			mph	km/h		Buses/hr				mph	km/h
	STOP @BANK ST.					(numbers in parentheses use t_c=15, out of parentheses t_c=10)					
3:30-3:45	19 0.81	120	12.8	20.6	19 (81%)	168 (145)	0.71 (0.83)	10.7	0.89 (0.77)	9.5 (8.2)	15.3 (13.2)
3:45-4:00	15 0.56	116	11.9	19.1	15 (56%)	223 (185)	0.52 (0.63)	11.4	0.97 (x.xx)	11.1 (10.6)	17.8 (17.1)
4:00-4:15	19 0.55	144	8.5	13.7	19 (55%)	193 (163)	0.75 (0.88)	10.7	0.85 (0.71)	9.1 (7.6)	14.6 (12.2)
4:15-4:30	16 0.65	100	9.7	15.6	16 (65%)	203 (171)	0.49 (0.59)	11.2	1.00 (0.94)	11.2 (10.5)	18.0 (16.9)
4:30-4:45	15 0.69	164	9.6	15.4	15 (69%)	212 (177)	0.77 (0.93)	11.4	0.83 (0.64)	9.5 (7.3)	15.3 (11.7)
4:45-5:00	15 0.58	132	11.1	17.9	15 (58%)	214 (179)	0.62 (0.74)	11.4	0.93 (0.86)	10.6 (9.8)	17.1 (15.7)
5:00-5:15	27 0.45	136	10.5	16.9	27 (45%)	159 (138)	0.86 (0.98)	9.6	0.74 (0.55)	7.1 (5.3)	11.4 (8.5)
5:15-5:30	19 0.46	124	9.8	15.8	19 (46%)	199 (168)	0.62 (0.74)	10.7	0.93 (0.86)	10.0 (9.2)	16.1 (14.8)

Notes:
1. g/C=0.60
2. Capacity computed using the highlighted values of D and C_v, with t_c = 10.
3. Average estimated speed computed using the critical dwell and C_v for determining V_o.
4. V_o interpolated from Table 6 for 5 stops/mi.

TABLE 17 Observed bus flowrates and speeds versus estimated capacity and speeds, Albert Street, Ottawa, Ontario (Assuming N_b = 2.75 and travel time delay = 0.6 min/mi)

Time Period (p.m.)	Average Dwell, Seconds Coef. of Var'n	Flow Rate, Buses /hr	Average Speed mph	Average Speed km/h	Average Dwell, sec. (Coef. of Var'n)	Capacity, Buses/hr	Bus v/c Ratio	V_s from Table 6, mph (Col. E)	Adj Factor f_s	Estimated Speed mph	Estimated Speed km/h
	Stop @ Bank St.					(numbers in parenthesis use t_c=15, out of parentheses t_c=10)					
3:30-3:45	19 0.81	120	12.8	20.6	19	168 (160)	0.71 (0.75)	11.9	0.92 (0.85)	10.9 (10.1)	17.5 (16.3)
3:45-4:00	15 0.56	116	11.9	19.1	15	245 (203)	0.47 (0.57)	12.7	1.00 (0.95)	12.7 (12.1)	20.4 (19.5)
4:00-4:15	19 0.55	144	8.5	13.7	19	212 (180)	0.68 (0.80)	11.9	0.90 (0.81)	10.7 (9.6)	17.2 (15.4)
4:15-4:30	16 0.65	100	9.7	15.6	16	223 (188)	0.45 (0.53)	12.5	1.00 (0.96)	12.5 (12.0)	20.1 (19.3)
4:30-4:45	15 0.69	164	9.6	15.4	15	233 (195)	0.70 (0.84)	12.7	0.89 (0.76)	11.3 (9.7)	18.2 (15.6)
4:45-5:00	15 0.58	132	11.1	17.9	15	236 (197)	0.56 (0.67)	12.7	0.95 (0.91)	12.1 (11.6)	19.5 (18.7)
5:00-5:15	27 0.45	136	10.5	16.9	27	175 (152)	0.78 (0.89)	10.6	0.83 (0.70)	8.0 (7.4)	12.9 (11.9)
5:15-5:30	19 0.46	124	9.8	15.8	19	219 (185)	0.57 (0.67)	11.9	0.95 (0.91)	10.2 (9.7)	16.4 (15.6)

TABLE 18 Summary comparison of alternatives analyzed, Albert Street, Ottawa, Ontario

Time Period (p.m.)	Number of Buses[1]	Average Dwell, sec.	Observed Speed (mph)		Estimated Speed (mph)			
			Average Speed	Standard Deviation	Table 16 (Delay=1.2 min/mi, N_b=2.5)		Table 17 (Delay=0.6 min/mi, N_b=2.75	
					t_c=10	t_c=15	t_c=10	t_c=15
3:30-3:45	30	19	12.8	3.6	9.5	8.2*	10.9	10.1
3:45-4:00	29	15	11.9	3.8	11.1	10.6	12.7	12.1
4:00-4:15	36	19	9.0	2.2	9.1	7.6	10.7	9.6
4:15-4:30	25	16	9.7	2.0	11.2	10.5	12.5*	12.0*
4:30-4:45	41	15	9.6	1.9	9.5	7.3*	11.3	9.7
4:45-5:00	33	15	11.1	1.3	10.6	9.8	12.1	11.6
5:00-5:15	34	27	10.5	1.6	7.1*	5.3*	8.0*	7.4*
5:15-5:30	31	19	9.8	1.3	10.0	9.2	10.2	9.7
Average Difference (absolute)= Σ [Estimated minus Observed]/n					1.2	2.2	1.6	1.2

Notes: [1] Observations with valid speed measurements in 15-min interval
*beyond ± 1 standard deviation

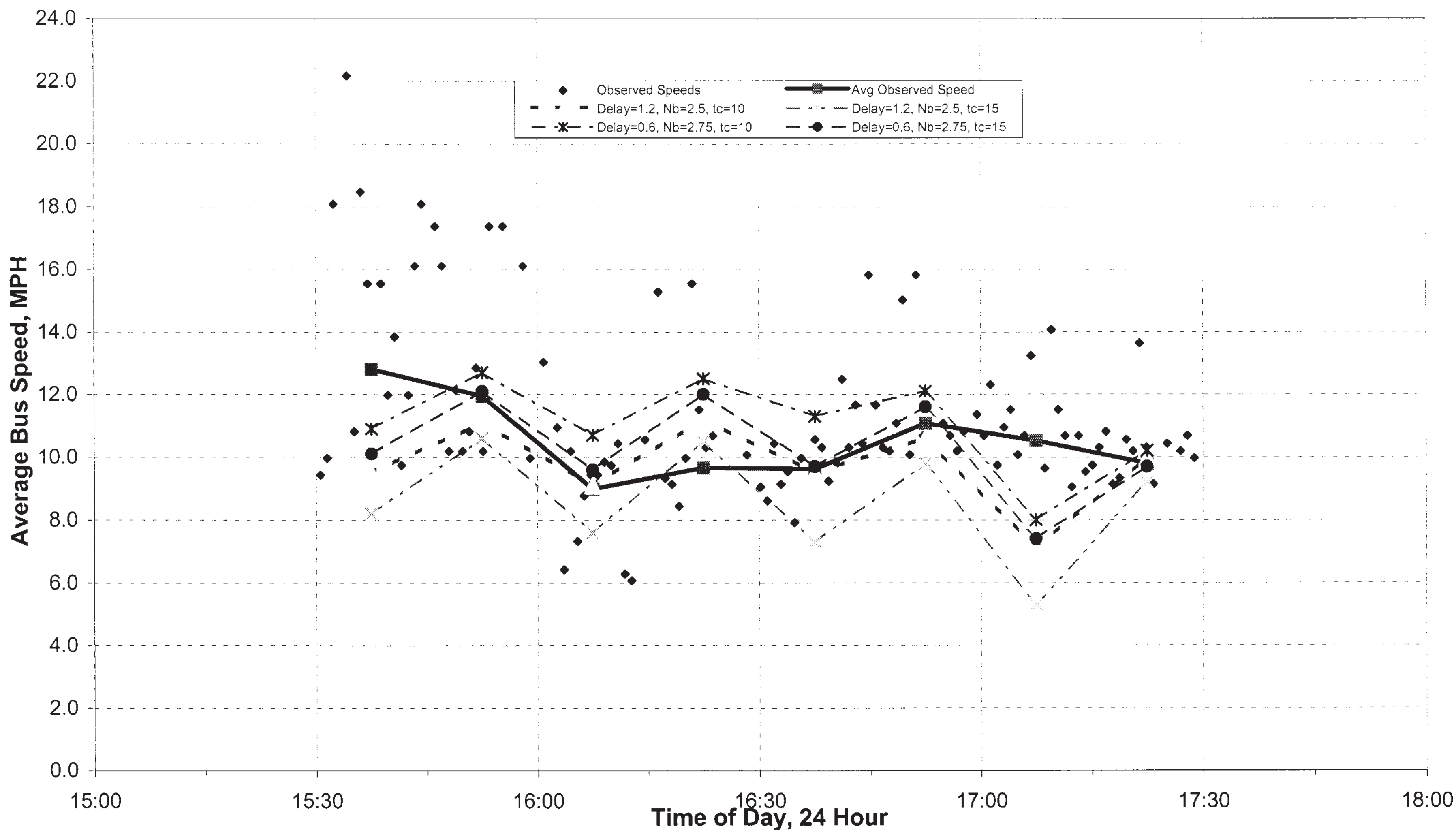


Figure 9. Observed versus estimated bus speeds, Albert Street study area, Ottawa, Ontario, Canada.

Observations and Comments

The survey on Albert Street bus operations was purposely taken downstream of Metcalf Street because queuing at the near-side Metcalf Street bus stop caused bus-bus delays that would have reduced the overall average bus speeds if the upstream block were included. Typically, three buses left the Metcalf stop in a platoon. The platooning of buses appears to create a higher efficiency in the bus berth use. This phenomenon suggests higher values for the number of effective berths (N_b), at least under such conditions.

Commerce and Market Streets, San Antonio, Texas

Commerce Street and Market Street have Type 2, normal-flow bus lanes that enable buses to use the adjacent lane when necessary. Most buses stopped at each bus stop in the study sections, although some buses entered and exited the bus lane between the beginning and ending points.

As shown in Figures 10 and 11, the block spacing varies from 250 to 550 ft (76 to 168 m), stop bar to stop bar. The stop density averages just over 10 stops/mi on Commerce Street and just under 8 stops/mi on Market Street. Bus stops are on the near side, and each bus stop can accommodate as many as five buses. However, bus-operating procedures discourage the fourth bus in line from proceeding past the stop without stopping at the first berth. Rarely were more than three buses observed to be queuing at any one stop in the study area.

The traffic signals along Market and Commerce streets operate on a 60-sec cycle. Offsets from block to block are approximately 7 to 12 sec, depending on the block length; the signals are set for traffic progression of approximately 30 mph.

Field Surveys and Data Summaries

Bus volumes and speeds were collected on Market Street from 3:30 to 5:15 p.m. on Tuesday, September 22, 1998, and on Commerce Street from 7:00 to 9:00 a.m. on Wednesday, September 23, 1998. A four-block segment of Market from Soledad to Presa and a four-block segment of Commerce from Presa to Soledad were surveyed.

On Commerce Street, 15-min average bus speeds during the a.m. study period ranged from 4.2 to 6.3 mph (6.8 to 10.1 km/h); 15-min bus flowrates ranged from 60 to 100 buses/hr; 15-min average dwell times ranged from 18 to 24 sec. On Market Street, 15-min average bus speeds during the p.m. peak study period ranged from 6.0 to 7.0 mph (9.8 to 11.3 km/h); 15-min flowrates ranged from 80 to 100 buses/hr; and 15-min average dwell times ranged from 17 to 26 sec.

Capacity and Speed Comparisons

Bus capacities and average bus speeds were estimated using the procedures set forth in *TCRP Report 26*.

Commerce Street. Table 19 compares observed and estimated bus speeds on Commerce Street. The estimated speeds are generally within 0.5 mi of the observed speeds. However, as shown in Figure 12, there are wide variations among individual bus speeds. All estimated speeds are within 1 standard deviation of the observed speeds.

Right turns were significant on Commerce Street and may have contributed to the speed variations. A review of the videotapes indicated that the effect of right turns depends on the variations of bus arrival (bunching) and whether the right-turning vehicles arrive before or after the buses.

A typical 60-sec cycle had 1.3 bus arrivals and 4.0 right turns at the intersection of Commerce and Navarro; at that level, only minor delays to the buses were observed. However, shortly after 8:00 a.m., seven buses arrived at the entry to the study section within 3 min (three signal cycles), equating to a peak flowrate of approximately 140 buses/hr. The presence of just under 10 right turns during these 3 min contributed to delays of at least one and possibly two cycle lengths to the last four buses during that period. For this 15-min period, estimated speeds were 0.8 mph greater than the observed speeds.

Market Street. Table 20 and Figure 13 compare observed and estimated speeds on Market Street. The estimated speeds are generally lower than the observed speeds by 0.8 to 1.4 mph. These speed differences are approximately 1 standard deviation from the observed speeds. However, a closer look at the bus operating characteristics indicates that numerous buses at Bus Stop 1 had a zero dwell time, which suggests that buses pulled through the bus stop in the bus lane, but did not stop to service passengers. These buses accounted for between one-fourth and one-half of the bus flow. Buses that did not stop at Bus Stop 1 would have a stop frequency of 4 bus stops/mi as compared with 8 bus stops/mi for those that did.

Accordingly, a second analysis was made in which the zero dwell times at Bus Stop 1 were not considered in the average dwell time computations and a net bus stop frequency of 6 stops/mi was used. The revised results are shown in Table 21 and are also in Figure 13. The revised computations show a close correspondence between observed and estimated bus speeds.

Table 22 compares the observed bus speeds with those estimated (assuming 8 and 6 stops/mi, respectively). The initial estimates, based on 8 stops/mi, have an average error of 0.9 mph; however, several individual observations are more than 1 standard deviation from the observed speed. The revised estimates are within 0.5 mph of the observed speeds, and all estimates are within 1 standard deviation.

Observations and Comments

The procedures provide reasonable estimates of estimated speeds along both streets. The Market Street analysis

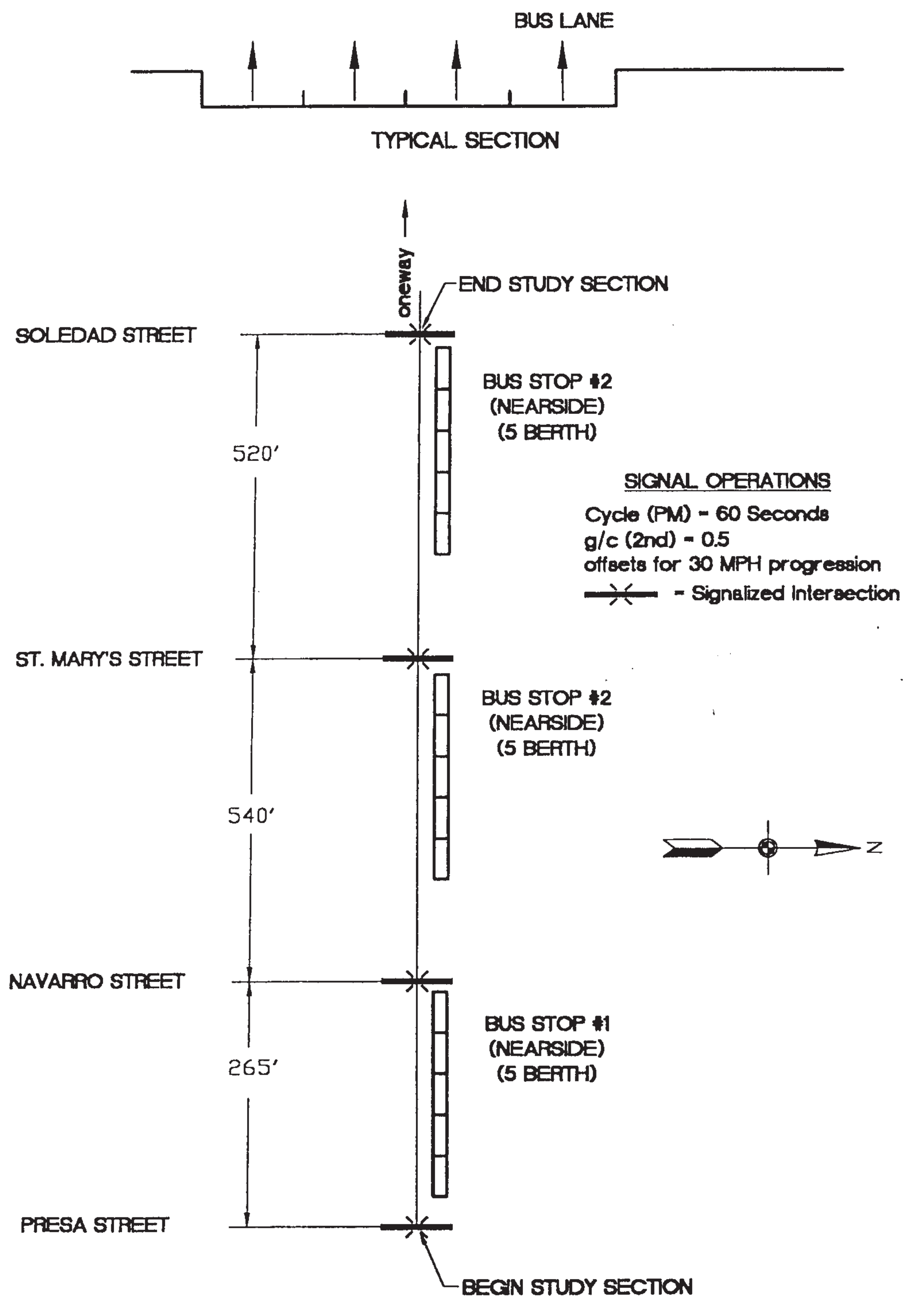


Figure 10. Commerce Street study area, San Antonio, Texas.

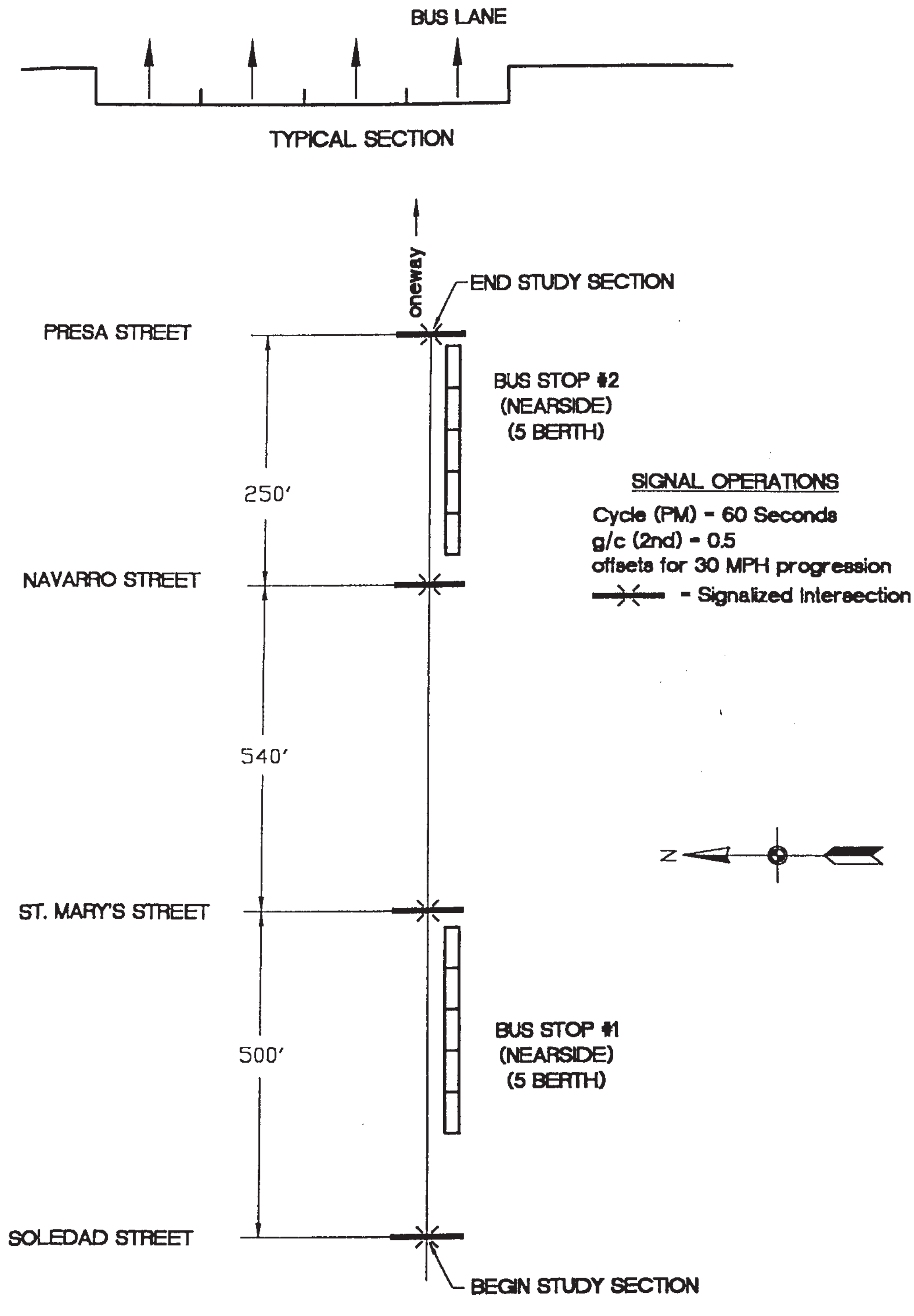


Figure 11. Market Street study area, San Antonio, Texas.

TABLE 19 Observed bus flowrates and speeds versus estimated capacity and speeds, Commerce Street, San Antonio, Texas

Time Period (a.m.)	Average Dwell, Sec / Coefficient of Variation			Flw rate, Bus/hr	Avg Speed		Avg. Dwell, Sec.	Capacity Buses/hr	Bus v/c Ratio	V_s from Table 6	Adj Factor f_b	Calc. Speed		Difference
	Stop A	Stop B	Stop C		mph (St'd Dev'n)	km/h						mph	km/h	Calc-Obs.
7:00-7:15	25 44%	24 52%	20 77%	100	4.2 (0.8)	6.8	23 58%	121	0.83	5.4	0.77	4.2	6.8	0.0
7:15-7:30	24 66%	24 58%	24 66%	80	5.3 (0.6)	8.5	24 63%	116	0.69	5.3	0.90	4.8	7.7	-0.5
7:30-7:45	24 75%	11 48%	32 55%	60	4.9 (1.2)	6.9	20 59%	133	0.45	5.4	1.00	5.4	8.7	+0.5
7:45-8:00	17 52%	11 36%	29 43%	92	5.1 (1.2)	7.9	19 44%	151	0.61	5.7	0.93	5.3	8.5	+0.2
8:00-8:15	18 52%	16 86%	22 49%	80	4.6 (1.1)	10.1	19 62%	134	0.60	5.7	0.94	5.4	8.7	+0.8
8:15-8:30	24 41%	10 66%	23 45%	56	6.3 (0.9)	10.1	19 51%	145	0.39	5.7	1.00	5.7	9.2	-0.6
8:30-8:45	21 55%	10 63%	25 61%	88	5.7 (1.5)	9.2	19 60%	142	0.62	5.7	0.92	5.2	8.4	-0.5
8:45-9:00	24 52%	14 59%	17 58%	72	5.3 (1.0)	8.4	18 56%	143	0.50	5.8	1.00	5.8	9.3	+0.5
Average Difference (absolute)/[Observed vs. estimated]														0.5

Notes:
g/c = 0.55
Capacity computed using the highlighted critical values of *D* and C_v.
Average estimated speed computed using the average of the 15-minute dwell times for the period.

highlights the importance of making appropriate allowances for buses that do not stop.

Third Avenue and Broadway, New York City, New York

Additional investigations were made of bus lane operations along Third Avenue and Lower Broadway in Manhattan. Both streets operate one-way and have normal-flow curb bus lanes. Figures 14 and 15 show the street segments where information was collected.

New York City Transit conducts systematic bus-by-bus speed surveys. Data are collected for beginning and ending times along specific street segments; however, bus dwell times are not collected. Speeds on both streets ranged from 4 to 5 mph during the periods of collection.

Third Avenue

Third Avenue is a one-way, multilane, northbound roadway linking Manhattan with the Queensboro Bridge and the Bronx. Buses stop at about 750-ft intervals, resulting in about 8 stops/mi. Reported bus flowrates and measured bus speeds provided by New York City Transit are summarized in Table 23**.** The 15-min bus flowrates ranged from 20 to 52 buses/hr—well below an estimated capacity of about 90 to 100 buses/hr. The average bus speeds ranged from 3.9 to 5.2 mph. However, there was wide variability among individual bus runs, as shown in Figure 16. Field observations suggest that spillback from the Queensboro Bridge (59th Street) and heavy northbound right turns reduce bus speeds beyond what would be estimated by Table 6.

For a normal bus lane in a CBD, Table 6 estimates speeds ranging between 5.2 and 5.9 mph for 40- to 30-sec dwell times. This assumes that the delay resulting from traffic and signals is 2.0 min/mi. Changing this assumption to 3.0 min/mi to account for congestion reduces the estimated speed range to between 4.8 and 5.3 mph.

Lower Broadway

Lower Broadway is served by various local and express buses. These create a complex stopping pattern. Block spacing and bus stop spacings are irregular.

Reported bus volumes exceed 100 buses/hr. New York City Transit buses use the street from 4:00 to 6:00 p.m., and the speeds they obtain are shown in Table 24. The 15-min bus flowrates range from 44 to 80 buses/hr, and 15-min average speeds range from 3.6 to 5.5 mph. As shown in Figure 17, individual bus speeds vary widely.

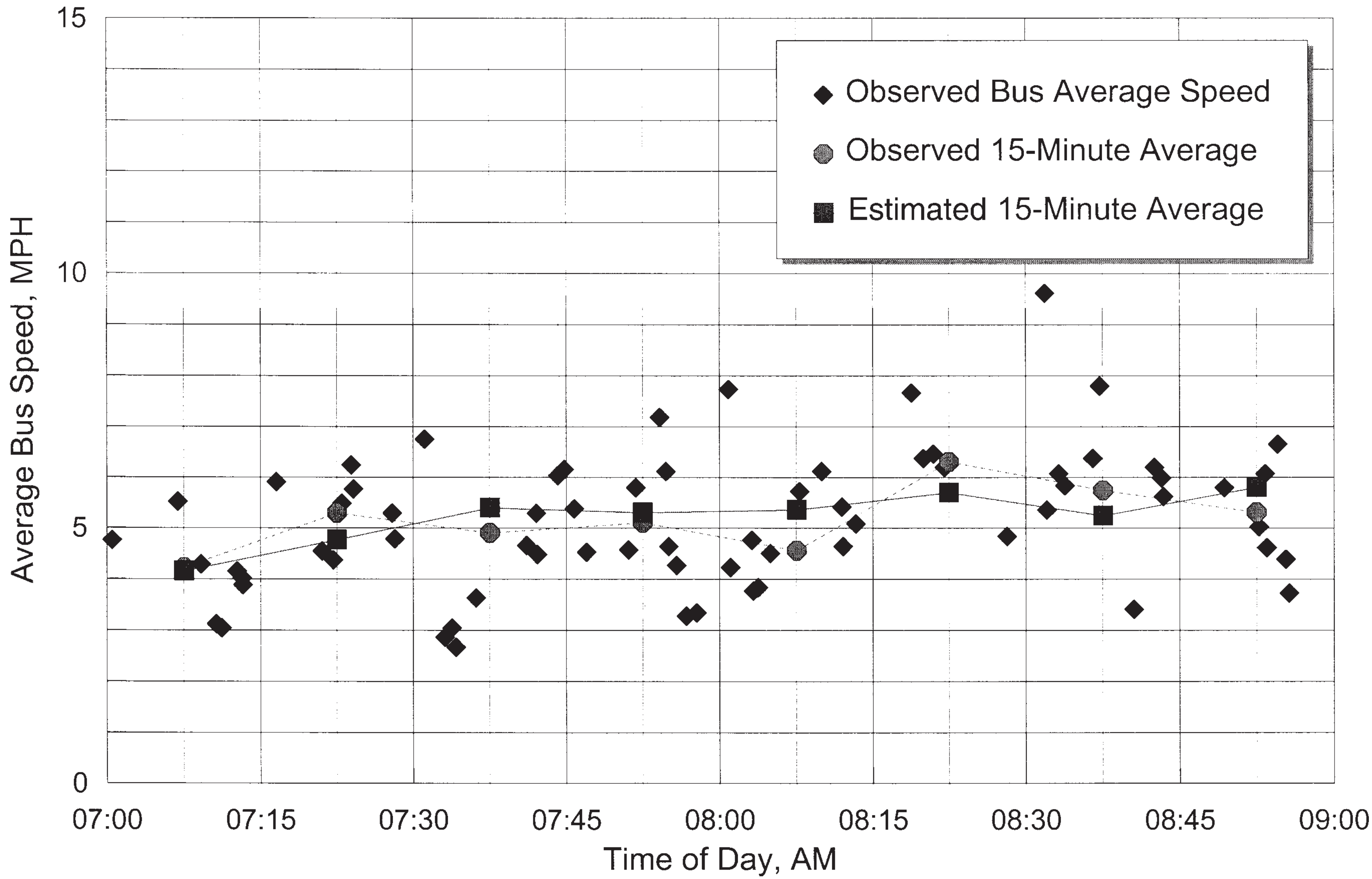


Figure 12. Observed versus estimated bus speeds, Commerce Street study area, San Antonio, Texas.

TABLE 20 Observed bus flowrates and speeds versus estimated capacity and speeds, Market Street, San Antonio, Texas

Time Period (p.m.)	Average Dwell, Seconds / Coeff. of Variation: Stop #A	Stop # B	Flow Rate, bph	Average Speed mph (St'd Dev'n)	Average Speed km/h	Average Dwell, Sec.	Capacity Buses/hr	Bus v/c Ratio	V_o from Table 6	Adjusted Factor f_s	Estimated Speed mph	Estimated Speed km/h
3:30-3:45	11	33	80	6.5	10.5	22	109	0.73	6.6	0.87	5.7	9.2
	112%	67%		(1.0)		90%						
3:45-4:00	20	21	96	6.9	11.1	21	141	0.68	6.7	0.90	6.0	9.7
	87%	66%		(1.4)		76%						
4:00-4:15	14	34	100	6.0	9.7	24	114	0.88	6.5	0.71	4.6	7.4
	87%	50%		(1.2)		69%						
4:15-4:30	11	31	100	6.6	10.6	21	127	0.79	6.7	0.82	5.5	8.8
	114%	45%		(1.0)		79%						
4:30-4:45	20	31	100	6.1	9.8	26	115	0.87	6.3	0.73	4.7	7.6
	90%	64%		(1.2)		77%						
4:45-5:00	12	21	88	6.3	10.1	17	152	0.58	7.2	0.95	6.6	10.6
	122%	55%		(1.1)		88%						
5:00-5:15	12	25	88	7.0	11.3	19	129	0.68	6.9	0.90	6.3	10.1
	110%	67%		(2.3)		89%						

Notes:
1. $g/c = 0.55$
2. Capacity computed using the highlighted critical values of D and C_v.
3. Average estimated speed computed using the average of the 15-min dwell times for the period
4. Average estimated speed computed using 8 stops/mi.
5. bph = buses/hr

Observations and Comments

The data provided by New York City Transit illustrates two points. First, the relationships among bus speed, capacity, and level of service can be used to estimate operations that are highly variable and depend on many factors. Driver behavior and passenger behavior can affect measured bus performance significantly. Second, assumptions of average dwell time, given known street operating parameters, can be used to estimate average bus travel speeds with reasonable accuracy. The availability of bus lanes can be observed in the field, as can arterial or intersecting street spillbacks across bus lanes. Dwell times can be spot-checked in the field. Operating experiences and default assumptions from similar roadways can serve as inputs. The real-world application of bus capacity and bus speed relationships should produce easily obtained or estimated parameters, should be adaptable to various field conditions, and should produce reasonable estimates.

APPRAISAL, CONCLUSIONS, AND SUGGESTED RESEARCH

The research was designed to analyze bus lane performance on downtown arterial streets. Field observations and measurements were used to test and refine the relationships developed in *TCRP Report 26*. The research focused on three basic questions:

- Do the established procedures provide reasonable estimates of bus lane capacity?
- Do the procedures produce realistic estimates of bus speeds and travel times?
- What adjustments of existing parameters, procedures, and default values are desirable to better reflect observed operating conditions and observed speeds?

This section presents answers to these questions; these answers are drawn from the case studies. This section also identifies possible refinements to established procedures and default values.

Dwell Times and Capacities

Stop frequencies, hourly bus flowrates, and dwell times for the six study sites are summarized in Table 25. The high bus throughput in a single bus lane along Albert Street in Ottawa results from fewer stops and from dwell times that are relatively low compared with those experienced in the

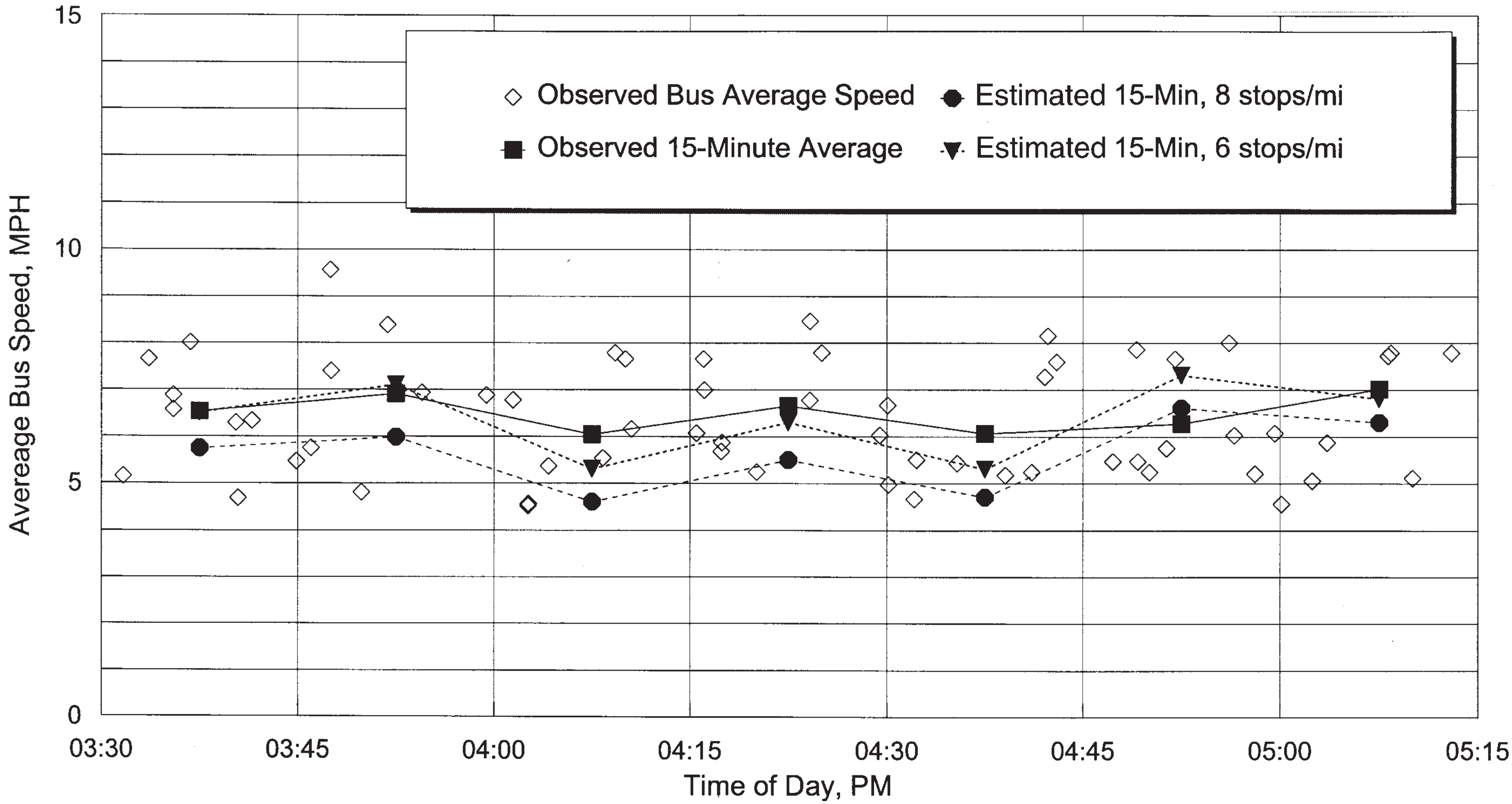


Figure 13. Observed versus estimated bus speeds, Market Street study area, San Antonio, Texas.

TABLE 21 Observed bus flowrates and speeds versus estimated capacity and speeds, Market Street, San Antonio, Texas (6 stops/mi)

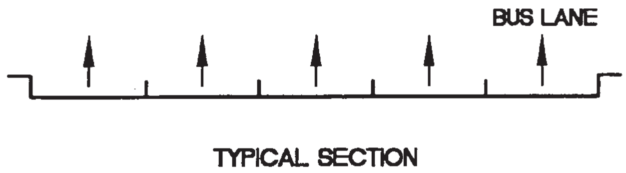
Time Period (p.m.)	Average Dwell, Seconds Coeff. of Variation		Flow Rate, Bus/hr	Average Speed		Average Dwell, Sec.	Capacity Buses/hr	Bus v/c Ratio	V_s from Table 6	Adjusted Factor f_s	Estimated Speed	
				mph	km/h						mph	km/h
	Stop #A	Stop # B		(St'd Dev'n)								
3:30-3:45	11 112%	33 67%	80	6.5 (1.0)	10.5	27 56%	109	0.73	7.5	0.87	6.5	10.5
3:45-4:00	20 87%	21 66%	96	6.9 (1.4)	11.1	23 63%	13	0.68	7.9	0.90	7.1	11.4
4:00-4:15	14 87%	34 50%	100	6.0 (1.2)	9.7	27 51%	114	0.88	7.5	0.71	5.3	8.5
4:15-4:30	11 114%	31 45%	100	6.6 (1.0)	10.6	25 50%	127	0.79	7.7	0.82	6.3	10.1
4:30-4:45	20 90%	31 64%	100	6.1 (1.2)	9.8	30 56%	115	0.87	7.2	0.73	5.3	8.5
4:45-5:00	12 122%	21 55%	88	6.3 (1.1)	10.1	23 58%	152	0.58	7.9	0.95	7.3	11.7
5:00-5:15	12 110%	25 67%	88	7.0 (2.3)	11.3	26 88%	129	0.68	7.6	0.90	6.8	10.9

Notes:
1. $g/c = 0.55$
2. Capacity estimated using the highlighted critical values of D and C_v.
3. Average estimated speed computed using the average of the 15-min dwell times for the period.
4. Dwell times recorded as zero in data were eliminated from average bus dwell times. Portion of buses with zero dwell were calculated as not stopping at bus stop, which equated to 4 stops/mi for those buses. Thus, Table 6 was entered for 6 stops/mi, which is the average of the two bus stopping patterns.

TABLE 22 Summary comparison of alternatives analyzed, Market Street, San Antonio, Texas

Time Period (p.m.)	Bus Flow Rate, Buses/hr	Observed Speeds (mph)		Table 20 (8 stops/mi)		Table 21 (6 stops/mi) (Adjusted)	
		Average Speeds	Standard Deviation	Average Dwell Sec.	Estimated Speeds mph	Average Dwell Sec. [1]	Estimated Speeds mph
3:30-3:45	80	6.5	1.0	22	5.7	27	6.5
3:45-4:00	96	6.9	1.4	21	6.0	23	7.1
4:00-4:15	100	6.0	1.2	24	4.6*	27	5.3
4:15-4:30	100	6.6	1.0	21	5.5*	25	6.3
4:30-4:45	100	6.1	1.2	26	4.7*	30	5.3
4:45-5:00	88	6.3	1.1	17	6.6	23	7.3
5:00-5:15	88	7.0	2.3	19	6.3	26	6.8
Average Difference (absolute) = Σ [Estimated minus Observed]/n					0.9		0.5

Notes: [1] Excludes buses that did not stop
* Beyond ± 1 Standard Deviation.



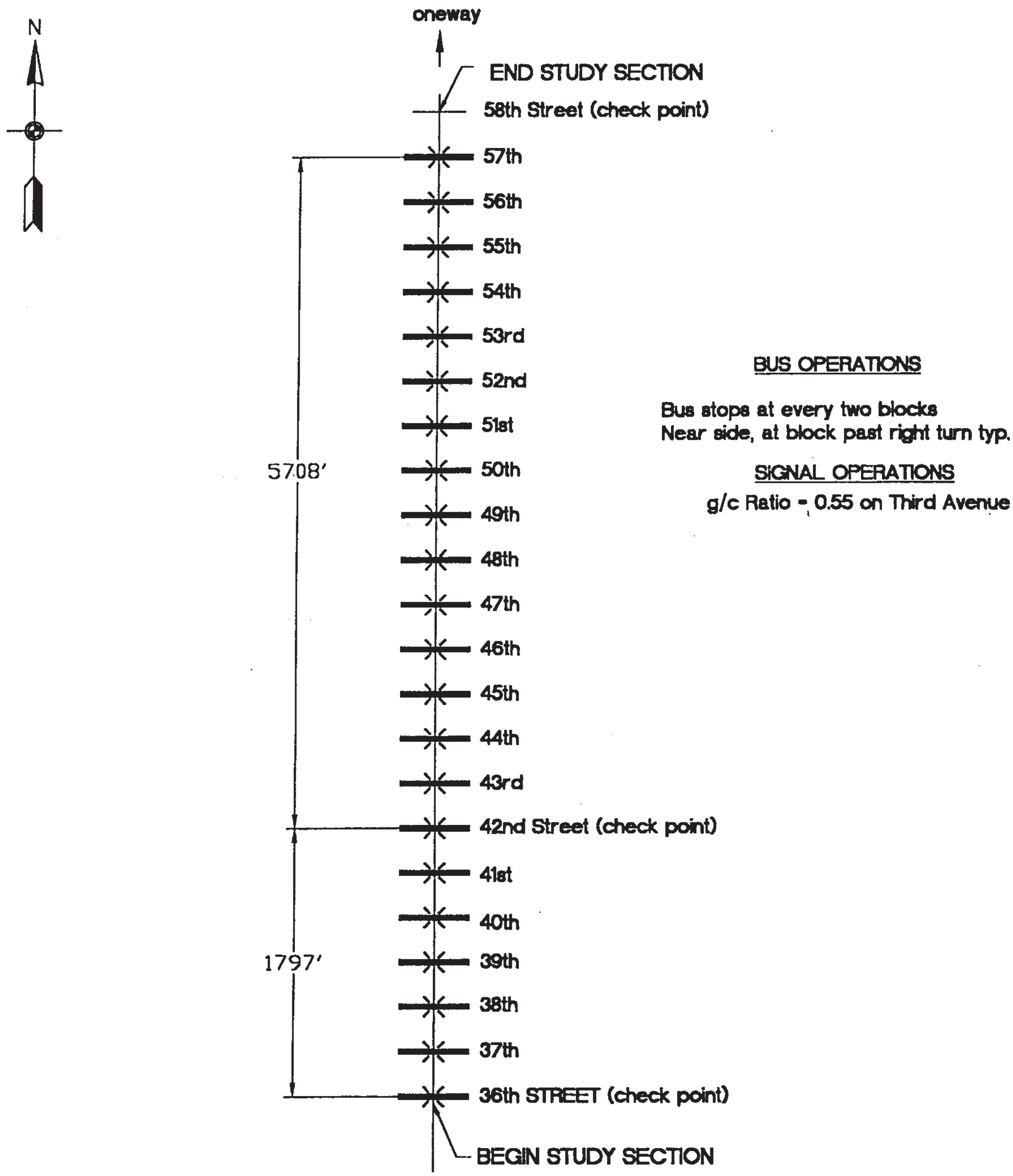


Figure 14. Third Avenue study area, New York City, New York.

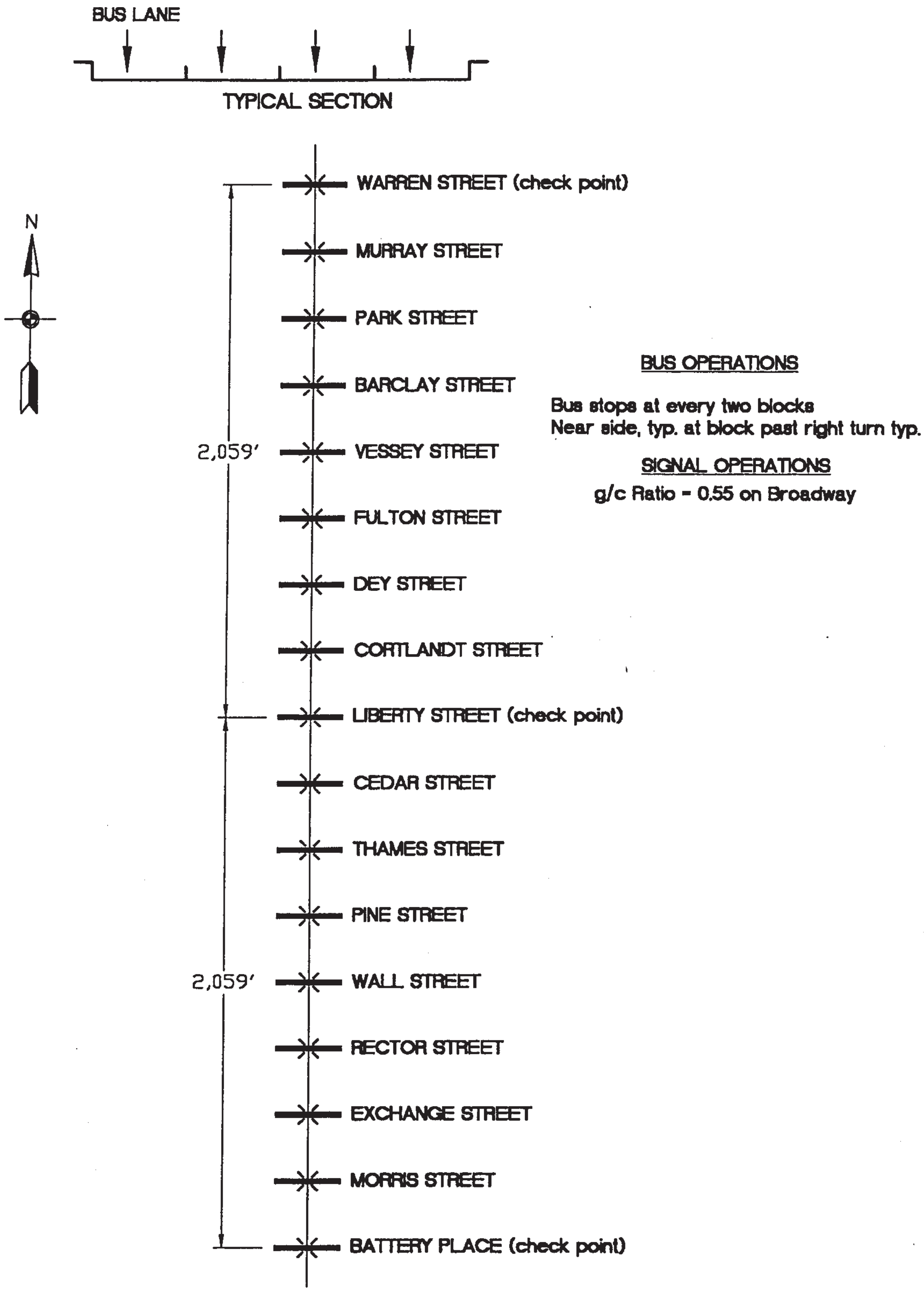


Figure 15. Broadway study area, New York City, New York.

TABLE 23 Observed bus flowrates and speeds, Third Avenue, New York City, New York (36th Street to 58th Street: June 8, 1995)

Time Period (p.m.)	Flowrate, Buses/hr	Measured Average Speed*	
		mph (Standard Deviation)	km/h
4:15-4:30	40	4.8 (1.6)	7.7
4:30-4:45	28	4.1 (1.2)	6.6
4:45-5:00	40	3.9 (1.0)	6.3
5:00-5:15	48	4.1 (1.0)	6.6
5:15-5:30	36	4.3 (0.3)	6.9
5:30-5:45	20	5.2 (1.1)	8.3
5:45-6:00	36	3.8 (1.3)	6.1
6:00-6:15**	36	4.5 1.1	7.2
6:15-6:30**	52	4.9 (0.9)	7.9

*Data provided by New York City Transit Authority
**Bus lane designation ends at 6:00 p.m.

other cities. Contributing factors include wide doors on articulated buses, extensive use of passes, platooned bus operations, and traffic signals timed to benefit bus operations.

The coefficients of dwell-time variation for all the 15-min intervals were averaged for each study section's critical stop. The resulting values, shown in Table 26, are consistent with the 60-percent coefficient of variation, C_v, used in *TCRP Report 26*.

The various capacity relationships and berth efficiency factors generally produced reasonable results, assuming a 25-percent failure rate. However, along Fifth and Sixth avenues in Portland, with nested pairs of two-berth stops, avoiding spillback was essential. Accordingly, the capacities were estimated assuming a 1-percent failure rate; this computation produced reasonable results.

Bus Speeds

Figure 18 compares the observed and estimated bus speeds. Most bus speed estimates are within 20 percent of observed speeds (approximately 1 standard deviation) and about one-half are within 10 percent of observed speeds. Some of the principal discrepancies are as follows:

- Along Fifth and Sixth avenues in Portland, observed bus speeds are relatively low. Along the arterials, signals are located at every block and buses stop every other block. The buses that are stopped at these intermediate signals have a different pattern of acceleration, cruise, deceleration, and stopping than is suggested by the basic speed table (Table 6).
- The observed bus speeds on Second Avenue in New York City are generally lower than the speeds estimated by the procedures in *TCRP Report 26*. The additional delays result from standing vehicles in the bus lane (not necessarily at the bus stop) and the need for buses to use the adjacent mixed-traffic lane.
- Some of the observed bus speeds on Albert Street in Ottawa are higher than those estimated. Three factors result in the higher speeds:

1. Signal progression is set for buses. As a result, the 1.2 min/mi signal delay component of the travel times overstates the delay incurred.
2. The berth-efficiency factor of 2.50 for five in-line berths suggested in the HCM and *TCRP Report 26* may be too low for platooned operations. Further analysis of the simulation results suggests that five

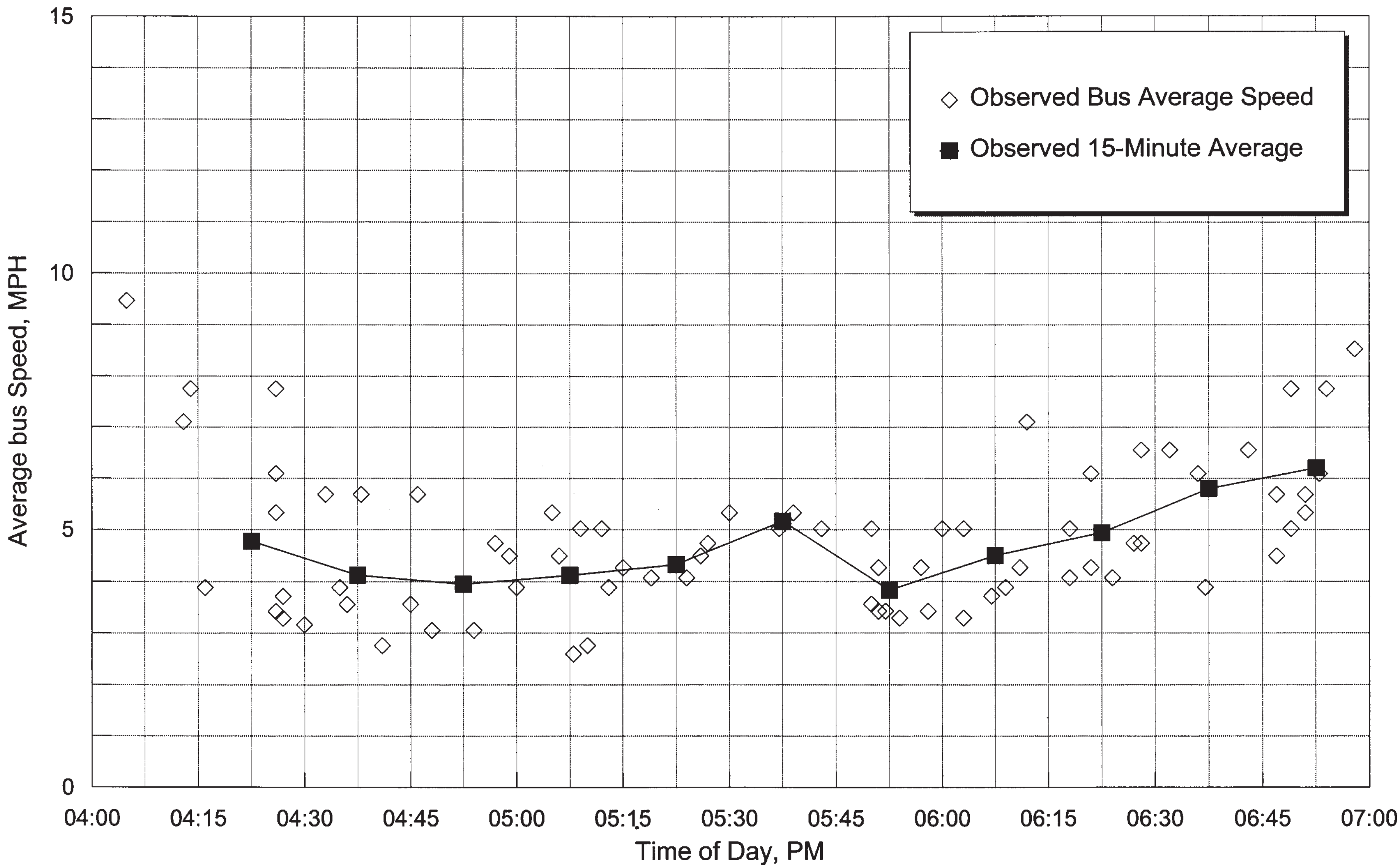


Figure 16. Reported bus speeds, Third Avenue, New York City, New York.

TABLE 24 Observed bus flowrates and speeds, Broadway, New York City, New York (Warren Street to Battery Place: June 21, 1995)

Time Period (p.m.)	Flow Rate, Buses/hr	Measured Average Speed*	
		mph	km/h
		(Standard Deviation)	
4:00-4:15	64	4.2 (0.4)	6.8
4:15-4:30	80	4.6 (0.6)	7.3
4:30-4:45	60	4.9 (1.7)	7.8
4:45-5:00	48	5.7 (1.5)	8.5
5:00-5:15	68	3.6 (1.0)	5.8
5:15-5:30	72	4.7 (0.5)	7.5
5:30-5:45	56	5.5 (0.8)	8.8
5:45-6:00	44	4.9 1.5	7.9

*Data provided by New York City Transit Authority

berths would have an efficiency of at least 2.70. In Ottawa, with effective bus platooning, this factor could range from 2.75 to 3.00. The result is a greater estimated capacity, lower bus *v/c* ratios, and less bus-bus interference.

3. The provision of right-turn bays, prohibition of selected right-turn movements, and curbside loading controls have minimized the interference of adjacent traffic on bus operations.

Accordingly, bus speed estimates were recalculated for these streets by modifying certain default values for the incremental traffic delay as follows:

- Along Fifth and Sixth avenues in Portland, the incremental delay was increased from 1.2 to 2.0 min/mi to better reflect the delays caused by the intermediate traffic signals.
- Bus speed estimates were recalculated for Second Avenue in New York City based on 3.0 (rather than 2.0) min/mi of incremental delays to represent traffic interference in the bus lanes.
- Bus speed estimates were recalculated for Albert Street in Ottawa based on 0.6 (rather than 1.2) min/mi of incremental delay to represent decreased delay resulting from signals set for buses. In addition, a berth efficiency factor of 2.75 (rather than 2.50) effective berths was used to reflect the greater use of the bus stops.

Figure 19 shows the resulting comparisons of estimated and observed bus speeds. Nearly all speed estimates are within 20 percent and over one-half are within 10 percent of the observed bus speeds. Although there was generally a good fit between observed and estimated speeds, there were some study sites where speeds were consistently over- or underestimated, even with adjustments. It should, however, be recognized that the observed speeds were highly variable. Standard deviations of 15-min observed speeds were as high as 3.6 mph, with values of 1.5 to 2 mph common. Coefficients of variation commonly ranged from 25 to 30 percent. Moreover, the speeds were usually measured across relatively short sections, which made small differences in travel time appear significant.

Table 27 summarizes the ranges in observed speeds and their standard deviations and shows the average differences between observed and estimated speeds. The adjusted average differences are generally within 1 mi of the observed speed and are usually less than 1 standard deviation of the observed speeds.

Table 28 gives a more detailed breakdown of absolute

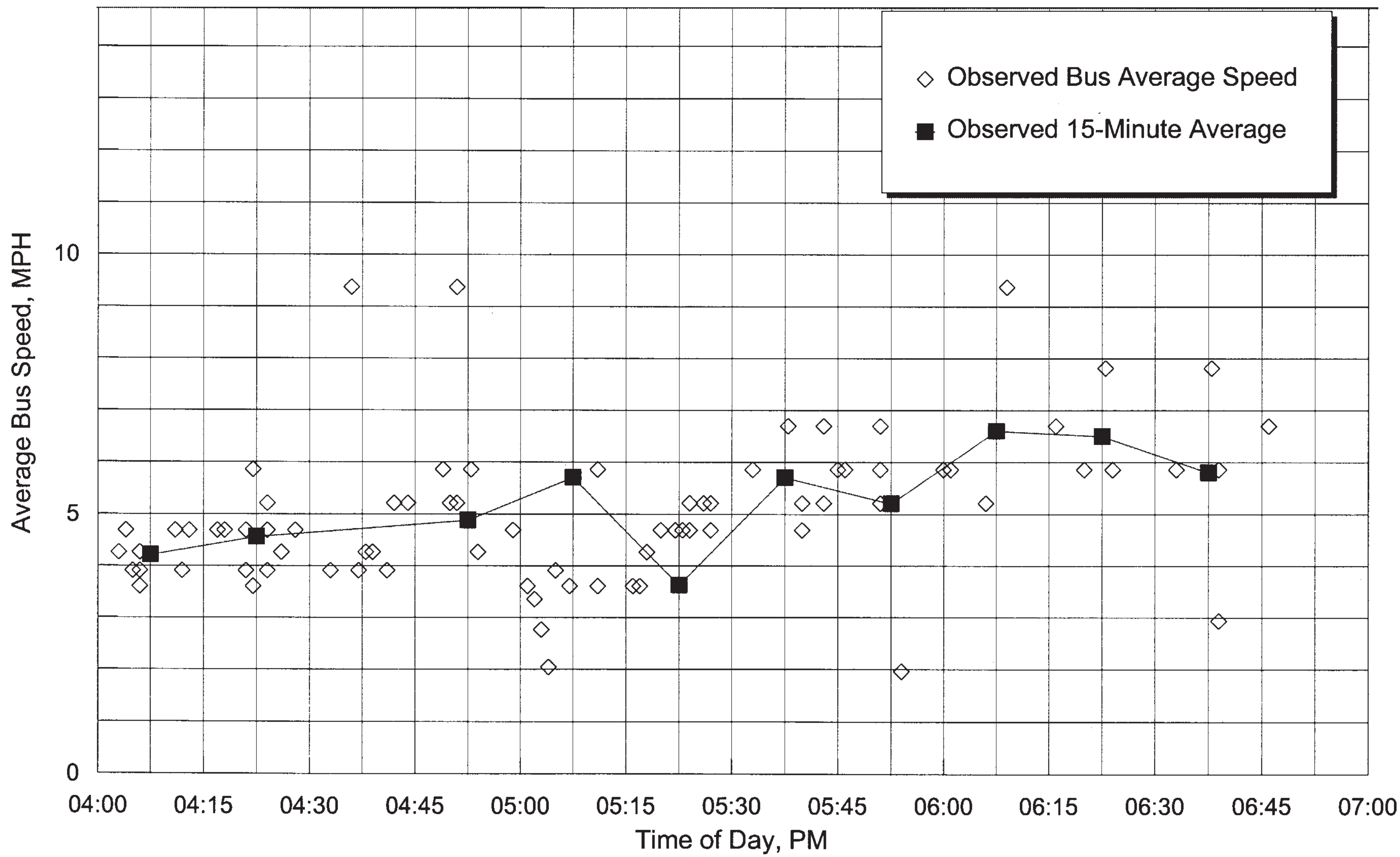


Figure 17. Reported bus speeds, Broadway, New York City, New York.

TABLE 25 Ranges in bus stop spacing, volumes, and dwell times

Site	Frequency of Bus Stops/mi.	Hourly Bus Flowrates (by 15-minute intervals)		15-Min Average Dwell Times, sec		
		Range	Median	Range	Median	Mean
Fifth Avenue-Portland	10	76-164	136	10 to 65	29	30
Sixth Avenue-Portland	10	88-112	96	8 to 55	32	30
Second Avenue-NYC	8	16-51	26	19 to 78	29	34
Albert St-Ottawa	5	100-164	132	15 to 27	18	18
Commerce St.-San Antonio	10	56-100	80	10 to 32	22	20
Market St.-San Antonio	6	80-100	96	23 to 30	26	26

TABLE 26 Coefficients of dwell-time variations by 15-min intervals

SITE	MEAN C_v
Fifth Avenue-Portland	0.52
Sixth Avenue-Portland	0.52
Second Avenue-New York	0.57
Albert St-Ottawa	0.59
Commerce St.-San Antonio	0.81
Market St.-San Antonio	0.57

Note: Excludes values <0.26 or> 1.60

differences between observed and estimated 15-min speeds by site. Overall, 43 percent of the differences were within 0.5 mph and 41 percent were within 1.0 mph of observed speeds. There was relatively little systematic over- or under-estimation of bus speeds.

Overall, the *TCRP Report 26* approaches and values appeared to provide reasonable estimates of bus speeds, except where operating conditions differ from those initially anticipated. The incremental travel time losses resulting from traffic delays may need upward or downward adjustments.

Recommended Modifications to *TCRP Report 26*

Several modifications to the procedures, parameters, and default values should be considered in updates to *TCRP Report 26*, the HCM, and the "Transit Capacity and Quality of Service Manual".[3] These modifications will produce estimates closer to actual bus operations. They will also give the user more flexibility in addressing various conditions encountered in practice.

Berth Efficiency Factors

Consideration should be given to increasing the efficiency of multiple berths. Further analysis and extrapolation of the TRAF-NETSIM simulation in *TCRP Report 26* suggests the factors for multiple in-line berths shown in Table 29.

Travel Times

The research indicates that single values of incremental traffic delays as presented in Table 6 for various types and locations of bus lanes (as well as for buses operating in mixed traffic) may not fully reflect specific operating conditions. Therefore, further latitude is desirable to better reflect traffic signal frequency and timing, blockage of bus lanes, and traffic congestion in mixed operation. Suggested amendments to Table 6 are given in Table 30 and include the following:

- When signals are set to favor bus operations, delay is reduced by 0.6 min/mi;
- When signals are more frequent than bus stops (e.g., buses skip blocks), delay is increased by 0.5 to 1.0 min/mi (depending on stop and signal spacing); and
- When lanes are blocked by traffic or no dedicated bus lane existed, delay is increased by 0.5 to 1.0 min/mi (depending on the amount of lane blockage).

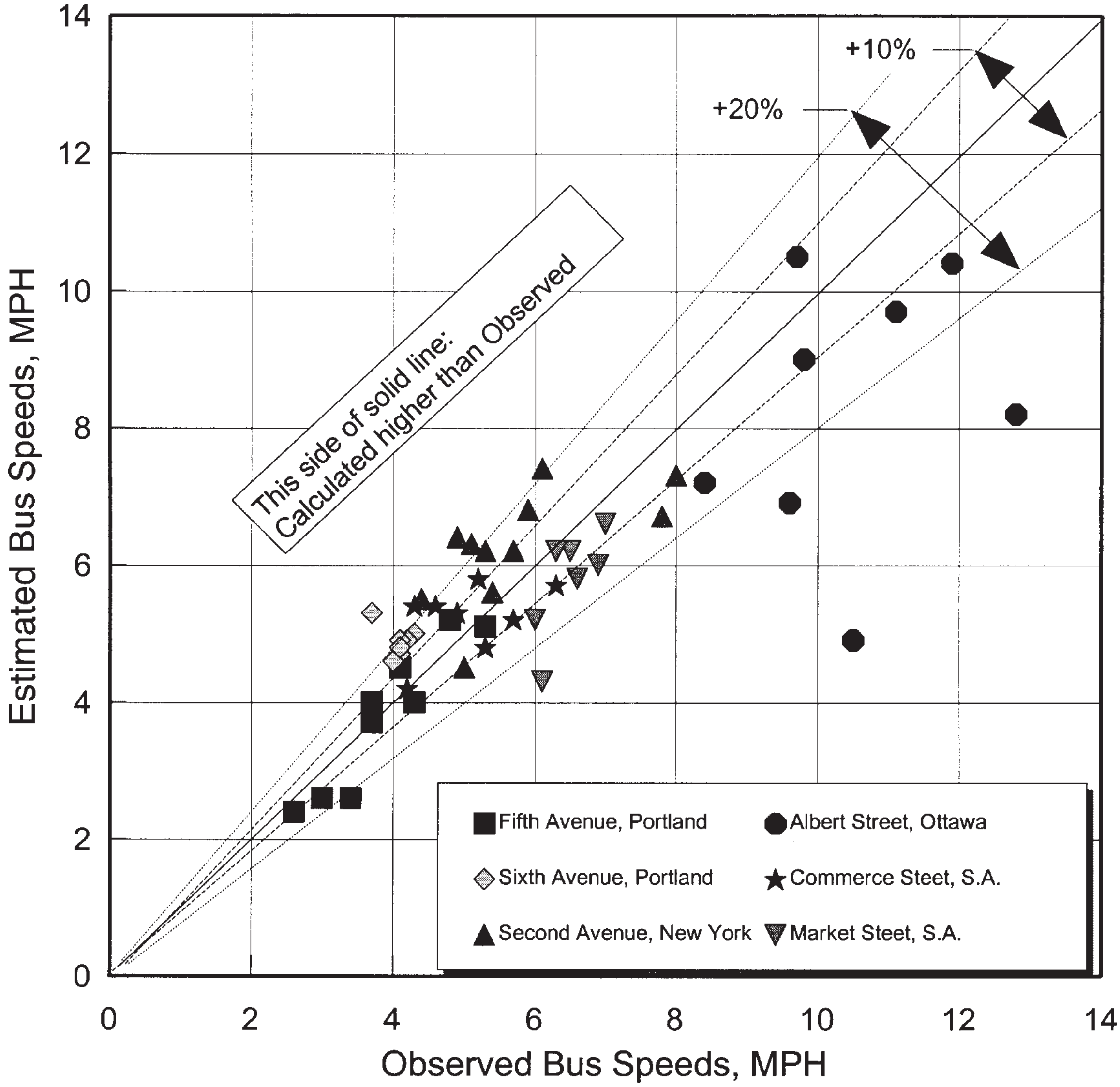


Figure 18. Observed versus estimated bus speeds.

Application Guidelines

Some additional guidelines follow:

1. The computation of average dwell times, as used in Table 3-3 in *TCRP Report 26*, is based on the average dwell time per stop. When bus lanes are being examined, the length of the study area, the number of bus stops, and the dwell times per stop will affect the speed results. The capacity calculation should be made at the critical points along the arterial (i.e., where the combination of signal timing, dwell time, and dwell variation results in the lowest calculated capacity).

2. Capacity should be estimated for each section analyzed, and locations with the greatest dwell time and dwell time variations should be used. This estimate should be compared with the observed bus lane flows to obtain the bus *v/c* ratio and the appropriate bus-bus interference speed reduction factor.

3. Average speeds can be calculated for any distance and series of stop patterns. The sections should have generally homogenous characteristics in terms of street geometry, bus lane features, stop frequency, and dwell times. Sections should be shorter in the CBD than along outlying arterial roads. Sections should be at least $^1/_4$ mi long, preferably $^1/_2$ mi long, within the CBD and in

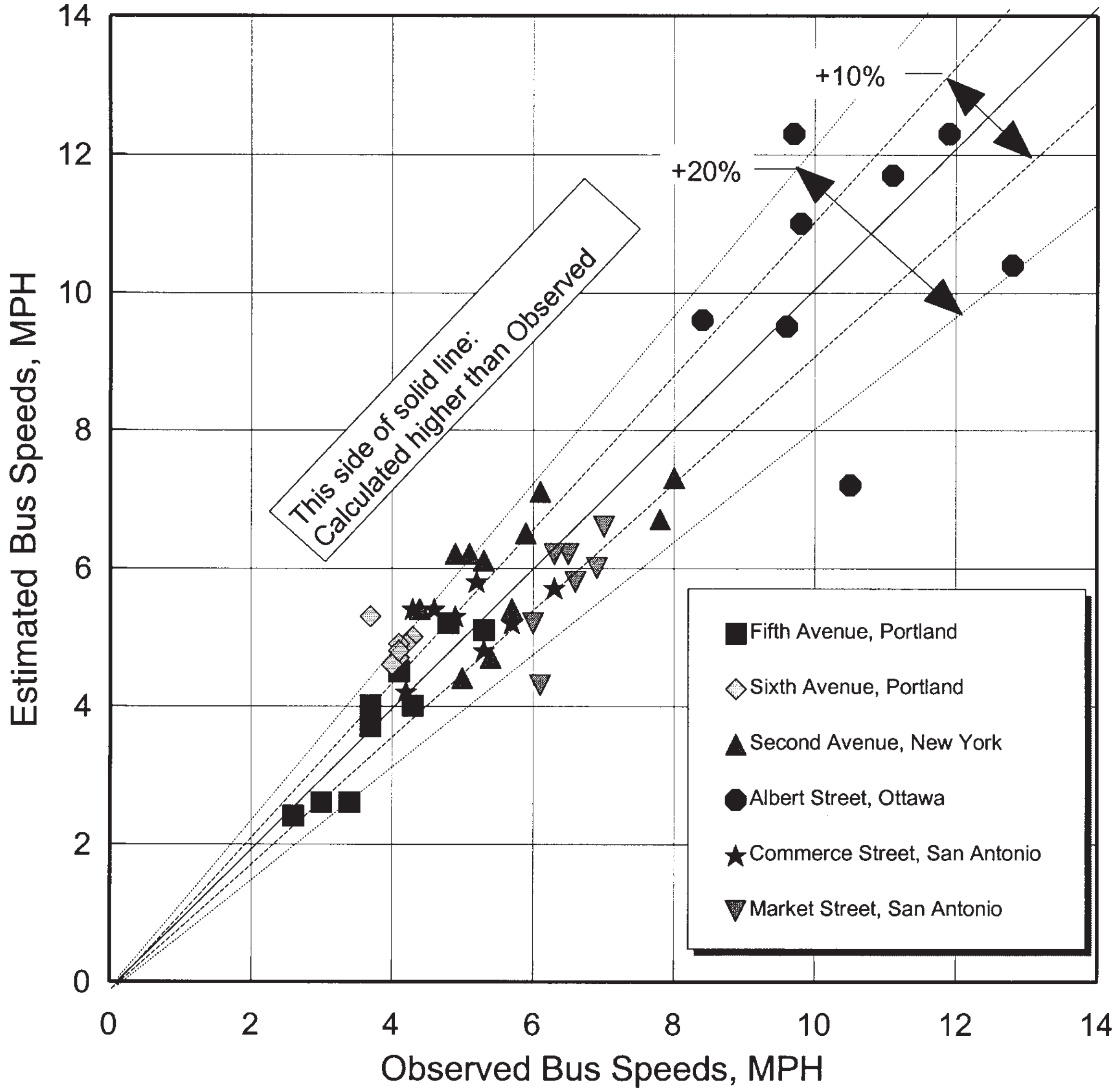


Figure 19. Observed versus estimated bus speeds (adjusted).

major outlying business districts. Sections along arterials should be at least 1/2 mi long, and preferably 1 to 2 mi long. The average dwell times in each section should be used to estimate speeds.

4. Where buses run in skip-stop patterns, individual estimates should be made for the group of buses using each stop.

Conclusions and Suggested Research

Many variables influence bus operations on downtown streets. These variables interact in a complex way, with variations in performance from day to day, from cycle to cycle of traffic signal, and from stop to stop.

The bus lane capacity and speed estimating procedures derived in *TCRP Report 26* show, in a systematic and sometimes simplified way, how the many factors influence bus performance. These procedures were tested in four cities, with observations of over 900 buses, to see how well the procedures would estimate or replicate observed conditions.

In the field tests, the procedures from *TCRP Report 26* provided a reasonable representation of observed field conditions. The ranges of error between observed and estimated speeds were generally within the variations associated with the observed speeds. The differences were often reduced when adjustments were made in the default values

TABLE 27 Summary comparison of bus speeds

Site	Range in Average Observed Speeds (mph) 15-Min Intervals	Range in Standard Deviation of Speed (mph)	Average Difference Between Observed And Estimated Speeds (Absolute)	
			Initial	Adjusted
Fifth Avenue-Portland	2.6-4.7	0.5-1.5	0.4	0.3
Sixth Avenue-Portland	3.7-4.2	0.9-1.5	1.0	0.8
Second Avenue-NYC	4.4-8.0	0.2-2.7	0.8	0.5
Albert St-Ottawa	9.0-12.8	1.3-3.6	2.0	1.6
Commerce St.-San Antonio	4.2-6.3	0.6-1.5	0.5	0.5
Market St.-San Antonio	6.0-7.0	1.0-2.3	0.9	0.5

TABLE 28 Summary comparison of estimated versus observed bus speeds (15-min intervals)

A. Initial Analyses						
Site	Total 15-Min Periods	Absolute Difference (mph)				
		0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	Over 2.0
Fifth Avenue-Portland	9	5	4	-	-	0
Sixth Avenue-Portland	7	1	4	1	1	0
Second Avenue-NYC	12	4	3	5	0	0
Albert St-Ottawa	8	2	0	3	0	3
Commerce St.-San Antonio	8	6	2	0	0	0
Market St.-San Antonio	7	3	1	3	0	0
TOTAL	51	21	14	12	1	3
%	100.0	41.2	27.4	23.5	2.0	5.9
B. Adjusted Speeds						
Site	Total 15-Min Periods	Absolute Difference (mph)				
		0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	Over 2.0
Fifth Avenue-Portland	9	7	2	0	0	0
Sixth Avenue-Portland	7	2	3	2	0	0
Second Avenue-NYC	12	2	8	1	1	0
Albert St-Ottawa	8	1	2	0	2	3
Commerce St.-San Antonio	8	6	2	0	0	0
Market St.-San Antonio	7	4	3	0	0	0
TOTAL	51	22	20	3	3	3
%	100.0	43.1	39.2	5.9	5.9	5.9

Note: Adjusted speeds are those obtained using modifications to the parameters contained in *TCRP Report 26*.

TABLE 29 Recommended effective bus berths for on-line bus stops

Number of Berths Provided	Effective Berths Factor, N_b	
	Random	Platooned
1	1.00	1.00
2	1.75	1.85
3	2.45	2.65
4	2.65	2.90
5	2.75	3.00

TABLE 30 Bus travel times for various stop spacing, dwell times, and operating environments (suggested)

A. Base Travel Time Rates (Min/Mi)									
Average Dwell Time	Stops/Mi								
Per Stop (sec.)	2	4	5	6	7	8	9	10	12
10	2.40	3.27	3.77	4.30	4.88	5.53	6.23	7.00	8.75
20	2.73	3.93	4.60	5.30	6.04	6.87	7.73	8.67	10.75
30	3.07	4.60	5.43	6.30	7.20	8.20	9.21	10.33	12.75
40	3.40	5.27	6.26	7.30	8.35	9.53	10.71	12.00	14.75
50	3.74	5.92	7.08	8.30	9.52	10.88	12.21	13.67	16.75
60	4.07	6.58	7.90	9.30	10.67	12.21	13.70	15.33	18.75

B. Additional Travel Time Losses (Min/Mi)				
CENTRAL BUSINESS DISTRICT				
	Bus Lane No Right Turns	Bus Lane With Right-Turn Delays	Bus Lanes Blocked by Traffic	Mixed Traffic Flow
Typical	1.2	2.0	2.5-3.0	3.0
Signal Set For Buses	0.6	1.4	N/A	N/A
Signals More Frequent Than Bus Stops	1.5-2.0	2.5-3.0	3.0-3.5	3.5-4.0

ARTERIAL ROADS OUTSIDE OF CBD		
	Bus Lane	Mixed Traffic
Typical	0.7	1.2
Range	0.5-1.0	0.8-1.6

Note: Add values from Part A and Part B to obtain suggested estimate of total bus travel time. Convert total travel time rate to estimated average speed by dividing into 60 to obtain mph. Interpolation between shown values of dwell time is done on a straight line basis.

for incremental traffic delay to account for conditions such as cars blocking bus lanes, traffic signals set for bus operations, or signal frequenies that are greater than the bus stop frequency.

Accordingly, default factors were suggested to better reflect the range of conditions commonly encountered.

There remains a need to test, validate, and refine suggested default values for bus speed relationships along outlying arterial roads.

Additional simulation studies may be desirable for bus operations both within the city center and along arterial roads. These simulation analyses should address the variability in bus speeds and travel times. Contributing components include variations in dwell times at stops, arrivals at traffic signals, and general traffic conditions. Representatives of several participating transit agencies indicated that the variability of bus speeds was a major concern.

Traffic signal timing and possible preemption strategies for buses could reduce bus delays. Traffic signals constitute a major source of delays, especially in downtown areas. Additional research and experimentation are needed to show how traffic signal timing can be better adapted to bus flow while still accommodating motorists and pedestrians. Selecting cycle lengths tailored to bus operations, better allocating green times along bus routes, and setting signal offsets for bus flow are among the subjects that need further exploration and application. Research should include further simulation of bus performance under various traffic signal timing and bus stop location patterns. Demonstration projects should be pursued to allow case study documentation of the benefits of preferential treatment of buses in the traffic flow.

Bus dwell times and their variability should be reduced to effect higher bus travel speeds and more predictable bus operation. There are many ways to control dwell times, including low-floor buses, fare collection strategies, and information systems. Current initiatives regarding bus rapid transit should examine and analyze these treatments.

The Ottawa experience—where stops are widely spaced, signals are timed for buses, and most riders use monthly passes—results in one-third less dwell time at stops and about double the bus speeds of other systems, with bus lane throughputs of over 100 to 160 buses/hr. The transferability of this experience to other cities should be explored.

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ACKNOWLEDGMENTS

The researchers appreciate the cooperation received from the following agencies and their representatives who provided insight and guidance on bus operations and special assistance during data collection:

- David Mendoza, Tri-Metropolitan Area Transit (Tri-Met), Portland, Oregon;
- Phillip Landry, Ottawa-Charleton Transport Authority (O-C Transpo), Ottawa-Ontario, Canada;
- Andrew Hollander, New York City Transit, New York City, New York; and
- Bill Barker, VIA Transit Authority, San Antonio, Texas.

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