APPENDIX D

STREET-SIDE STUDIES

A number of alternatives are available when choosing the location, type of facility, and design for a bus stop. These alternatives include near-side, far-side or midblock locations, and curb-side or bus bay designs. None is ideal in all respects, but one design may offer a better balance of benefits to bus patrons and through vehicles given certain conditions. Therefore, the factors influencing the location and type of facility provided need to be analyzed, and a method for selecting the optimum alternative developed.

Appendix D presents the findings from studies that analyzed traffic and bus operations around various bus stop locations and designs. The studies included **regional visits** to agencies involved in transit operations, **field studies** of existing bus stops, and **computer simulation**. How different bus stop designs operate was explored during the regional visits. The objective of the field studies was to learn how different bus stop locations and designs influence traffic operations and driver behavior around a bus stop. The effects of bus stop design on suburban arterial traffic operations were further analyzed with the use of computer simulation.

Appendix D devotes a section to each study approach and concludes with a summary of findings.

REGIONAL VISITS

Both mail and telephone surveys were conducted during this project. (The findings from those surveys are documented in the *Location and Design of Bus Stops*, *Final Report*, Project A-10, available from TCRP.) While phone surveys provided an understanding of different concerns at various agencies, site visits were critical to provide a full appreciation of how different bus stop designs operate. On-site visits also provided the opportunity to photograph examples of bus stop designs for use in the final reports.

Researchers conducted three regional visits that included several transit agencies in each region. The three regions included the southwest, central, and the west coast. Information obtained from the mail surveys was used to identify potential agencies. A broad range of agency types and operational environments were visited. Agency sites were specifically selected based on their responses to the mail survey, the nature of their bus stop design, their bus stop policy, and the extent to which they represent a distinct category of bus stop practice, service area type, or regional category. Selection was also influenced by geographic grouping for efficient travel plans.

Data Collection Methodology

The three key personnel for the project (Fitzpatrick, Perkinson, and Hall) participated on each trip. Each individual was responsible for his or her particular area of expertise. For example, Fitzpatrick made observations on the influence of the street design on bus stop operation, while Hall noted bus patron and pedestrian interaction with the bus stop. Perkinson observed various need-related aspects of each bus stop, such as spacing, placement in relation to adjacent land uses, and so on. All three researchers participated in the interviews with transit agency staff.

The team approach was critical for the site visits. Stop location and design involve many disciplines, as reflected in the expertise of the personnel assembled for this project. However, unification of these perspectives into a single coherent vision of bus stop location and design is critical for the practical application of this research. Consequently, the site visit team integrated their respective observations and insights on a real-time basis during the site visit, as well as immediately following the conclusion of each regional trip.

The mechanics of the site inspection process involved extensive pre-visit planning to identify bus stop locations with certain specified features and to set up interviews with key agency staff. Interviewed agency staff typically had planning and/or operational responsibility. Site-specific survey issues were identified from earlier screening and survey data.

Before interviewing the staff, a typical site survey routine was done with the physical inspection of previously identified key design or location features of the sites. Completion of the inspection before the interview enabled the researcher to prepare for discussion of details during the scheduled interviews. The pre-interview aspect of the field work, however, involved more than interview preparation. This relatively unstructured field work by the team allowed for the application of various unobtrusive research methods. Unobtrusive research in this context means passive observation of the actual use of physical facilities, including the individuals using those facilities and the artifacts of their use. This tactic is appropriate for bus stop location and design because the level and nature of the use of a facility is a critical indicator of the success of the design and placement of that facility.

The relatively unstructured field work was followed by scheduled interviews with appropriate transit agency staff, and others where appropriate. The interviews were guided by a set of interview notes prepared upon completion of the initial site investigations to ensure coverage of predetermined critical issues and questions. The interview was not, however, limited to these questions, allowing for probing and follow up on unanticipated elements in the discussion.

In addition to the largely spontaneous real-time comparisons of observations and impressions between project team members, a more formal "de-briefing" was performed at the end of each regional visit. These sessions consolidated and documented the findings from the site visit, minimizing the loss of data due to the inherently coarse nature of field notes, as well as avoiding confusing the sites and regions.

Overview of Regional Visit Data

Bus stop data were collected for almost 300 bus stops in more than 15 cities, representing more than one dozen transit systems (public and private), during the three regional visits. Table D-1 shows the number of stops examined by region, city, and transit agency. These observations were documented in some 2,000 photographs.

Findings

Several findings emerged from the field observations and the interviews of key agency staff. This appendix presents the findings from the site visits regarding street-side design and location of bus stops. A summary of the findings associated with curb-side issues (such as shelter placement, need for amenities, etc.) is presented in Appendix E.

Table D-1. Summary of Regional Visits by Agency, City, and Number of Stops.

REGION	AGENCY	CITY	STOPS
SOUTH WEST	Phoenix RTA	Phoenix	28
	Phoenix RTA & City of Scottsdale	Scottsdale	14
	Phoenix RTA	Tempe	4
	Mesa Sun Runner	Mesa	2
	Phoenix RTA & City of Chandler	Chandler	17
	SunTran	Tucson	38
			103
CENTRAL	Grand Rapids Area Transit Authority	Grand Rapids	21
	Capital Area Transportation Authority	Lansing	26
	Ann Arbor Transit Authority	Ann Arbor	25
	Detroit Suburban Mobility Authority	Detroit suburbs	17
			89
WEST COAST	San Francisco Municipal Railway	San Francisco	13
	Central Contra Costa Transit Authority	Concord/Walnut Creek	20
	AC Transit	Milpitas	4
	Transportation Agency	San Jose	15
	SamTrans	San Carlos	1
	SamTrans	San Mateo	26
			79

Safety

Pedestrian safety involves both the defined bus stop area and areas used while getting to and from the bus stop. Examples of traffic considerations include traffic control devices with adequate pedestrian cycles, clearly marked crosswalks, adequate setback from the street, good visibility for drivers and pedestrians, positioning of stops and waiting areas away from intersections and driveways, and avoiding mixing stops and vehicle turning movements. While these elements are acknowledged and well known, in practice, compromises such as placing a bus stop near driveways, are often made as shown in Figure D-1.

Figure D-1. Bus Stop Between Driveways.

Vehicle safety relates to the provision of sufficient visibility to other vehicles and to pedestrians. Consideration is needed of the effect that the stopped bus will have on sight distance for parallel traffic and cross traffic. The potential for conflicts in the traffic stream as a bus enters or leaves a stop also needs to be considered. Figure D-2 shows a vehicle passing a stopped bus on a two-lane street. In this situation, adequate sight distance is needed so that the passing vehicle can safely use the opposing traffic's lane to pass the bus. Adequate sight distance for pedestrians in the crosswalk is also needed.

Figure D-2. Example of a Vehicle Passing a Stopped Bus on a Two-Lane Street.

Bus stops are sometimes located between the driveways of gasoline service stations and convenience stores. While this location has several advantages, some disadvantages exist as well. For example, because these facilities are usually on corners, vehicle turning movements abound, and pedestrian access is seldom clearly marked. Since parking is important, sufficient right-of-way to set back the waiting area from the street is rare. Finally, traffic entering and departing the store passes nearby and conflicts with pedestrian access (as illustrated in Figure D-3).

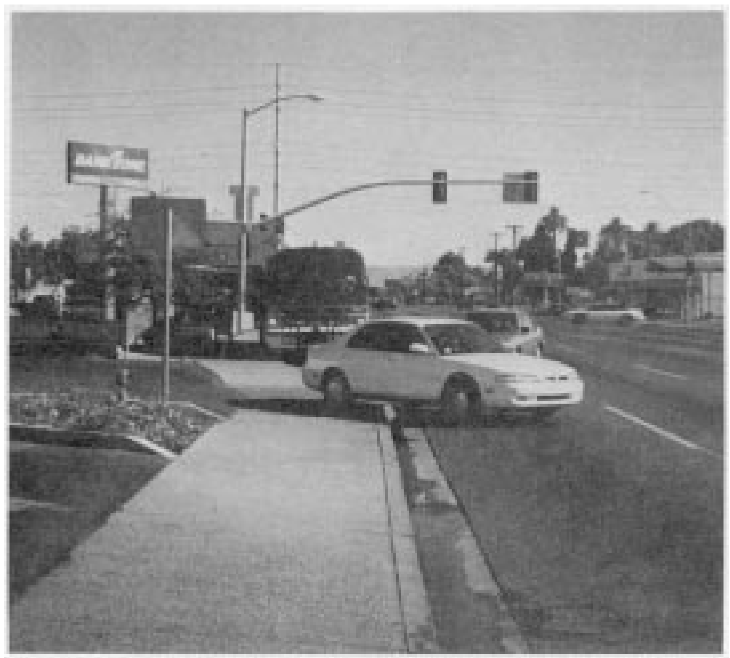


Figure D-3. Vehicle Conflicts with Pedestrian Access.

Roadway Geometry

Two aspects of roadway geometry are critical for good bus operations: 1) turning radius and 2) the contour of the acceleration and deceleration portions of bus bays. While turning radius is not properly a part of the bus stop, the project team observed many buses swinging wide and blocking traffic in the adjacent lane as shown in Figure D-4. In many cases, the adjacent land uses or other factors clearly prevented the use of an adequate turning radius. In others, however, a better design was possible. Good roadway design is well understood and documented in the traffic engineering literature. Interviews and subsequent discussion confirmed that institutional (jurisdictional and coordination) and budget constraints prevented better geometry.

Figure D-4. Bus Using More Than One Lane to Complete a Turn.

Institutional and budget constraints were also identified as preventing the implementation of desirable acceleration and deceleration portions of bus bays. While the performance requirements of buses, in terms of acceleration and deceleration, may be less widely known, they are obtainable. On the other hand, bus operators demonstrated a clear mastery of operating under less than optimal conditions, such as taking advantage of upstream traffic signals that create gaps which allow the bus to re-enter the traffic stream (see Figure D-5).

Figure D-5. Bus Taking Advantage of Upstream Traffic Signal.

Pavement

The project team observed a wide range of pavement conditions at bus stops. Unreinforced pavement at a bus stop will deform and deteriorate in a short time, even with only moderate bus activity. The nature and magnitude of pavement deterioration at bus stops were well documented during the regional visits as shown in Figure D-6.

There are two primary concerns regarding pavements at bus stops: 1) initial design of the pavement and 2) maintenance and repair of existing pavement. Pavement design and management are typically a city or state responsibility; however, the transit agency may provide supplemental funding for the repair of pavements at bus stops. Debate is ongoing concerning how much of the pavement damage near a bus stop is caused by transit buses because other heavy vehicles, such as large trucks and garbage trucks, also contribute to the pavement problems near an intersection. These institutional/organizational conflicts, combined with the difficulties of maintaining a quality roadway pavement (especially at bus stops), point to the value of installing bus pads.

Figure D-6. Poor Pavement Condition at Bus Stop.

Bus Pads

A bus pad is an area of reinforced pavement at a stop. It is designed to handle the additional stresses of the frequent stopping of heavy buses, as illustrated in Figure D-7. (The bus at the stop in this figure would probably make a right turn because of the adjacent right-turn lane.) Bus pads may be installed during street construction or rehabilitation or may be installed as a separate project. Either way, the benefits in reduced maintenance and pavement damage appear to be recognized by both transit and city staff. Unfortunately, the use of bus pads is not as widespread as the recognition of their merit. The primary reasons appear to be the expense involved and the limited constituency they are perceived to benefit. An in-depth analysis of bus pads is beyond the scope of this project; however, it appears that a clear cost/benefit analysis might help clarify this issue.

Bus Stop Location (Far-Side, Near-Side, Midblock)

The team's observations and subsequent interviews confirmed that the advantages and disadvantages of each type of stop placement (far-side, near-side, and midblock) are well understood, although the conclusions drawn and agency preference or policy varies among transit agencies. In practice, bus stop placement is affected by a combination of site-specific considerations, precedent, and transit agency and city policy.

Figure D-7. Reinforced Pavement (Bus Pad) at a Stop.

FIELD STUDIES

To study the operations around existing bus stops, the research team collected data at several field sites. Results from the phone surveys and regional visits were used to select field sites that would be studied. The goal was to include a variety of bus stop designs, including curb-side stops, bus bays, queue jumpers, and nubs. The two major field data collection trips took place in Arizona and California; an additional site in College Station, Texas, was also visited.

Results from the data collection trips were used to study how different bus stop locations and designs influence the traffic operations and driver behaviors around the bus stop. Once the field data were collected, the observed bus stops were divided into two categories: urban stops and suburban stops. Urban stops included stops on low-speed arterials (less than 35 mph) in areas with heavy development and high driveway densities. In contrast, suburban stops were in areas with relatively higher speeds (greater than 35 mph), lighter development, and lower driveway densities.

Objective

The objective of the street-side field studies was to observe the operations at existing field sites to learn how the location and design of bus stops influence traffic and bus operations. To accomplish the objective of these studies, the following tasks were performed:

- Collect field data at bus stops with varying locations and designs in both urban and suburban areas.
- Observe and record traffic operations at each of the field sites for use in the field studies and the computer simulation studies.
- Summarize the information concerning the characteristics and operations at each field site.
- Compare the observations at both urban and suburban bus stop locations.

To learn how different bus stop locations and designs affected the traffic operations around the bus stop area, the bus and traffic operations and erratic maneuvers observed at the sites were analyzed and compared. The findings from the field sites were grouped by bus stop design. By studying the operations and erratic maneuvers occurring at different bus stop designs, certain maneuvers could be associated with a particular design.

Suburban Sites

Data were collected at eight suburban field sites in Tucson, Arizona; Tempe, Arizona; San Jose, California; and College Station, Texas. The sites ranged in location and design. Table D-2 describes each of the suburban sites studied. The following sections describe the study design, discuss each field site, and summarize the findings.

Table D-2. Description of Suburban Study Sites.

Site	City	Location	Bus Stop Location, and Design	Cross Section[a]	Surrounding Development	Speed Limit	Recording Time
S1	Tucson, Arizona	Speedway @ Campbell	Far-Side, Queue Jumper Bus Bay	6 lanes, raised median	hotels, restaurants	35	7am-7pm
S2	Tucson, Arizona	Speedway, Mountain - Cherry	Midblock, Bus Bay	6 lanes, raised median	University of Arizona	35	7am-5pm
S3	Tempe, Arizona	Mill @ University	Far-Side, Curbside	6 lanes, raised median	gas station, restaurants, strip mall	35	7am-1pm
S4	San Jose, California	Bird @ San Carlos	Far-Side, Curbside	6 lanes, raised median	gas stations and strip development	35	12pm-5:30pm
S5	San Jose, California	San Carlos @ Bird	Near-Side, Bus Bay	4 lanes, raised median, parking	gas stations and strip development	35	7am-5:30pm
S6	San Jose, California	San Carlos @Bird	Far-Side, Open Bus Bay	4 lanes, raised median, parking	gas stations and strip development	35	7am-5:30pm
S7	San Jose, California	Santa Clara @ Market	Far-Side, Open Bus Bay	4 lanes, TWLTL, parking	shops and restaurants	35	11am-5pm
S8	College Station, Texas	University @Texas Ave.	Far-Side, Curbside	6 lanes, raised median	apartments, Texas A&M University	40	7am-9am (on two days)

[a] TWLTL = two-way left-turn lane

Study Design

Data Collection. The research team collected data at five sites in Arizona. Data from three of the sites were used for the traffic study in suburban areas. These three sites consisted of two in Tucson and one in Tempe. Portable 8-mm video cameras were used to study the traffic operations around these sites. Typically, from four to five cameras were placed around the bus stop to record traffic volumes, queues behind buses, and bus arrival/departure times. The cameras also recorded erratic or unique behaviors by the bus operators or drivers of other vehicles.

Some of these sites were also used to aid in the traffic simulation study (see following section); therefore, turning movements and travel times were also collected. Travel times were measured from several hundred feet upstream of the bus stop to several hundred feet downstream of the bus stop.

Typically, video cameras taped the following locations: the bus stop; a specific point several hundred feet upstream of the bus stop; a specific point several hundred feet downstream of the bus stop; and the intersection upstream of the bus stop. In some cases, the entire bus stop area could not be captured using only one camera; therefore, an additional camera was used.

The research team collected data at 13 sites in California, four of which were used for the suburban traffic study. The four sites were located in the city of San Jose. While in San Jose, the team collected data with the help of the City of San Jose's Traffic Management Center, which has several high-powered video cameras stationed throughout the downtown area to monitor traffic during special events at the downtown sports arena. Consequently, the data collection team collected data at several different sites using these cameras. Typically, a camera was focused on an area several hundred feet upstream and downstream of the bus stop to record volumes, turning movements, queues behind buses, travel times, bus arrival/departure times, and erratic behaviors.

After the data collection trips to Arizona and California, an additional field site was selected in College Station, Texas to further study the effects that a curb-side stop has on traffic operations. This site was selected because it is known to have high traffic volumes during the a.m. peak period. Traffic operations around this site were recorded using a surveillance camera operated by the Texas Transportation Institute.

Data Reduction and Analysis. The data from the video tapes were reduced by technicians. The technicians recorded information concerning each bus, including the arrival time, departure time, queue behind bus, and delay to bus re-entering traffic. During each bus arrival, any erratic maneuvers observed were also recorded. An erratic maneuver was defined as an unusual action by the bus operator or driver of another vehicle caused by the presence and location of the bus. The erratic maneuvers observed are listed in Table D-3.

Table D-3. Erratic Maneuvers Observed in the Field.

1. Traffic queue occurs due to bus blocking lane while stopped (curb-side stop).
2. Traffic queue occurs due to vehicle stopping in through lane to allow bus to re-enter traffic stream (bus bay).
3. Driver of vehicle changes lanes due to bus (curb-side stop).
4. Bus operator pulls out in front of car causing driver to slow down, change lanes, or stop (bus bay).
5. Conflict occurs between bus and car while bus is re-entering traffic stream causing delay to bus.
6. At a bus bay, bus driver stops in main lanes to board passengers.
7. Conflict occurs between bus and car due to driveway location.

Travel time and traffic volume data from selected sites (sites S1, S2, and S4) were also used to calibrate a computer simulation model for the traffic simulation study. Because these sites were used for calibration, more detailed information was obtained (i.e., intersection turning movements, average speeds, and traffic signal timings). Traffic volume and travel time data were reduced in five-minute intervals around each bus arrival (for example, two minutes before a bus arrived to three minutes after the arrival).

To measure travel times during a five-minute increment, the technicians would record the time a vehicle entered the system, track the vehicle through the system, and record the time that the vehicle left the system. The system was typically defined as either a set distance upstream and downstream of the bus stop or the intersection upstream and the intersection downstream of the bus stop. Once the data were reduced from the video tapes, they were put into a spreadsheet for data manipulation.

After the field data were collected and reduced, the results were summarized for each site. Included in the summary are descriptions of each of the study sites and descriptions of the bus and vehicular operations observed. After analyzing each site separately, the operations at all suburban sites were compared.

Study Sites

This section describes the eight suburban sites studied. Included are discussions of the findings at each site.

Site S1: Tucson, Arizona; Speedway at Campbell. Site S1 is a queue jumper bus bay located in the central part of Tucson, Arizona. Figure D-8 presents the plan view of the site. For the 12 hours that site S1 was video taped, 68 bus arrivals were observed. During the study time, very few erratic maneuvers occurred. Conflicts between the bus and other vehicles occurred only twice when drivers of vehicles changed lanes to avoid a bus. Also, the delay to traffic caused by the bus was minimal because the bus stop was located off the main lanes. The delay to the bus re-entering traffic was also minimal. The 200-foot acceleration lane permitted the bus to merge with traffic smoothly.

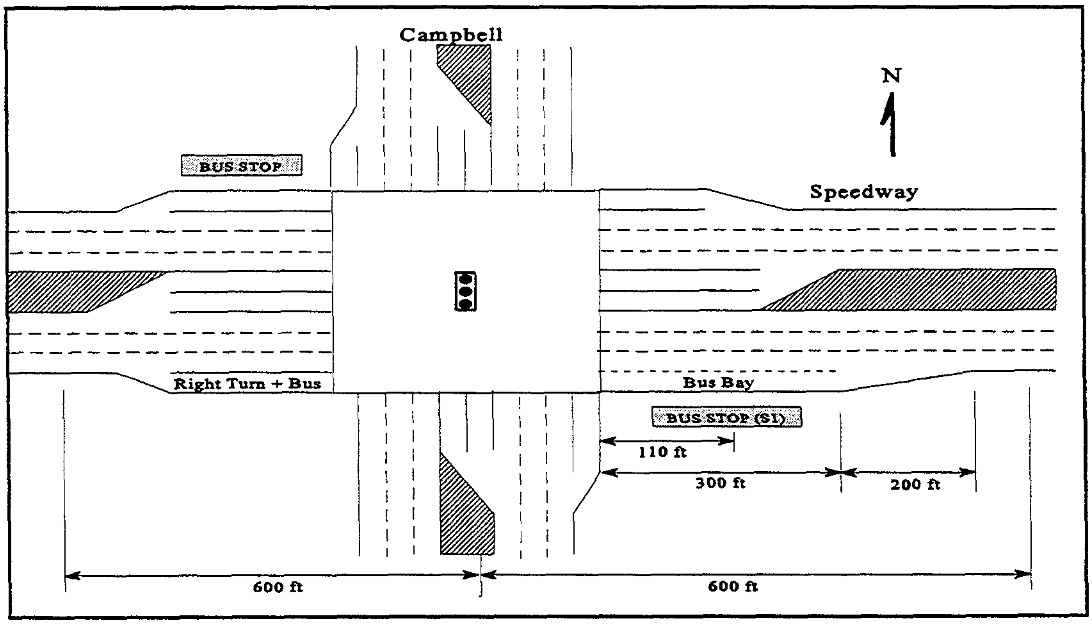


Figure D-8. Site S1: Speedway at Campbell.

Site S2: Tucson, Arizona; Speedway between Mountain and Cherry. Site S2 is a midblock stop with a bus bay located in Tucson, Arizona. Figure D-9 presents the plan view for Site S2. Most of the conflicts observed at Site S2 occurred between buses leaving the stop and through traffic. However, out of 35 bus arrivals, conflicts only occurred seven times. The conflicts occurred when a bus using the acceleration lane trying to re-enter the traffic stream had to slow and wait for an adequate gap in the through traffic before merging. For the seven conflicts observed, the delay ranged from two seconds to five seconds with an average delay of three seconds.

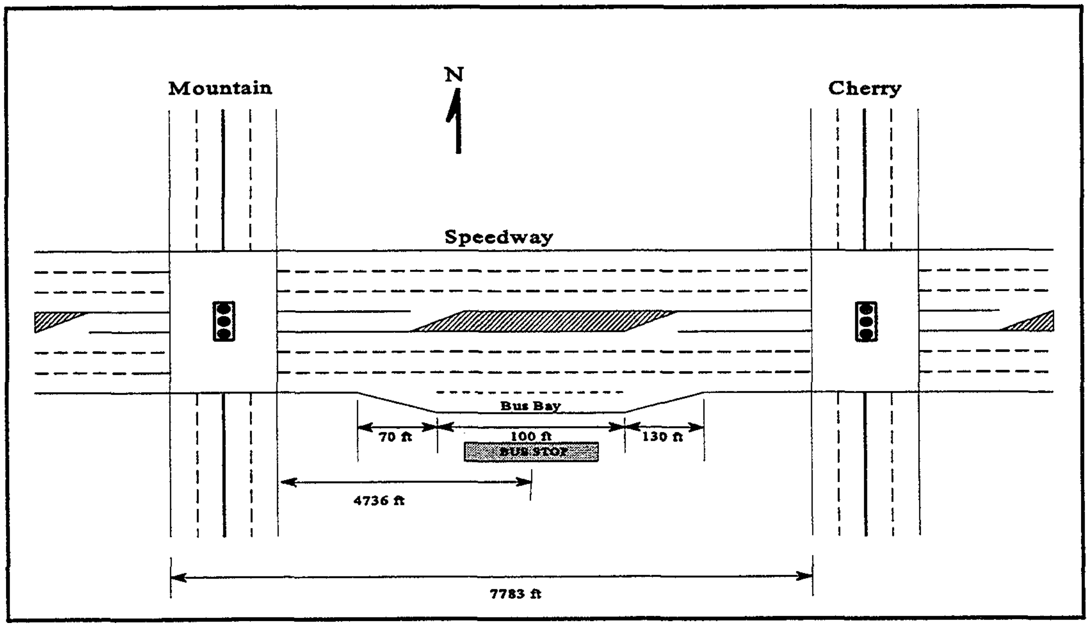


Figure D-9. Site S2: Speedway between Mountain and Cherry

Site S3: Tempe, Arizona; Mill at University. Site S3 is a far-side curbside bus stop located in the central area of Tempe, Arizona. The stop is positioned between two driveways leading into a gas station. Two southbound lanes are on Mill until approximately 220 feet north of University. At this point, an additional through lane is added (see Figure D-10).

For the time that Site S3 was studied, very few erratic maneuvers occurred. Conflicts between the bus and other through vehicles were minimal. Also, queues and delay to the traffic caused by the bus were minimal. This was due in part to the lane configuration at this site. As stated above, an additional outside lane is added to Mill approximately 220 feet upstream of the bus stop. Buses traveling along Mill, approaching the bus stop, were observed moving into the additional lane before reaching the stop; however, the majority of through vehicles did not move into this lane if a bus was present. Therefore, stopped buses typically did not interfere with the through vehicles; thus, delay to through vehicles was minimized.

Conflicts were observed between stopped buses and vehicles entering and exiting the driveways because the bus stop was located between two driveways, leading to a gas station. Drivers wanting to enter or exit the driveways experienced conflicts when a bus blocked one of the driveways. In these situations, the drivers of the vehicles either waited for the bus to move or went to the next driveway. Conflicts for exiting vehicles also occurred when the view of oncoming traffic along Mill was blocked by the bus.

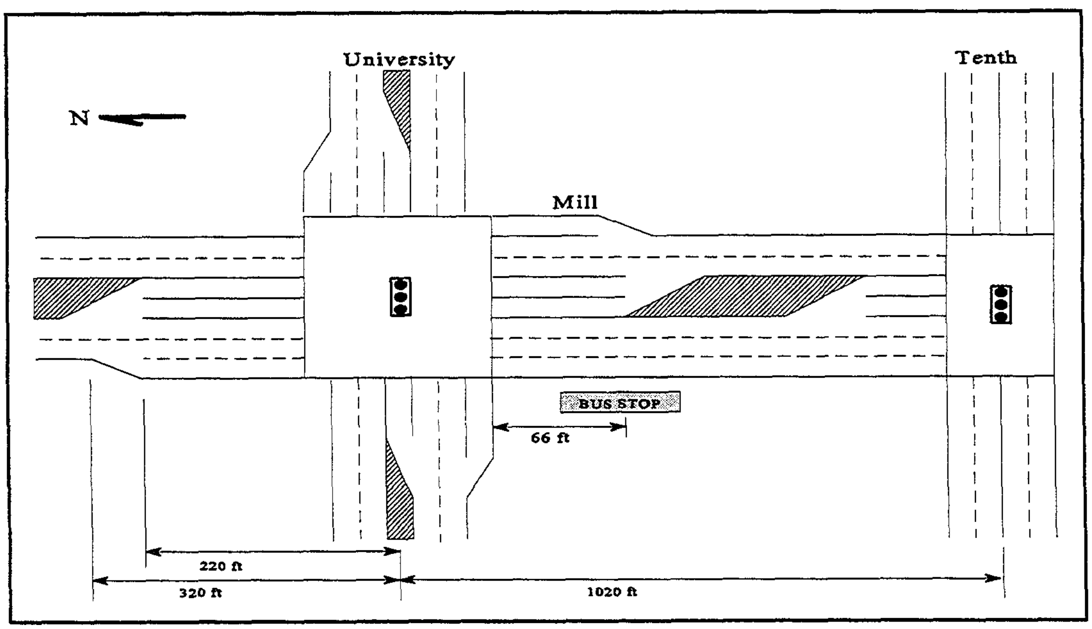


Figure D-10. Site S3: Mill at University.

Site S4: San Jose, California; Bird at San Carlos. Site S4 is a far-side curbside bus stop located in the southern part of San Jose. Figure D-11 presents the plan view of the site. At Site S4, 30 bus arrivals were observed. Eighteen conflicts occurred between stopped buses and through traffic in which the drivers of through vehicles changed lanes to avoid the bus. However, because of the relatively low volumes observed, vehicles never queued behind the stopped buses and, therefore, the delay to through traffic was minimal.

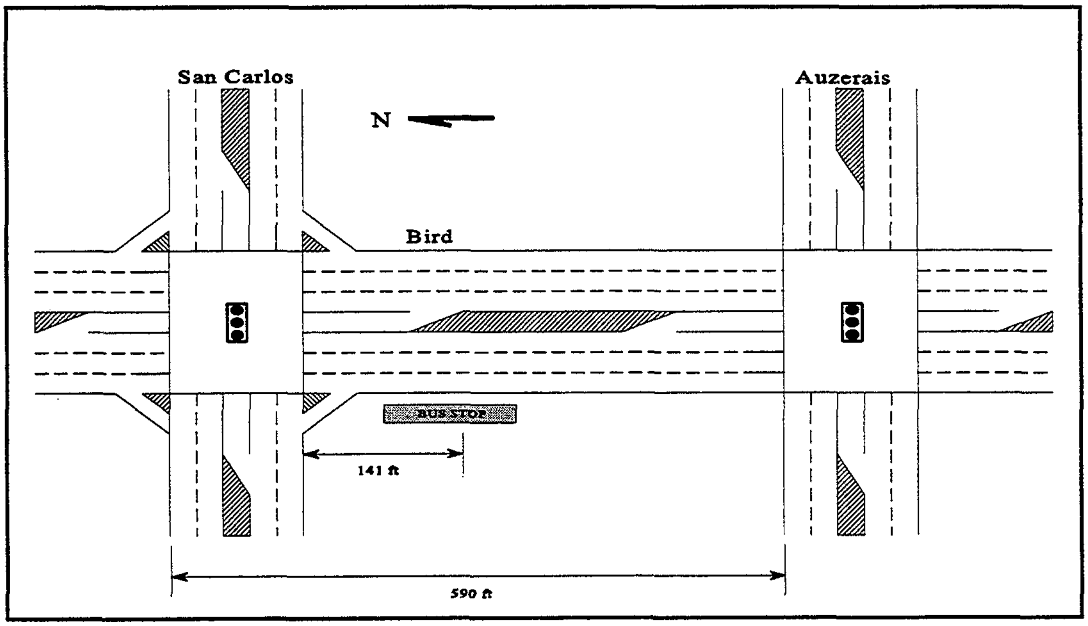


Figure D-11. Site S4: Bird at San Carlos.

Sites S5 and S6: San Jose, California; San Carlos at Bird. Sites S5 and S6 were both located at the intersection of San Carlos at Bird (just north of Site S4). Parking is discontinued where the bus stops are located so that the buses can stop next to the curb. Since the buses pull off the main lanes to drop off and pick up passengers, the bus stops function as bus bays (i.e., while stopped, buses have minimal effects on through traffic). Figure D-12 presents of the plan view for sites S5 and S6.

For the time that Site S5 was studied, 47 bus arrivals were observed. During these arrivals few conflicts occurred between the buses and other traffic. Those erratic maneuvers observed typically occurred when buses were leaving the stop and re-entering the traffic stream. These erratic maneuvers included the following: bus operators pulling out in front of other traffic causing the drivers to slow, stop, or change lanes (three times); and drivers of vehicles stopping to allow the bus to re-enter traffic (three times). Also, twice during the day, buses were observed stopping in the through lanes to board passengers instead of pulling up to the curb. During the study of this stop, a bus re-entering traffic was only delayed once for only for five seconds.

At Site S6, 45 bus arrivals were observed. The conflicts that occurred included drivers of vehicles changing lanes to avoid a bus (four times). This typically occurred when a bus was slowing down in the through lanes before making a stop. Delay to buses re-entering the traffic stream occurred four times ranging from two to four seconds.

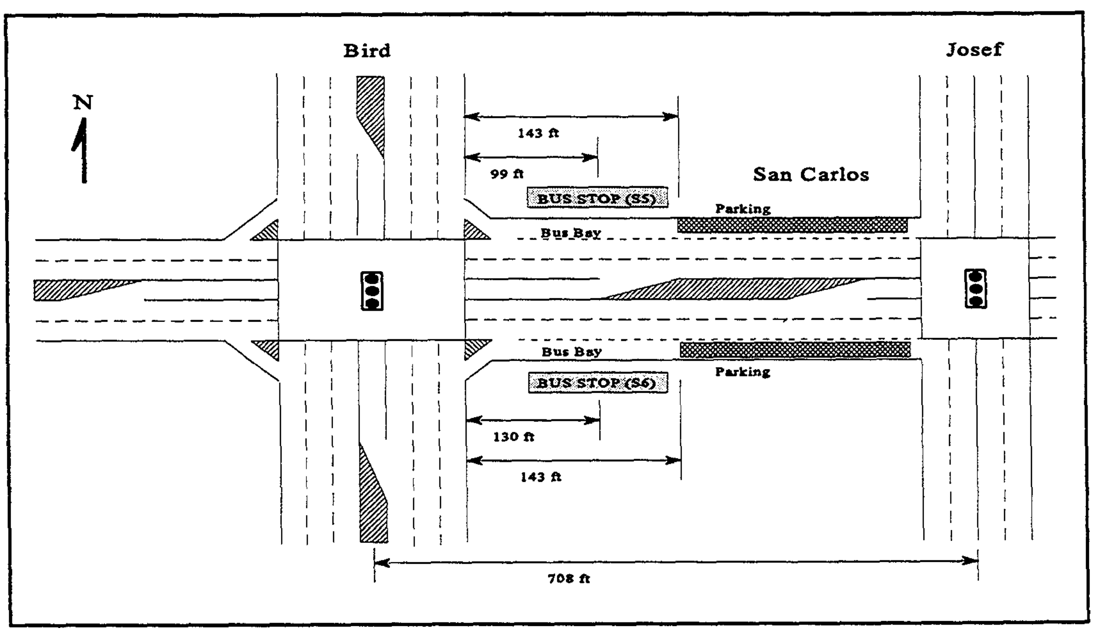


Figure D-12. Sites S5 and S6: San Carlos at Bird.

Site S7: San Jose, California; Santa Clara at Market. Site S7 is a far-side bus stop located in the central part of San Jose (see Figure D-13). Parking is discontinued where the bus stop is located so that the buses can stop next to the curb; therefore, the bus stop functions as an open bus bay. For the time that this site was studied, no erratic maneuvers were observed.

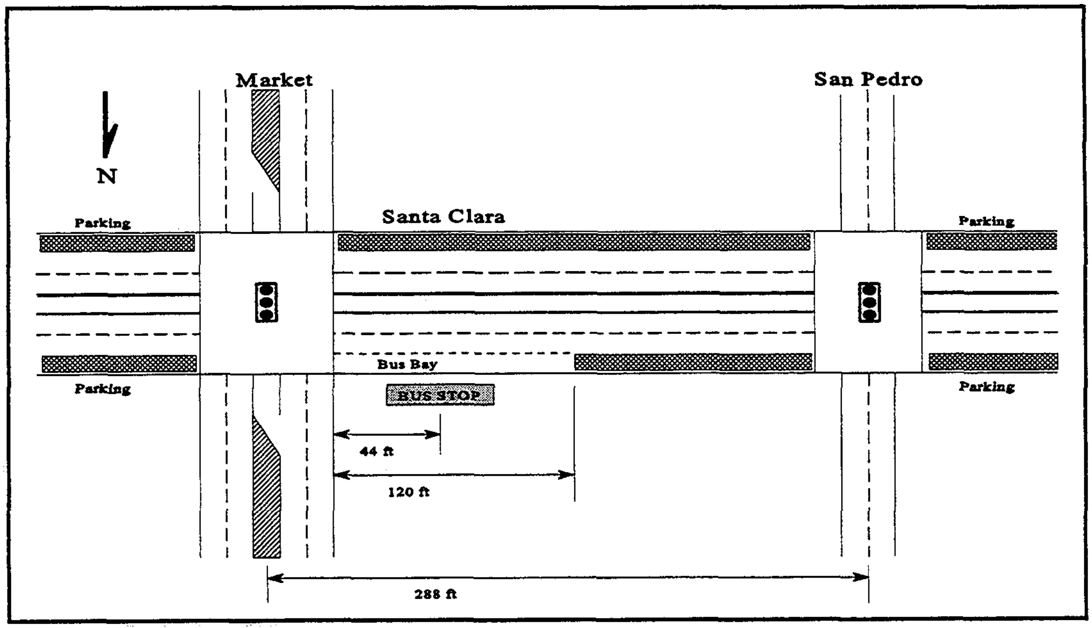


Figure D-13. Site S7: Santa Clara at Market.

Site S8: College Station, Texas; University at Texas. To further study the effects that a curbside stop has on traffic operations, an additional field site was selected in College Station, Texas. Site S8 is a far-side curbside bus stop located in the central part of College Station near Texas A&M University and the Texas Transportation Institute. The buses accessing this stop are university shuttle buses serving university students. This site was selected because it is known to have high traffic volumes during the a.m. peak periods. Figure D-14 presents the plan view for site S8.

The erratic maneuvers observed at Site S8 included vehicles changing lanes to avoid stopped buses and vehicles queuing behind stopped buses. At this site, vehicles were observed changing lanes to avoid a bus 46 times and queuing behind stopped buses 14 times. The maximum queue length ranged from one vehicle to seven vehicles.

Observing the operations at this site, for lower traffic volumes drivers would change lanes to avoid a stopped bus. As traffic volumes increased, the opportunity for through vehicles to change lanes decreased and more queues were observed. Figure D-15 illustrates the relationship between maximum queue and volume for Site S8. Observing this figure, queues began forming at volumes above 300 vphpl. Queues greater than three vehicles in length formed at volumes above 900 vphpl.

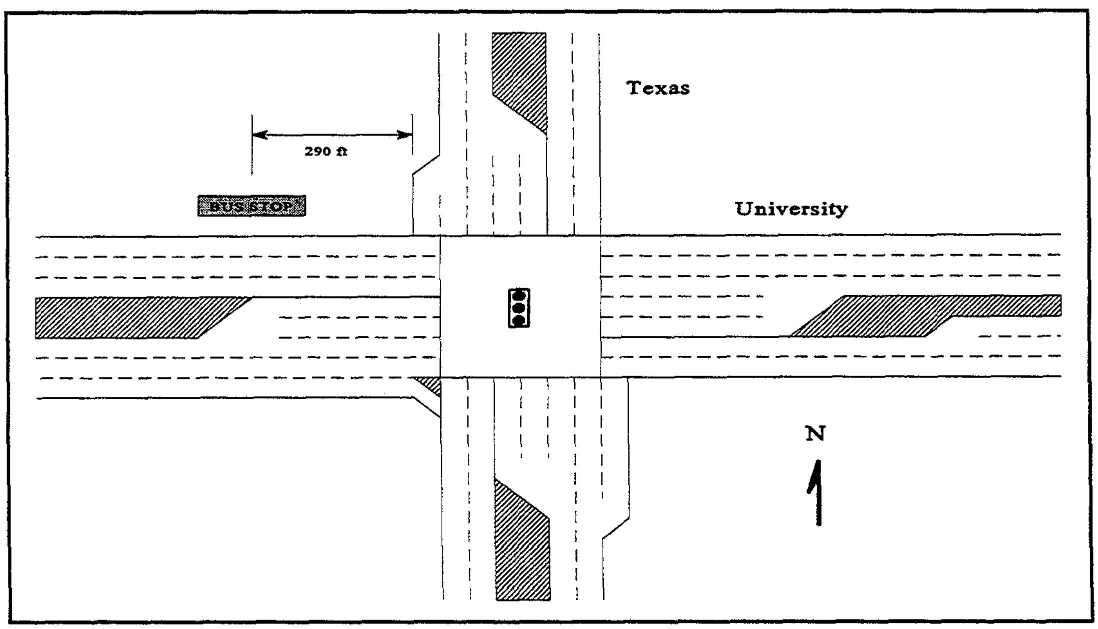


Figure D-14. Site S8: University at Texas.

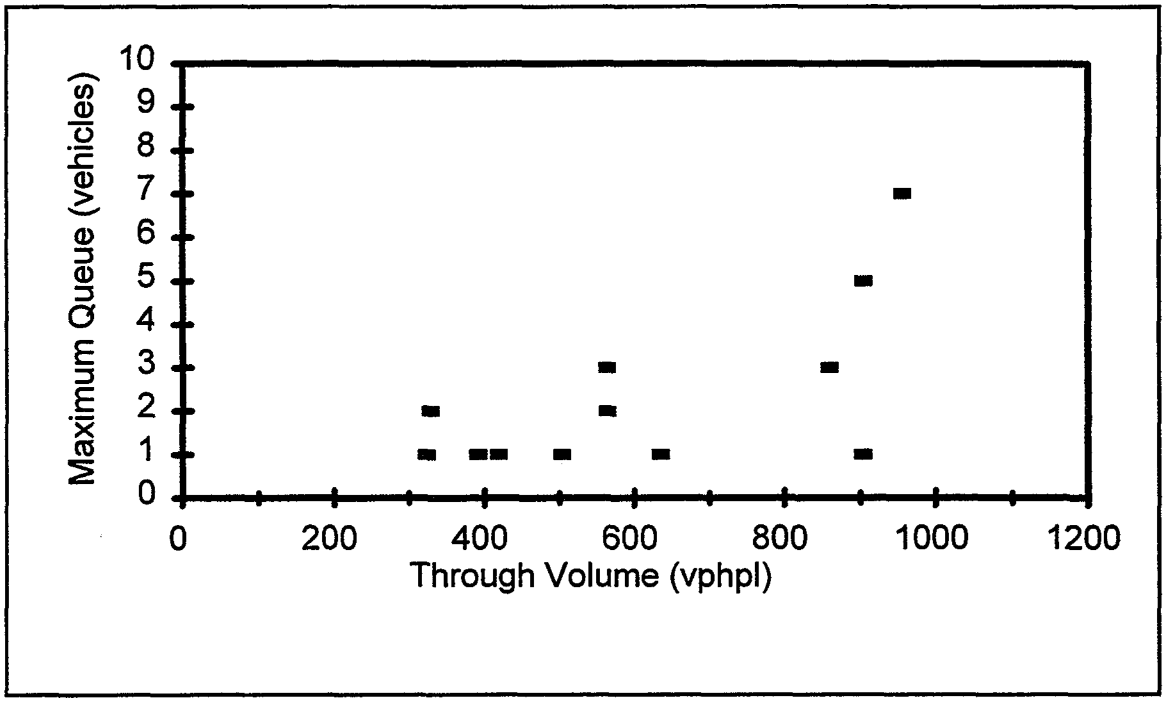


Figure D-15. Relationship between Maximum Queue and Volume for Site S8.

Findings

Tables D-4 and D-5 summarize the research findings for the suburban sites. Table D-4 includes the operational characteristics measured from the field and Table D-5 summarizes the erratic maneuvers observed. The operational characteristics include the following: speed (either measured or posted speed limit); maximum through volume observed; minimum, maximum, and average dwell time for the buses; minimum and maximum number of vehicles in queue behind a stopped bus; and minimum and maximum delay to buses re-entering the traffic stream. In Table D-5, the erratic maneuvers observed in the field (see Table D-3) were combined into three categories: those that involved traffic queuing near a bus stop because of the presence of bus, those that involved a vehicle changing lanes because of the presence of a bus, and those that involved delay to a bus reentering the traffic stream. The erratic maneuvers are summarized by number (total number observed) and rate (number of erratic maneuvers / number of bus arrivals).

Table D-4. Observational Characteristics for Suburban Sites.

Site	Location[a]	Design[b]	Speed (mph)[c]	Max. Through Volume (vphpl)	Dwell Time (sec)			Number of Vehicles in Queue[d]		Delay to Bus (sec)[d]	
					Minimum	Maximum	Average	Minimum	Maximum	Minimum	Maximum
S1	FS	OBB QJ	43 (m)	830	7	180	33	--	--	--	--
S2	MB	BB	43 (m)	670	8	35	15	--	--	2	5
S3	FS	CS	35 (p)	330	11	150	53	--	--	--	--
S4	FS	CS	36 (m)	500	9	110	28	--	--	--	--
S5	FS	OBB	35 (p)	300	7	140	26	1	2	0	5
S6	NS	BB	35 (p)	420	11	195	54	--	--	2	4
S7	FS	OBB	35 (p)	280	7	34	14	--	--	--	--
S8	FS	CS	40 (p)	910	12	90	35	1	7	--	--

[a] FS=Far-Side, NS=Near-Side, MB=Midblock
[b] BB=Bus Bay, OBB=Open Bus Bay, QJ=Queue Jumper, CS=Curbside
[c] m=85th percentile speed measured in field; p=posted speed limit
[d] — signifies that no queues or delays were observed

Table D-5. Erratic Maneuvers for Suburban Sites.

Site	Location and Design[a]	Number of Bus Arrivals Observed	Traffic Queue[b]		Lane Changes[c]		Delay to Bus[d]	
			Number[e]	Rate[f]	Number	Rate	Number	Rate
S1	FS, QJ	68			2	1 / 34.0		
S2	MB, BB	35					7	1 / 5.0
S3	FS, CS	27						
S4	FS, CS	30			18	1 / 1.7		
S5	FS, OBB	47	4	1 / 11.8	3	1 / 15.7	1	1 / 47.0
S6	NS, BB	45			4	1 / 11.3	4	1 / 11.3
S7	FS, OBB	13						
S8	FS, CS	28	14	1 / 2.0	46	2 / 1.0		

[a] FS=Far-Side, NS=Near-Side, MB=Midblock, BB=Bus Bay, OBB=Open Bus Bay, QJ=Queue Jumper, CS=Curbside
[b] Traffic queue occurs near bus stop because of the presence of a bus.
[c] Driver of vehicle changes lanes because of the presence of a bus.
[d] Bus experiences delay while re-entering traffic stream.
[e] Total number of erratic maneuvers for the number of bus arrivals observed.
[f] Number of erratic maneuvers / number of bus arrivals.

Bus Stop Design. After data from each of the suburban field sites were analyzed and the results summarized, the next step was to investigate the effects that different bus stop locations and designs had on the traffic operations near a bus stop. This was accomplished by grouping the study findings by bus stop design. The bus stop designs analyzed in this study included curbside, bus bay, open bus bay, and queue jumper. Following is a discussion on the findings for each suburban bus stop design and a comparison of the results.

Curbside. A curbside bus stop is located on the outside main lane along the curb. Because the stop is located in the travel lane, conflicts may occur between through traffic and stopped buses. While the delay to through vehicles may increase with a curbside design, the delay to buses is decreased because bus operators do not have to re-enter the traffic stream (as with bus bay designs). An example of a curbside bus stop is illustrated in Figure D-16.

From the suburban field sites studied, three sites (Sites S3, S4, and S8) included curbside designs. Observations at the suburban sites included recording the number of queued vehicles behind a stopped bus and erratic maneuvers of through traffic drivers due to the presence of a bus.

Figure D-16. Example of a Curb-side Bus Stop.

For the three suburban sites studied with curb-side designs, queues behind stopped buses were only observed for one site, Site S8.

The probable reason that queues were not observed at Site S3 was due to the lane configuration at this site. This road has a lane added approximately 220 feet upstream of the far-side bus stop. Bus operators traveling in the through lane approaching the bus stop were observed moving into the additional lane before reaching the intersection preceding the stop; however, the drivers of through vehicles typically did not move into this lane if a bus was present. For this reason, and because of the relatively low through volumes observed (approximately 330 vphpl maximum), queues were basically nonexistent.

Queues were minimal at Site S4 because drivers of through vehicles were able to change lanes before reaching the stopped bus. Drivers easily changed lanes to avoid the stopped bus because of the number of through lanes (three) and the relatively low traffic volumes (approximately 500 vphpl maximum).

As traffic volumes increase, drivers have less opportunities to change lanes before reaching the stopped bus. This was the primary reason for the number of queues observed at Site S8. At this site, vehicles were observed queuing behind a stopped bus for eight different bus arrivals. The maximum queue length ranged from one vehicle to seven vehicles. Observation of the operations at this site indicate that, for lower traffic volumes, drivers would change lanes to avoid a stopped bus. Queues began forming at volumes above 300 vphpl. Queues greater than three vehicles in length formed at volumes above 900 vphpl.

Site S3 included a bus stop located between two driveways leading to a gas station. This allowed the research team to study conflicts between buses and vehicles entering and exiting the driveways. As anticipated, for drivers wanting to enter or exit the driveways, conflicts occurred when a bus was blocking one of the driveways. Conflicts for exiting vehicles also occurred when the view of oncoming traffic on the main lanes was blocked by the bus.

Bus Bay/Open Bus Bay. A bus bay or an open bus bay is a specially constructed section off the normal roadway to provide for bus loading and unloading in an area separated from the main lanes. This separation allows through traffic to flow freely without being impeded by stopped buses. Bus bays are provided primarily on high-volume or high-speed roadways. Additionally, bus bays are frequently constructed in heavily congested downtown and shopping areas where large numbers of passengers may board or disembark. Although the delay to through traffic is minimized with the use of a bus bay, the delay to the bus may increase due to the difficulty in re-entering the traffic stream. The delay to the bus re-entering traffic is dependent upon the traffic volume and whether an acceleration lane is provided on the bus bay. While bus bays may be positioned at far-side, near-side or midblock locations, open bus bays are typically located at far-side locations. Figures D-17 and D-18 illustrate examples of a bus bay and an open bus bay, respectively.

Note in Figure D-18 that the bus is changing lanes while in the intersection to access the open bus bay. This illustrates one of the benefits associated with an open bus bay. The bus operator has the width of the intersection available for decelerating and accessing the bay. Because the open bus bay design does not need to include a deceleration lane or an entrance taper, less right-of-way is needed.

For the eight suburban sites studied, sites S2 and S6 contained bus bays and sites S1, S5, and S7 contained open bus bays. The majority of bus delays observed occurred at Site S2 (midblock stop) and Site S6 (near-side stop). Seven buses were delayed in 10 hours of observations at S2, while four buses were delayed in 10.5 hours of observations at S6. For sites S1, S5, and S7 (far-side stops), the delays to buses re-entering the traffic stream were minimal. These findings reveal that for the sites studied, far-side, bus bay stops resulted in less delay than near-side or midblock bus bay stops.

One reason for the minimal delays at the far-side stops was due to the breaks in traffic caused by the upstream signalized intersection. Another reason was the acceleration lanes provided. For those sites with acceleration lanes, bus operators were observed merging smoothly with the through traffic with minimal conflicts. Site S1 had an acceleration lane, and Site S7 had a continuous shoulder to be used for acceleration.

Figure D-17. Example of a Bus Bay.

Figure D-18. Example of an Open Bus Bay.

Queue Jumper. When buses can use a right-turn lane to by-pass traffic queued at congested intersections to access a far-side open bus bay, a substantial amount of time savings may result for the bus passengers. When this situation is allowed, the right-turn lane may be defined as a "queue jumper". The effects on average delay to right-turning traffic would be based upon several factors such as the number of buses expected; however, the average delay to right-turning traffic is generally assumed to be minimal. The right-turn lane is typically signed as "Right Turns Only—Buses Excepted" or with the sign shown in Figure D-19.

Figure D-19. Example of Sign Used at Queue Jumper.

Figure D-20 illustrates the travel time savings to a bus using a queue jumper. In part (a) of Figure D-20, the bus is approaching the queue jumper and the vehicles queued at the intersection. In part (b) the bus is entering the queue jumper to bypass the queue. The bus then proceeds through the intersection in (c) and arrives at the stop in (d).

At Site S1, the travel time savings to buses using the queue jumper was estimated for a select number of buses. To estimate travel time savings, the travel time of each selected bus using the queue jumper was measured and compared to that of a through vehicle entering the system at the same time as the bus. Travel times were measured from 600 feet upstream of the intersection preceding the bus stop to the stop bar at the intersection. Travel time savings for each selected bus was estimated by subtracting the travel time of the bus from the travel time of the through vehicle entering the system at the same time as the bus.

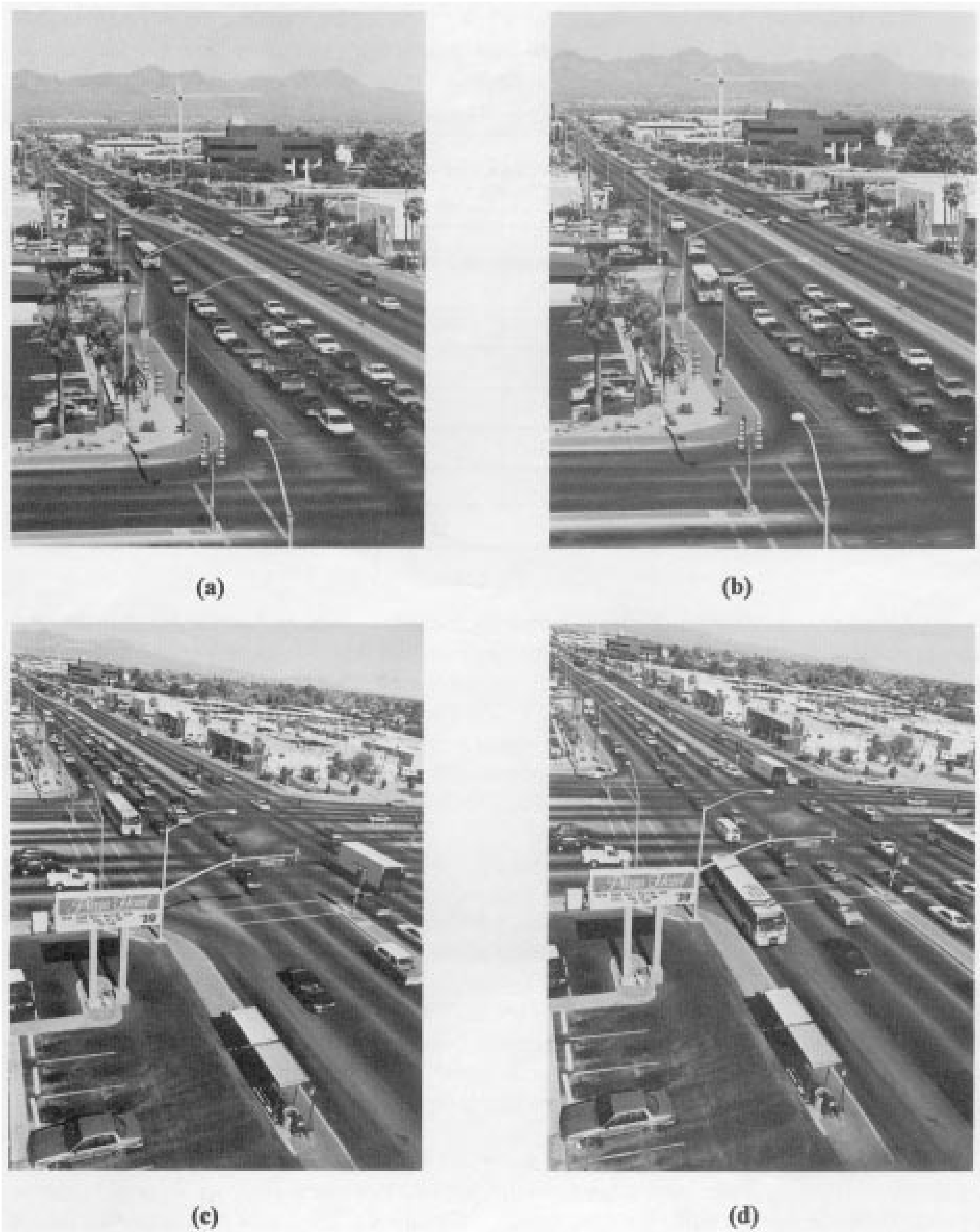


Figure D-20. Example of a Queue Jumper.

Travel time savings were estimated for six buses during high volume periods. Table D-6 contains the results from this study. The travel time savings to buses ranged from 0 to 14 seconds with an average of 6.5 seconds. The travel time savings was dependent upon the queue length at the intersection and the number of right turning vehicles.

Table D-6. Travel Time Savings of Bus Using Queue Jumper.

Volume (vph)	Travel Time (sec)		Travel Time Savings to Bus (sec)
	Bus	Through Vehicle	
1460	10	13	3
2150	56	66	10
2350	11	25	14
1500	10	10	0
1300	48	58	10
1800	8	10	2
		Average:	6.5

Comparison of Design Types. Comparing the results from each of the bus stop designs studied revealed that the majority of conflicts between through vehicles and buses occur at bus stops with curbside designs. The predominate conflicts observed included drivers changing lanes to avoid a stopped bus or queuing behind a stopped bus. The queue length behind a bus is dependent upon traffic volume. For lower traffic volumes, vehicles are able to change lanes to avoid the bus; however, as traffic volumes increase the opportunity for drivers to change lanes decreases. Therefore, as traffic volumes increase, the delay to through traffic due to the presence of a bus increases.

The research also reveals that buses may experience more delay at stops with bus bays; however, for the sites studied the delay was only on the order of five seconds. With the bus bay design, bus operators desiring to safely re-enter the traffic stream are required to wait for an adequate gap in the through traffic. When volumes are low, adequate gaps are frequent. When volumes are high, the presence of adequate gaps decrease and also are influenced by the platooning effects of signals. For the sites studied, far-side stops resulted in less delay to buses when compared to near-side or midblock stops. One of the reasons for the minimal delays at the far-side stops is due to the breaks in traffic caused by the upstream signalized intersection.

In addition, for the bus bay sites studied, delay was minimized for those sites with acceleration lanes. Acceleration lanes typically provide bus operators with an area to merge smoothly with the through traffic resulting in minimal conflicts. The use of an acceleration lane is demonstrated in Figure D-21.

Figure D-21. Example of a Bus Bay with an Acceleration Lane.

The findings from this study also revealed that travel time savings may result for bus passengers when buses can use a queue jumper to access a far-side open bus bay. The travel time savings to buses are dependent upon the queue length at the intersection and the number of right turning vehicles.

Urban Sites

Data were collected at six sites in San Francisco and San Jose, California to study the operations around bus stops in urban areas. The sites varied in locations and designs. Table D-7 describes each of the urban sites studied. Following is a description of the study design, discussions for each of the field sites studied, and a summary of the findings.

Study Design

Data Collection. During the field data collection trip to San Francisco, California, data were collected at three urban sites. Because San Francisco is a dense urban center, data could not be collected using portable video cameras. Traffic data were collected manually because the use of video equipment in this environment would draw the immediate attention of both general pedestrian traffic and bus patrons.

Table D-7. Description of Urban Study Sites.

Site	City	Location	Bus Stop Location and Design	Cross Section[a]	Surrounding Development	Speed Limit (mph)	Collection Technique (time)
U1	San Francisco, California	Polk Clay-Sacramento	Midblock, Nub	4 lane, undivided	hotels, restaurants, shops	30	manual (11am-2pm)
U2	San Francisco, California	Polk @ Sutter	Near-Side, Nub	4 lane, undivided	hotels, restaurants, shops	30	manual (7am-9am)
U3	San Francisco, California	Polk @Pine	Far-Side, Nub	4 lane, undivided	hotels, restaurants, shops	30	manual (11am-12:30 pm)
U4	San Francisco, California	Alameda @ Montgomery	Midblock, Bus Bay	4 lane, raised median	sports arena	30	video (9am-12pm)
U5	San Francisco, California	San Carlos @ Market	Near-Side, Curbside	4 lane, light rail	shops, restaurants	30	video (8:30 am-5:30 pm)
U6	San Francisco, California	Santa Clara @ Almaden Ave.	Far-Side, Bus Bay	4 lane, TWLTL	shops, restaurants	30	video (7am-5:30pm)

[a]TWLTL = two way left-turn lane

Travel times were collected using a license plate matching software program (LP Match) developed by TTI. Two members of the data collection team were positioned at set locations upstream and downstream of the bus stop being studied. Each member loaded and entered the license plate numbers of vehicles on a laptop computer as they passed by. The time that a vehicle entered or exited the study zone was automatically recorded in the laptop computer when a license plate number was entered. After the data collection was complete, the upstream and downstream files were combined. The software matched the license plate numbers for each vehicle passing through the system and computed a travel time.

Volumes and turning movements were collected manually by positioning a team member at the intersection upstream of the bus stop. Also recorded manually were bus arrival and departure times, and queues behind the bus. The team did not attempt to record erratic maneuvers at the San Francisco sites.

Three of the nine field sites studied in San Jose were included in the urban traffic study. As with the suburban field sites studied, the team was able to collect data at urban sites with the aid of the City of San Jose's Traffic Management Center. A description of this effort is given in the summary of the data collection efforts for suburban sites.

Data Reduction and Analysis. The effort required to reduce the data collected from the license plate match technique in San Francisco was minimized because most of the field data were collected in a usable format. The software used to collect the travel times produced output in a format that could be easily imported into a spreadsheet. Therefore, reducing the data involved entering the traffic volume and bus arrival information into a spreadsheet and importing the travel time data. Since data at these sites were not collected using video cameras, erratic maneuvers could not be observed during the data reduction efforts.

The data from the video tapes collected in San Jose were reduced with the same techniques used on the suburban sites. Data were again reduced in five minute intervals around each bus arrival. The data reduced included bus arrival time, bus departure time, queue behind bus, and delay to bus re-entering traffic. The team studied the operational behaviors occurring in the field at or near the bus stops by viewing the video tapes of each site. During each bus arrival, any erratic maneuvers observed were recorded. The erratic maneuvers studied for the suburban sites (see Table D-3) were also studied for the urban sites.

Once the field data were collected and reduced, the results were summarized for each field site. The summary contains a description of each of the study sites and the bus and vehicular operations observed. After analyzing each site separately, the operations at all urban sites were compared. The findings from the field sites were grouped by bus stop design. The goal was to determine how different bus stop locations and designs affected the traffic operations around the bus stop area.

Study Sites

To study the operations around bus stops in urban areas, data from six field sites in San Francisco and San Jose, California were studied. The stops in San Francisco all contained nub designs while those in San Jose contained bus bay and curb-side designs. Nubs are an extension of a sidewalk from the curb of a parking lane to the edge of the through lane. A bus bay is a specially constructed area off the normal section of a roadway that provides for the pick up and discharge of passengers in an area separated from the travel lane. At a curb-side design, buses stop in the travel lane. Following are discussions on each of the urban sites studied.

Site U1: San Francisco, California; Polk between Clay and Sacramento. Site U1 is a midblock stop with a nub design. Figure D-22 presents the plan view of the site. To estimate the delay to through traffic caused by the bus, the travel times were separated into the following two categories: travel times when a bus was not in the system, and travel times when a bus was in the system. The travel times for each category were then averaged and compared. For Site U1, the average travel time of vehicles when a bus was not in the system was 24 seconds, compared with an average travel time of 30 seconds when a bus was in the system. Therefore, the average delay to vehicles when a bus was in the system was approximately 6 seconds. For the 16 bus arrivals observed at Site U1, traffic queued behind a stopped bus 6 times. The queue lengths ranged from one to four vehicles.

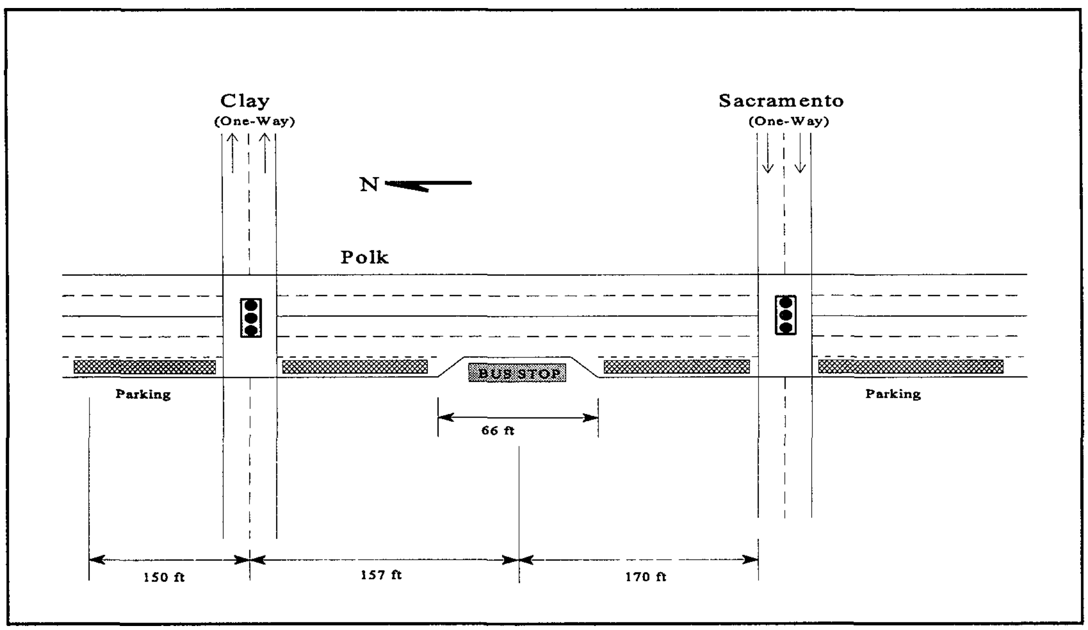


Figure D-22. Site U1: Polk between Clay and Sacramento.

Site U2: San Francisco, California; Polk at Sutter. Site U2 is a near-side stop with a nub design (see Figure D-23). To estimate the delay to through traffic caused by the bus, the travel times were again separated into travel times when a bus was not in the system, and travel times when a bus was in the system. For site U2, the average travel time of vehicles when a bus was not in the system was 60 seconds, compared to an average travel time of 67 seconds when a bus was in the system. Therefore, the average delay to vehicles when a bus was in the system was approximately 7 seconds. For the time period observed (12 bus arrivals), queues did not form behind the stopped buses.

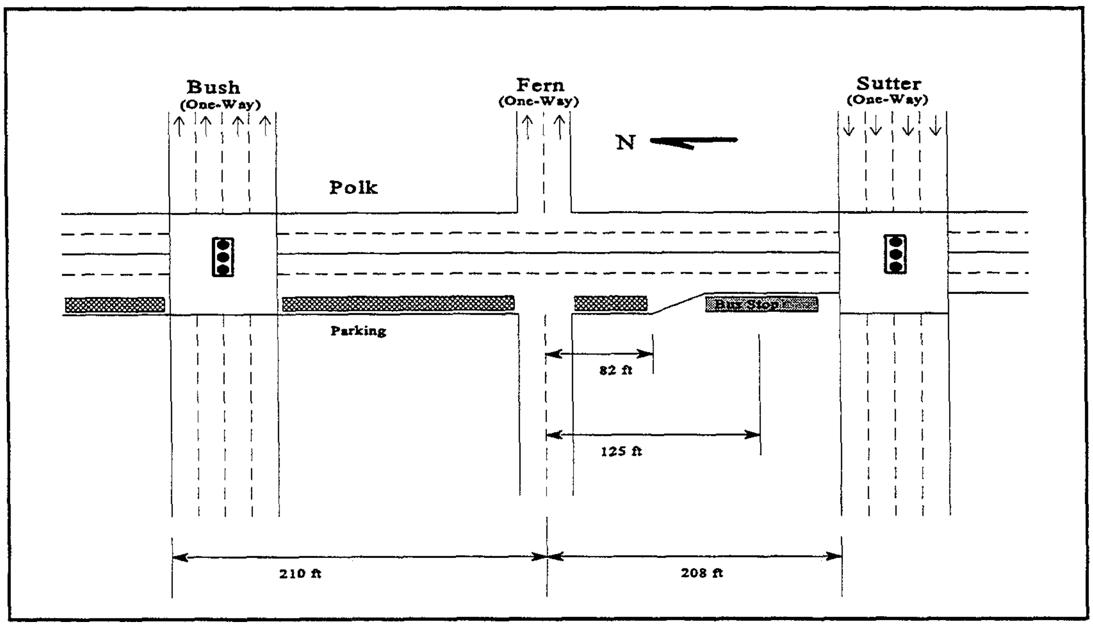


Figure D-23. Site U2: Polk at Sutter.

Site U3: San Francisco, California; Polk at Pine. Site U3 is a far-side stop with a nub design (see Figure D-24). The average travel time of vehicles when a bus was not in the system was 65 seconds, compared to an average travel time of 85 seconds when a bus was in the system. Therefore, the average delay to vehicles when a bus was in the system was approximately 20 seconds. For the time period observed (11 bus arrivals), queues behind the stopped buses formed twice with maximum queues of one and three vehicles.

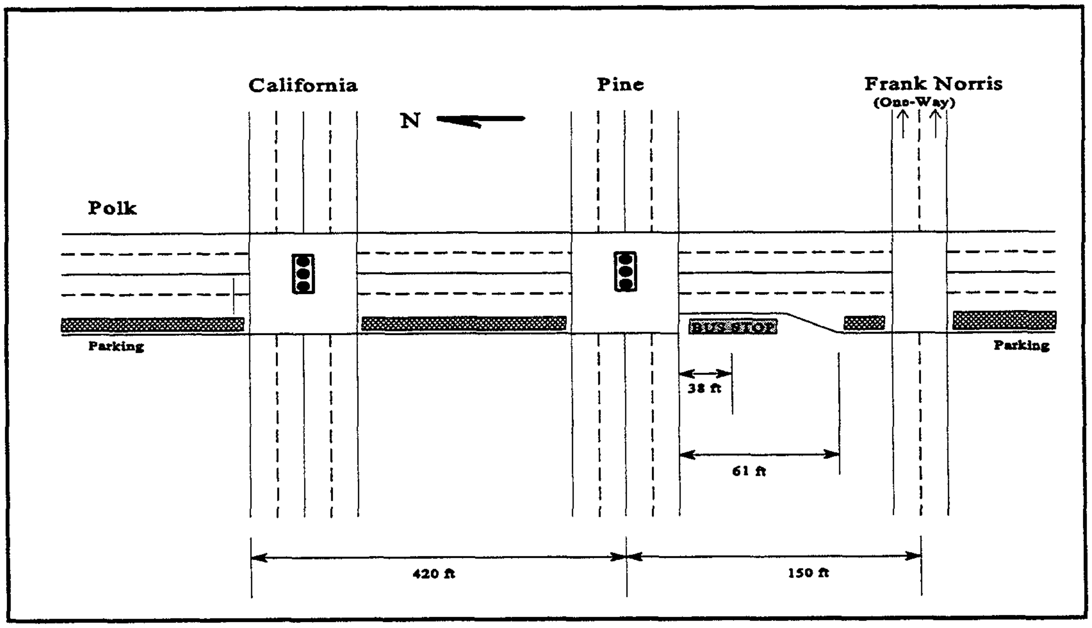


Figure D-24. Site U3: Polk at Pine.

Site U4: San Jose, California; Alameda at Montgomery. Site U4 is a midblock bus stop located in the central part of San Jose at Alameda and Montgomery. Since the buses pull onto the shoulder to drop off and pick up passengers, the bus stop functions as a bus bay. Figure D-25 presents the plan view for site U4.

Few conflicts occurred between the buses and other traffic at Site U4. Those erratic maneuvers that were observed occurred when buses were leaving the stop and re-entering the traffic stream. For the 26 bus arrivals studied at Site U4, drivers of vehicles were observed stopping to allow the bus to re-enter the traffic stream three times. While this minimized the delay to the bus, it increased the delay to the through traffic. Buses re-entering the traffic stream were only delayed twice for four and six seconds, respectively.

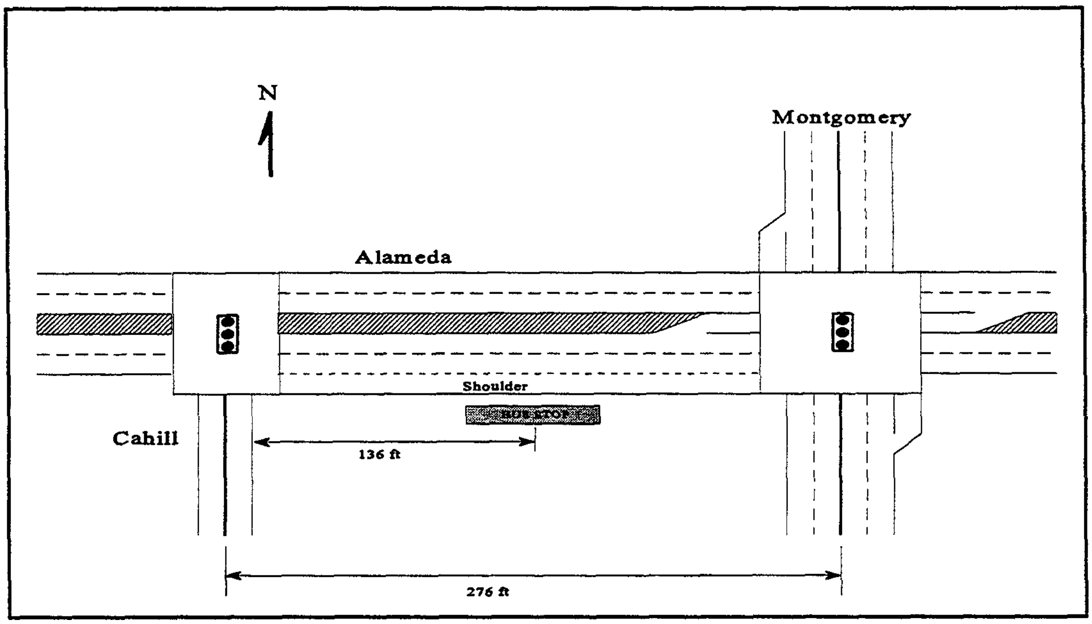


Figure D-25. Site U4: Alameda at Montgomery.

Site U5: San Jose, California; San Carlos at Market. Site U5 is a near-side, curb-side bus stop located in the central part of San Jose (see Figure D-26). For the time that Site U5 was studied, very few erratic maneuvers were observed. Out of the 30 bus arrivals, only five drivers changed lanes to avoid a bus. Queues behind the stopped buses were observed 6 times with a maximum queue of one vehicle each time.

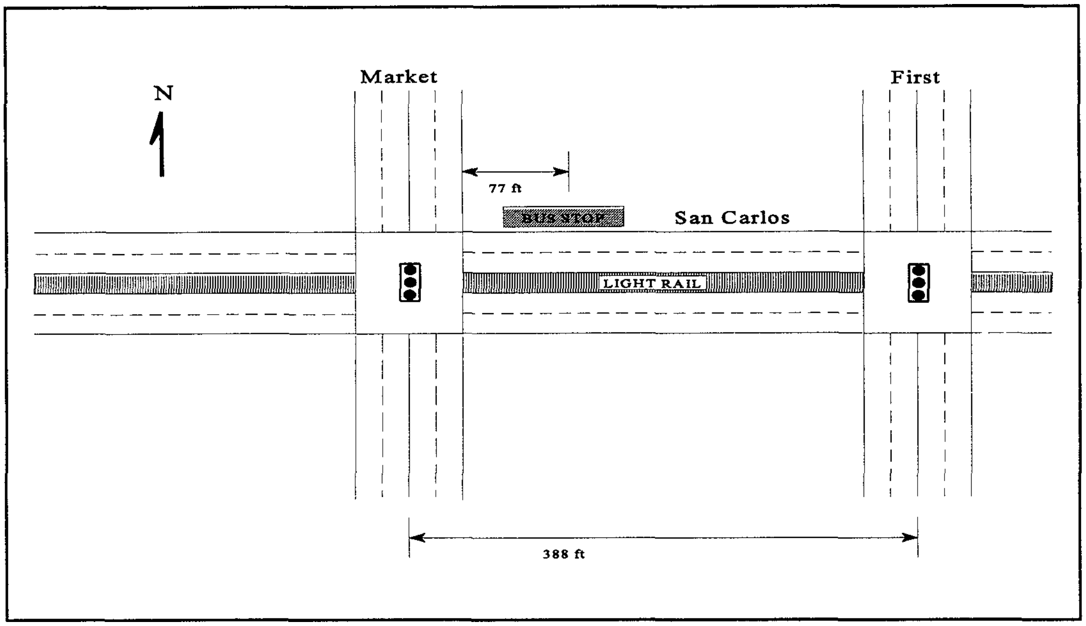


Figure D-26. Site U5: San Carlos at Market.

Travel time and volume data were collected for a total of nine 5-minute periods. For site U5, the average travel time of vehicles when a bus was not in the system was 30 seconds, compared to an average travel time of 28 seconds when a bus was in the system. Therefore, the average travel time of vehicles when a bus was in the system was very close to the average travel times when a bus was not in the system. In other words, the overall delay to through vehicles caused by the presence of a bus was minimal. For the time period observed, queues behind the stopped buses formed 6 times; however, the maximum queue each time was one vehicle.

Site U6: San Jose, California; Santa Clara at Almaden. Site U6 is a far-side bus stop located in the central part of San Jose at Santa Clara and Almaden. Since the buses pull off on the shoulder to drop off and pick up passengers, the bus stop functions as a bus bay with an acceleration lane. Figure D-27 shows the plan view for this site. The erratic maneuvers observed at this site were again few. For the 37 bus arrivals observed, drivers changed lanes to avoid a bus only twice. Also, a bus was only delayed once trying to re-enter traffic and the delay was 4 seconds.

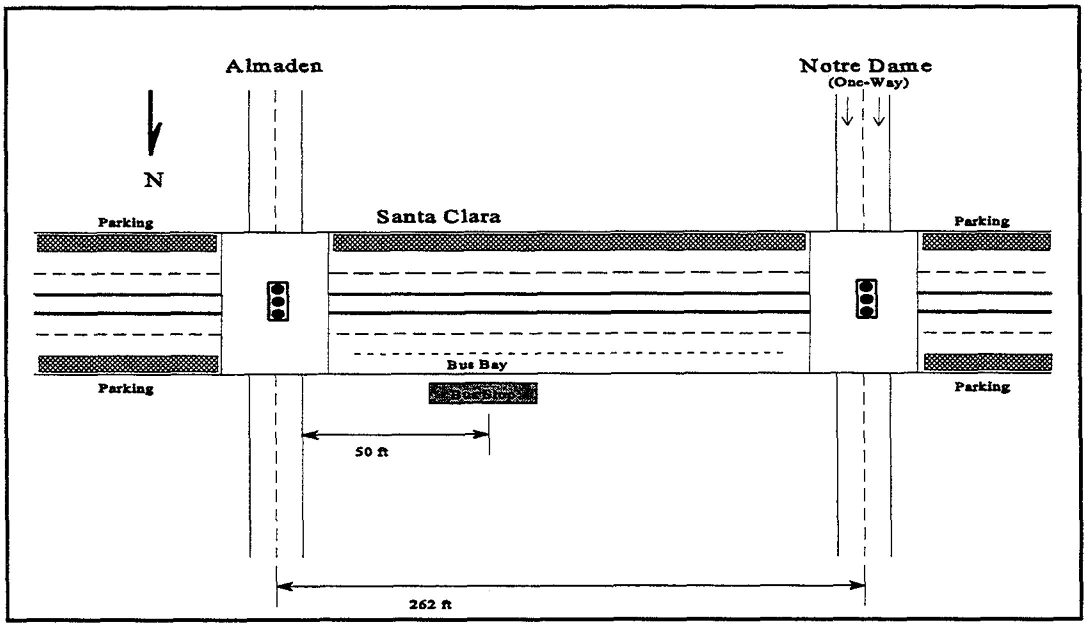


Figure D-27. Site U6: Santa Clara at Almaden.

Findings

Tables D-8 and D-9 summarize the findings for the urban sites. Table D-8 includes the operational characteristics measured from the field and Table D-9 summarizes the erratic maneuvers observed. The operational characteristics include the following: posted speed limit; maximum through volume observed; minimum, maximum, and average dwell time for the buses; minimum and maximum number of vehicles in queue behind a stopped bus; minimum and maximum delay to buses re-entering the traffic stream; and estimated delay to through vehicles.

Table D-8. Observational Characteristics for Urban Sites.

Site	Location	Design[b]	Posted Speed Limit (mph)	Max. Through Volume (vphpl)	Dwell Time (sec)			Number of Vehicles in Queue[c]		Delay to Bus (sec)[c]		Vehicle Delay (sec)[d]
					Minimum	Maximum	Average	Minimum	Maximum	Minimum	Maximum	
U1	MB	NB	30	350	10	45	23	1	4	--	--	6
U2	NS	NB	30	350	10	44	31	--	--	--	--	7
U3	FS	NB	30	350	10	35	19	1	3	--	--	20
U4	MB	BB	30	325	8	56	20	--	--	4	6	x
U5	NS	CS	30	200	5	25	13	0	1	--	--	0
U6	FS	BB	30	450	8	32	16	--	--	0	4	x

[a] FS=Far-Side, NS=Near-Side, MB=Midblock
[b] NB =Nub, BB=Bus Bay, CS=Curbside
[c] — signifies that no queues or delays were observed
[d] x signifies that delays were not measured

Table D-9. Erratic Maneuvers for Urban Sites.

Site	Location and Design[a]	Number of Bus Arrivals Observed	Traffic Queue[b]		Lane Changes[c]		Delay to Bus[d]	
			Number[e]	Rate[f]	Number	Rate	Number	Rate
U1	MB, NB	16	6	1 / 2.7	--	--		
U2	NS, NB	12			--	--		
U3	FS, NB	11	2	1 / 5.5	--	--		
U4	MB, BB	26					2	1 / 13.0
U5	NS, CS	30	6	1 / 5.0	5	1 / 6.0		
U6	FS, BB	37			2	1 / 18.5	1	1 / 37.0

[a] FS=Far-Side, NS=Near-Side, MB=Midblock, NB=Nub, BB=Bus Bay, CS=Curb-side
[b] Traffic queue occurs near bus stop because of the presence of a bus.
[c] Driver of vehicle changes lanes because of the presence of a bus. (Note: Lane change behavior was not collected for Sites U1, U2, and U3.)
[d] Bus experiences delay while re-entering traffic stream.
[e] Total number of erratic maneuvers for the number of bus arrivals observed.
[f] Number of erratic maneuvers / number of bus arrivals.

Bus Stop Design. To summarize the results from urban field sites studied, the findings were grouped by bus stop design. The bus stop designs analyzed in this study included nub, curb-side, and bus bay. Following is a discussion on the findings for each bus stop design and a comparison of the designs.

Nub. Nubs are a section of sidewalk that extends from the curb of a parking lane to the edge of the through lane. They permit buses to make a stop in a traffic lane without weaving around parked cars. Nubs are typically located in urban areas and operate similarly to curb-side stops, except they offer additional area for patrons to wait. Nubs are also referred to as "curb extensions" or "bus bulbs." An example of a nub is illustrated in Figure D-28.

From the six urban sites studied, three included nubs (sites U1, U2, and U3). For these sites, the effects that buses had on the operations of through vehicles was estimated by dividing the travel times measured in the field into two categories: travel times when a bus was not in the system and travel times when a bus was in the system. By averaging the travel times for each of these categories and comparing the averages, delays due to the presence of a bus could be estimated. The estimated delays to through traffic are included in Table D-8. Because of other factors influencing vehicle delay, the values in Table D-8 are not meant to represent actual delays to through vehicles due to the presence of a bus; however, comparing the delays measured at separate sites should provide some insight into how bus stop location affected delay.

Figure D-28. Example of a Nub.

The resulting delays to through vehicles for Site U1 (midblock stop) and Site U2 (near-side stop) were very similar (see Table 8); however, the delays measured for Site U3 (far-side stop) were somewhat higher. Although the magnitude in the differences in delay may not be accurate, the results signify that higher delays for traffic existed at the far-side location.

Curb-Side. From the urban sites studied, only Site U5 contained a curb-side design. Similar to the sites with nubs, travel times were measured at Site U5 and were divided into two categories: travel times when a bus was in the system and travel times when a bus was not in the system. Comparing the average travel times for these two categories revealed that the overall delay to through vehicles due to the presence of a bus was minimal.

The minimal delays to through traffic were most likely due to the relatively low traffic volumes observed at Site U5 (200 vphpl). For the low traffic volumes, drivers of through vehicles had little difficulty in changing lanes to avoid a stopped bus, resulting in low delays. Even though a queue behind the bus was observed 6 times for the period that Site U5 was studied, the maximum queue each time was only one vehicle. In addition, the drivers in queue behind a stopped bus were observed changing lanes quickly because of the low traffic volumes, again resulting in low delays.

Bus Bay. For the urban sites studied, delays to buses due to through traffic occurred at bus stops with bus bays. Out of the six urban sites studied, sites U4 and U6 operated as bus bays. At Site U4 (midblock stop), buses were delayed twice for 4 and 6 seconds. A bus at Site U6 (far-side stop) was delayed only once for 4 seconds. Therefore, even though the volumes at the far-side stop were higher than the volumes at the midblock stop (450 vphpl compared to 325 vphpl), the buses were delayed less at the far-side stop (corresponding to the results from the suburban sites).

Because of the limited number of sites, the relatively low traffic volumes, and the limited number of delays observed, additional data are needed to develop a definable relationship between volume, delay, and stop location for urban bus bay designs. The traffic volume level that has significant influence on urban bus bay operations cannot be determined from the data collected in this study. Based on the data, that point appears to be above 450 vphpl. Additional field data at high volume locations or computer simulation would provide more insight into the relationship.

Comparison of Design Types. Similar to the results from the suburban sites, the results from the urban bus stop designs studied revealed that conflicts between through vehicles and buses were more likely to occur at bus stops with curb-side (or nub) designs. For the sites studied, the nub design located at the far-side of an intersection resulted in more delay to through vehicles when compared to nubs at near-side or midblock locations. At near-side stops, delay to through traffic due to a bus loading/unloading passengers and delay due to a signalized intersection overlap, resulting in less delay.

Also corresponding to the results from the suburban sites, results from the urban sites studied revealed that buses experience slightly more delay at stops with bus bays when compared to curb-side (or nub) stops; however, whether the amount of delay is significant is debatable. Also, the far-side stop resulted in less delay to buses when compared to the near-side or midblock stops. Again, the reason for the minimal delays at the far-side stops is due to the breaks in traffic caused by the upstream signalized intersection.

COMPUTER SIMULATION

This study involved using computer simulation to study the effects of bus stop design on traffic operations. Traffic simulation programs have been used for years to analyze traffic operations under various conditions. The benefit of using computer simulation is that operations can be analyzed over a wide range of variables in a relatively short period of time (compared to collecting data in the field).

Objective

Other studies have been conducted to determine the optimum location of a bus stop (i.e., near-side, far-side, or midblock) for given situations; however, few have investigated the effects of bus stop design. The objective of this study was to use computer simulation to determine how specific factors influence traffic operations near a bus stop. Bus stop designs analyzed in this study included curb-side, bus bay/open bus bay, and queue jumper. Far-side and midblock locations were used in the simulation. The results can be used to aid in the selection of a preferred bus stop design for a given location and traffic volume. To accomplish the objective of this study, the following tasks were performed:

- Select a traffic simulation program to be used.
- Use field data to aid in calibrating the traffic simulation program.

- Perform the simulation for various traffic volumes and bus dwell times.
- Analyze the data from the simulation runs.
- Develop conclusions from the study that can aid in the selection of a preferred bus stop design for given bus stop locations and traffic characteristics.

Study Design

To investigate how various bus stop designs and locations influence traffic operations, field data and computer simulation were used. The intent was to use the field data to calibrate the traffic simulation program and to use the simulation program to study traffic and bus operations under various conditions. The results from computer simulation could then be used to identify the preferred bus stop design for a given situation.

Field Data

Field data from three of the suburban sites studied during the field studies were used to calibrate the traffic simulation program. Two of the sites were located in Tucson, Arizona, and one of the sites was located in San Jose, California. The three bus stop designs studied were a queue jumper, a bus bay, and a curb-side stop. Table D-10 provides a description of the calibration sites.

Table D-10. Description of Field Sites Selected for Calibration.

Site	City	Location	Bus Stop Location and Design	Cross Section[a]	85th Percentile Speed (mph)
1	Tucson, Arizona	Speedway @ Campbell	Far-Side, Queue Jumper Bus Bay	6 lanes, raised median	43
2	Tucson, Arizona	Speedway, Mountain - Cherry	Midblock, Bus Bay	6 lanes, raised median	43
3	San Jose, California	Bird @ San Carlos	Far-Side, Curb-Side	6 lanes, TWLTL	36

[a] TWLTL = Two-Way Left-Turn Lane

Data at each site were collected in the form of video tapes. For calibration purposes, technicians reduced the following data from the video tapes: traffic volumes, turning movements, travel times, speeds, bus arrival time, bus dwell time, and maximum queue behind bus. In some cases, because of the camera locations, the turning volumes could not be obtained; therefore, in these situations, the turning percentages were estimated. Signal timing information for the intersections was obtained from the respective cities. A summary of the data collection and data reduction efforts is presented in the second section of this appendix entitled *Field Studies.*

Traffic volume and travel time data were reduced in 5-minute intervals around each bus arrival. Travel times were measured from a set location upstream of the bus stop to a set location downstream of the bus stop. Since it would be difficult to measure the travel times of all vehicles, technicians only measured the travel times of selected vehicles which were believed to be traveling at speeds representative of other traffic. Travel times of selected vehicles were calculated by recording the time that a vehicle entered the system and the time that the vehicle left the system.

For each site, the free-flow speeds of approximately 100 vehicles were measured. Speeds were measured by recording the time that it took a vehicle to travel a known distance. The speed was then calculated by dividing the distance traveled by the travel time.

Computer Simulation Programs

Traffic simulation programs have been used effectively for many operations-related traffic studies and research projects. These programs can be used to analyze the effects that a wide range of roadway, traffic and bus characteristics have on the operations of a system. This wide range of data is very difficult to collect in the field; however, it can be easily studied using computer simulation. The two traffic simulation programs investigated for use in this study were TRAF NETSIM and TexSIM.

TRAF-NETSIM. TRAF is a software system which consists of several macroscopic and microscopic simulation programs which can be used to analyze traffic operations in large urban areas containing surface street networks and freeways. NETSIM is one of the modules in the TRAF package and is a microscopic model of urban street traffic. For NETSIM, each vehicle is a distinct object which is moved every second, and every event is updated every second. Vehicles are moved according to car-following logic, response to traffic control, and response to other demands. Outcome in NETSIM is stochastic (i.e., a similar set of input data can generate different output data for different runs).

NETSIM has the capabilities of simulating bus operations including routing, stops, number of buses at each stop at any one time, dwell times, and bus headways (flow rates). Each bus is identified by bus path, route, and bus flow rate. The bus path is the geometric path which the bus follows as it travels through the network. The bus route is the sequence of bus stops which the bus services. The bus flow rate is the mean headway for buses which service a particular route. Bus stops can be placed anywhere on a link, and "protected" or "unprotected" stops can be coded. This would be synonymous to bus bays and curbside stops, respectively.

TexSIM. The microscopic traffic network simulation program TexSIM is currently being developed by the Texas Transportation Institute. TexSIM runs under the Microsoft Windows environment and is being developed using C++ language. The system is built on a completely object-oriented architecture. The initial purpose for developing TexSIM was to evaluate the response of signal systems to new types of control strategies. TexSIM is an extremely flexible program. The users are allowed to dynamically interact and examine the network system during and after the simulation. Options are also provided to directly interact with real-time traffic controllers. TexSIM also simulates vehicles using a car following model. Vehicle movement and response occur in increments of one tenth of a second. Outcome in TexSIM is also stochastic.

TexSIM uses a system involving routes and links to determine the movement of a bus during simulation. Coding for buses and bus routes is split into three sections: routes, buses, and bus stops. The number of routes that are to be simulated are identified initially. A route system is determined by the links that the bus is to follow. A link is defined by the intersection number and the approach to that intersection. The route logic within TexSIM was developed so that bus routes must have adjoining links. Links within the route that have bus stops on them are assigned to a number specific to that bus stop. This allows for several stops within the system.

The buses are coded next. The route that the bus is to follow is coded along with the start time at which the bus enters the system. This allows for multiple buses to follow one route at different start times.

The bus stop information is the final coding requirement for bus operations within TexSIM. The bus stop number is coded and it corresponds with the route information given above. Next the location of a bus stop is defined by the intersection ID, link ID, and the lane ID along with the length of the bus stop. The set back length from the start of the link is coded to allow for the movement of the bus stop to different locations on the link. The set back length is the length from the start of the link to the upstream end of the bus stop. The bus dwell time is the final coding requirement for the bus stop. This is the time in seconds that a bus would typically spend at a bus stop loading passengers. This time is coded as an average and a variance around that average.

Selection of Program. TexSIM was selected as the traffic simulation program to be used for this study because of its flexibility and its capability to simulate unique bus stop designs such as queue jumpers. Most importantly, output from TexSIM can be given for each individual vehicle passing through the system. This feature allowed the researchers to monitor the traffic operations only when a bus was in the system (opposed to average travel times over a set period of time which might include times in which a bus was in the system and times that no bus was in the system). In addition, TexSIM can generate output which separates queues associated with the bus from queues caused by other factors such as an intersection. Because members of the research team were in close contact with the developers of TexSIM, there was a greater opportunity to customize TexSIM for research team use and to receive any needed assistance during the simulation process.

Development and Calibration of Models. Once TexSIM was selected as the program to be used for simulation, the first step was to develop models for each bus stop design to be studied (i.e., curb-side, bus bay/open bus bay, and queue jumper). Three TexSIM models were developed based upon the three field sites. After the models were developed, the next step was to calibrate TexSIM. This was accomplished by comparing output from TexSIM (i.e., average travel times and maximum number of vehicles in queue behind bus) to the operations observed in the field. TexSIM coding was then modified so that the models produced results similar to that expected in the field. This procedure helped the researchers determine how closely the computer simulation models represented what was actually happening in the field.

Figure D-29 presents schematics of the three field sites studied. For calibration purposes, data at each field site were collected for approximately 3 hours. Site information and operational data collected at the field sites are provided in Table D-11.

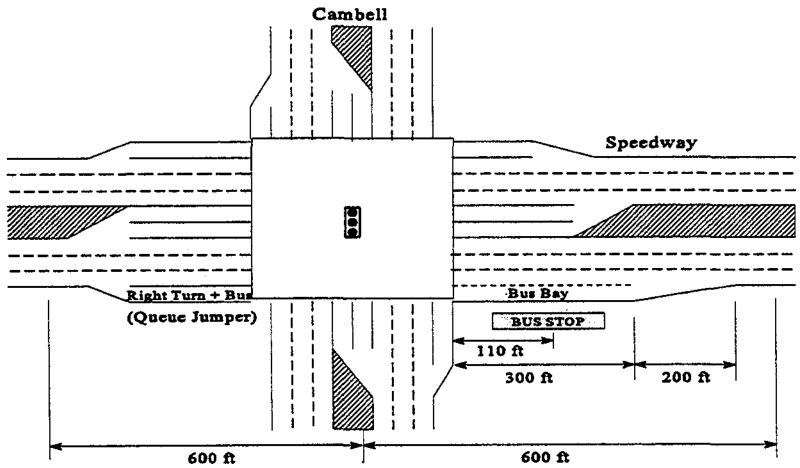
Table D-11. Operational Data Collected at Field Sites.

Site	Time of Study	No. of Bus Arrivals	Length of Study Section (ft)	Maximum Through Volume (vph)	85th Percentile Speed (mph)
1	7:00 am - 10:00 am	9	1200	2500	43
2	2:00 pm - 5:00 pm	9	7783	2000	43
3	2:00 pm - 5:00 pm	7	590	1500	36

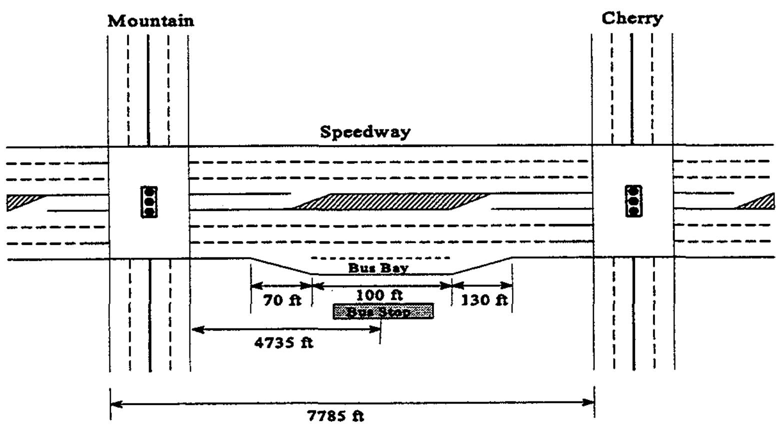
For each of the three sites, a TexSIM run was made for each bus arrival observed. Therefore, for Sites 1, 2, and 3, the number of TexSIM runs made was 9, 9, and 7, respectively, for a total of 25 runs. For each run, the 5-minute traffic volumes and turning movements, as well as the traffic speeds (85th percentile), bus arrival time, and bus dwell time observed in the field were coded.

Because outcome from TexSIM is stochastic, the output may not be the same for given input. For this reason, each run was simulated for 1 hour with a bus arriving every 10 minutes. Therefore, for each run a total of six bus arrivals were included. Travel times and maximum queues behind bus were then averaged for each run and compared to the observations made in the field. If the output from TexSIM was drastically different from the field observations, then the necessary coding in TexSIM was modified until the researchers believed that the output from TexSIM was representative of the field observations.

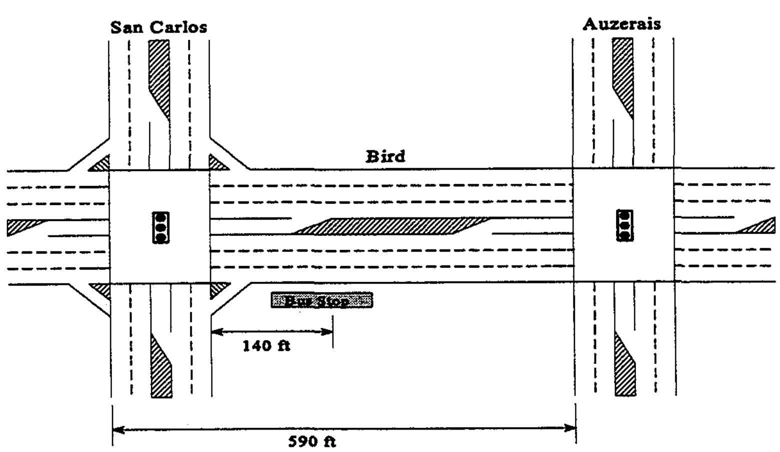
Table D-12 shows a comparison between field observations and output from the TexSIM models developed for each field site. The travel times and maximum queue lengths shown were averaged for the number of bus arrivals studied. Although there was some variance between the travel times measured in the field and the travel times predicted by TexSIM, the majority of the differences were caused by the traffic signals. As mentioned earlier, some of the turning movements at each intersection could not be obtained and had to be estimated. Because the signals were semiactuated, it was difficult to replicate the actual signal operations observed in the field, therefore affecting the overall travel times.



(a) Site 1



(b) Site 2



(c) Site 3

Figure D-29. Field Sites Used for Calibration of TexSIM.

Table D-12. Comparison of TexSIM Output to Field Data.

Site	Bus Stop Design	Average Travel Time (sec)		Average Maximum Queue (vehicles)[a]	
		Field	TexSIM	Field	TexSIM
1	Queue Jumper Bus Bay	53	49	N.A.	N.A.
2	Midblock, Bus Bay	31	30	N.A.	N.A.
3	Far-Side, Curb-Side	32	39	1.2	1.5

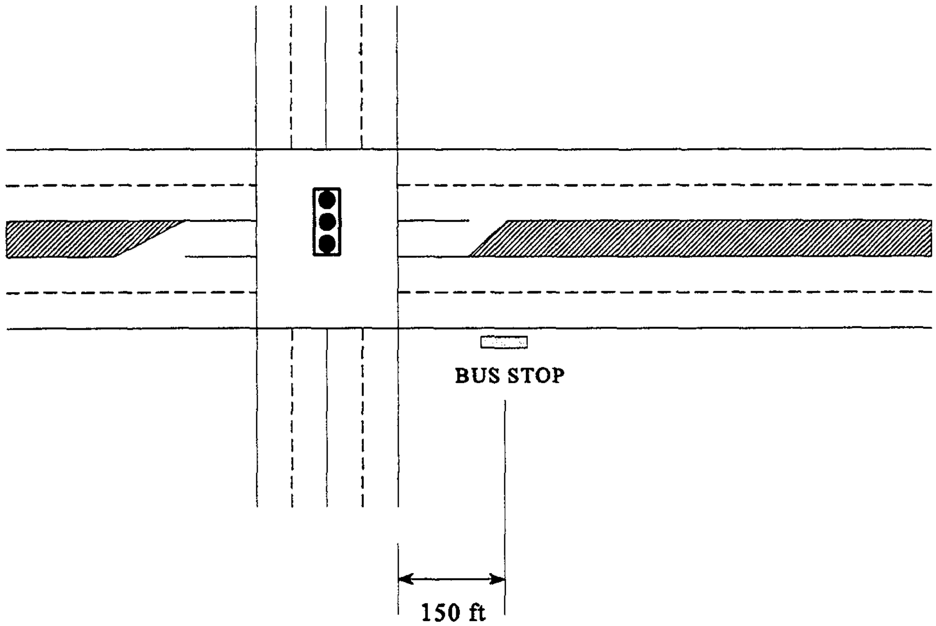
[a] N.A. - Bus bay present resulting in no queue.

To further calibrate TexSIM, the on-line graphical interface was used to compare the operations of buses and other traffic around the bus stop area to field observations. Maneuvers observed from TexSIM that were compared to field observations included vehicles changing lanes to avoid a stopped bus, vehicles queuing behind a stopped bus, and buses re-entering the traffic stream after completing a stop. The researchers agreed that the final TexSIM models provided a good representation of the actual field operations.

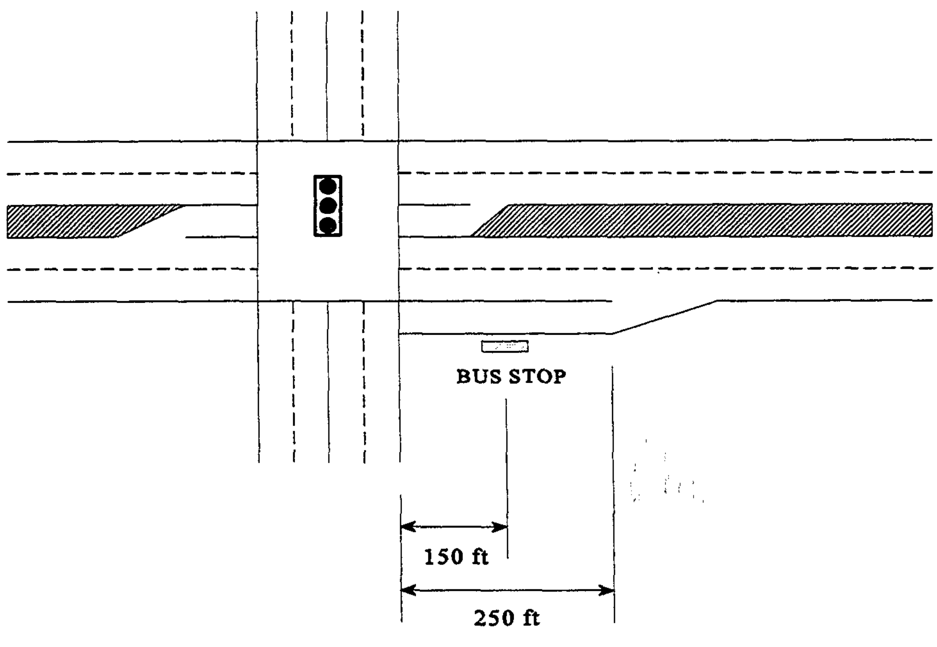
Performing the Simulation. The first two bus stop designs studied were curb-side and bus bay/open bus bay. The goal was to develop recommendations as to when a curb-side stop should be converted into a bus bay/open bus bay. TexSIM was used to compare different bus stop designs at both far-side (curb-side versus open bus bay) and midblock (curb-side versus bus bay) locations.

Schematics of the models used to study curb-side and bus bay designs for both far-side and midblock locations are shown in Figures D-30 and D-31, respectively. The models consisted of a single signalized intersection with four approaches. The main street approach consisted of two through lanes with left turn bays at the intersection. The bus stop under investigation was located either at the far-side of the intersection or at a midblock location downstream of the intersection on the main street. To remove the effects of the downstream intersection on vehicle travel time, a downstream intersection was not included in the model. This allowed the researchers to investigate only the effects that the bus stop design had on traffic operations for various traffic volumes.

The queue jumper design was also studied to determine the effects of a queue jumper on bus operations. The goal was to determine the situations in which a queue jumper would provide the greatest benefit. The models studied included a far-side open bus bay with a queue jumper and a far-side open bus bay without a queue jumper (see Figure D-32).

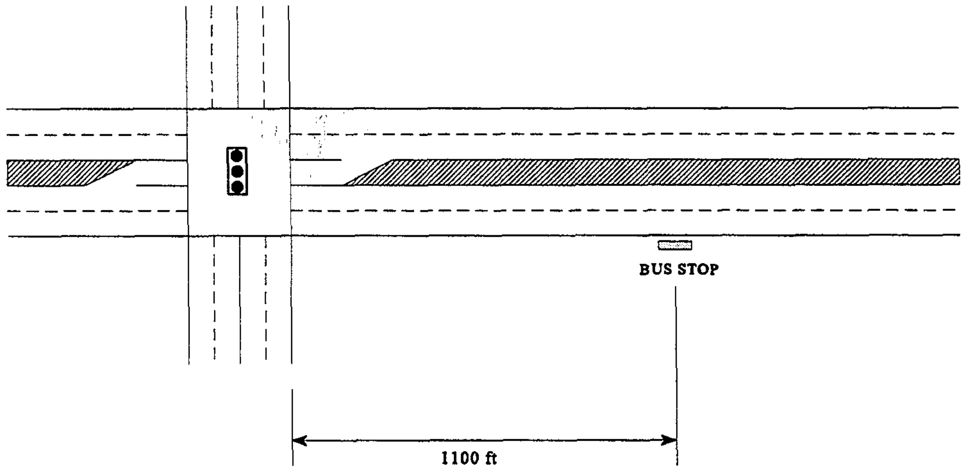


(a) Far-Side, Curbside

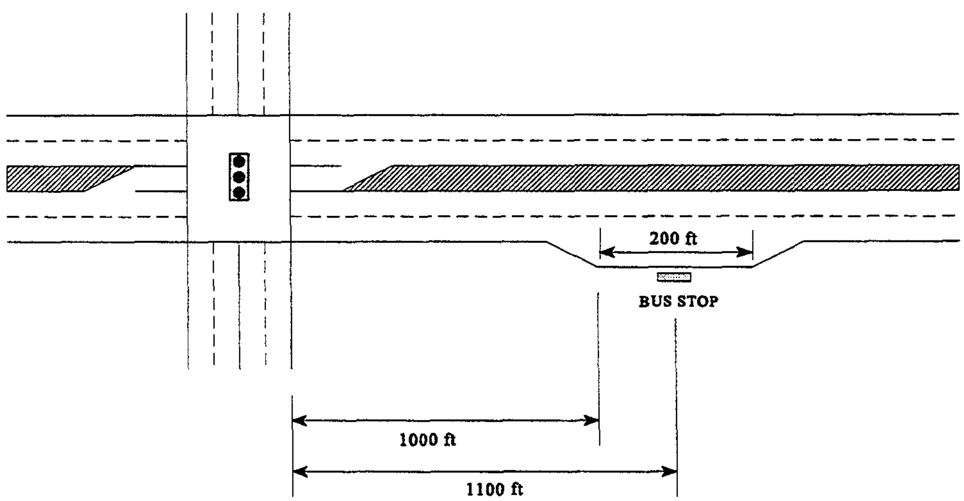


(b) Far-Side, Open Bus Bay

Figure D-30. Far-Side Bus Stop Designs.

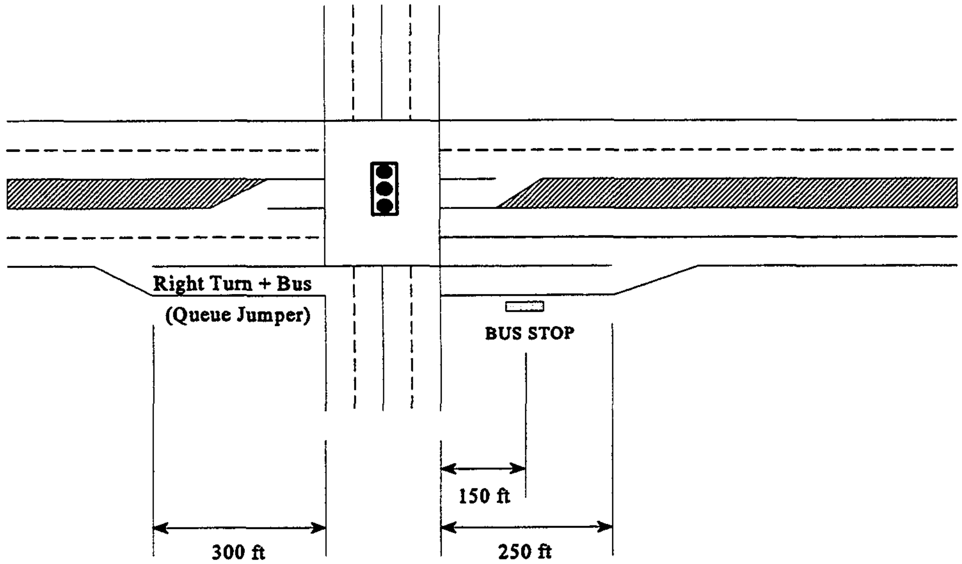


(a) Midblock, Curbside

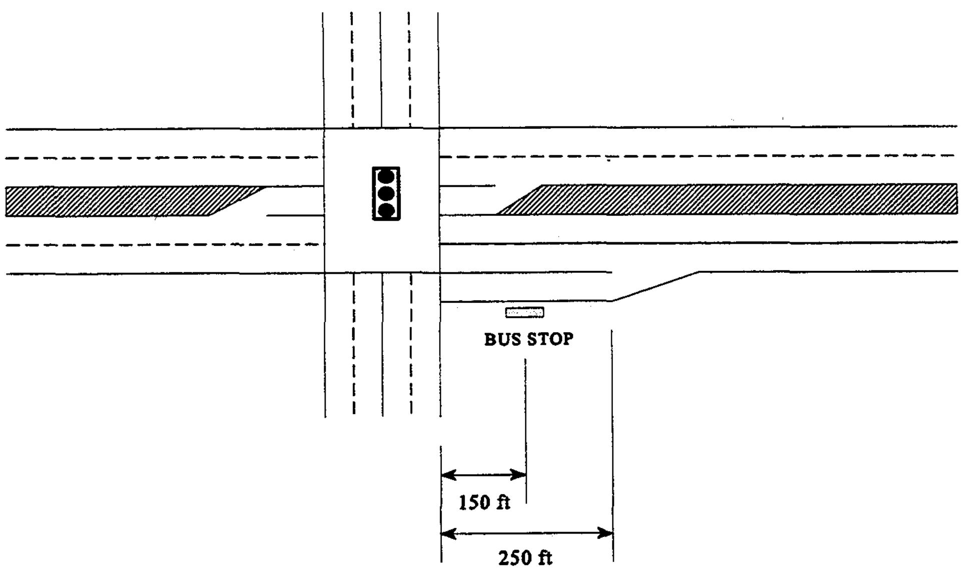


(b) Midblock, Bus Bay

Figure D-31. Midblock Bus Stop Designs.



(a) Queue Jumper



(b) No Queue Jumper

Figure D-32. Queue Jumper Bus Stop Designs.

To perform the simulations, variables to be adjusted and their increment size were selected. Specific inputs required by TexSIM included traffic volumes, turning percentages, speed, bus headways, bus dwell times, and signal timings. The values used for each of the above variables are shown in Table D-13. Optimum signal timings were computed using the signal optimization package, PASSER II. The variables adjusted included main street through traffic volume (100 to 3000 vph) and bus dwell time (20 to 60 seconds). For the queue jumper study, right turn percentages of 10% and 25% were used, and only a dwell time of 20 seconds was studied. Again, because outcome from TexSIM is stochastic, each run was simulated for 1 hour with a bus arriving every 10 minutes. Therefore, a total of six bus arrivals was included for each run.

Table D-13. TexSIM Model Variables.

Variables	Values
Desired Speed	45 mph
Main Street Through Volumes	100, 300, 500, 1000, 1500, 2000, 2500, 3000 vph
Main Street Turning Percentages: Left Through Right[a]	 10 % 80 % 10 %
Cross Street Through Volume	750 vph
Cross Street Turning Percentages: Left Through Right	 20 % 60 % 20 %
Bus Headway	10 min
Bus Dwell Time[b]	20, 40, 60 sec

[a] Right turn percentages of 10% and 25% were used for queue jumper study.
[b] A dwell time of 20 seconds was used for queue jumper study.

Data Reduction. After each simulation run, the necessary data were retrieved from the TexSIM output. The data reduced included vehicle travel times and the number of vehicles queued behind a stopped bus (for curb-side design). Output from TexSIM was given for each vehicle which traveled through the system; therefore, the researchers were allowed to record the travel time of vehicles only when a bus was in the system.

Travel times were measured from a set point upstream of the bus stop to a set point downstream of the bus stop. The output generated from TexSIM included the time that each vehicle entered the link containing the bus stop and the time that the vehicle left the link. From the entry and exit times, the actual travel time was computed.

Table D-14 contains an example of the output generated by TexSIM for a midblock curb-side bus stop with a dwell time of 60 seconds. The first column contains the vehicle ID which is assigned to each vehicle as it enters the system. The vehicle type, shown in the second column, specifies whether the vehicle is a passenger car (C) or a bus (B). The third and fourth columns include the time (in milliseconds) that each vehicle entered and exited the bus stop link. The travel time was computed by subtracting the entry time from the exit time. By noting the times that the bus entered and exited the link, the vehicle travel times when a bus was on the link could be identified (shown as the shaded area in Table D-14. In this example, the vehicles traveling through the system when the bus was present took, on average, 20.1 seconds to travel the link. In comparison, the bus took 78.4 seconds (18.4 seconds travel time and 60 seconds dwell time).

For the curb-side bus stops, TexSIM recorded the number of vehicles queued behind a stopped bus. The number of vehicles in queue was recorded for each second that the bus was stopped. Table D-15 shows an example of the output from TexSIM for a midblock curb-side stop with a dwell time of 20 seconds. As shown in this table, the amount of dwell time remaining is recorded each second along with the number of vehicles in queue. Observing the output, a queue only exists for the last 5 seconds that the bus is stopped, and the maximum number of vehicles in queue is two.

Data Analysis. After the TexSIM data were reduced, they were analyzed. Output from TexSIM recorded for the curb-side versus bus bay/open bus bay study included vehicle travel times when a bus was in the system and number of vehicles queued behind the stopped bus. For the far-side stops, travel times were measured from the intersection to a point 1000 ft downstream of the intersection. For the midblock stops, travel times were measured from 100 ft upstream of the bus stop to a point 900 ft downstream of the bus stop. The travel times were used to compute average speeds. Then, the speeds for the curb-side designs were compared to the speeds for the bus bay designs for various volumes.

Output recorded for the queue jumper study included travel times for the bus both upstream of the queue jumper and through the queue jumper. Travel times were measured from a point 3300 ft upstream of the intersection to the intersection. This information helped to determine the travel time savings to a bus when a queue jumper was present. Again, average speeds were computed from the travel times, and the travel times and speeds for the queue jumper designs were compared to those for bus stops without a queue jumper.

Results

The calibrated TexSIM models for curb-side, bus bay, open bus bay, and queue jumper designs were run for various combinations of traffic volumes and bus dwell times. Following is a discussion of the results from the curb-side versus bus bay/open bus bay study and the queue jumper study.

Table D-14. Example of TexSIM Output — Travel Time Data.[a]

Vehicle ID	Vehicle Type	Entry Time (millisec)	Exit Time (millisec)	Travel Time (sec)
960	C	1001800	1017600	15.8
997	C	1008600	1025900	17.3
1040	C	1023100	1036500	13.4
1045	C	1025100	1039900	14.8
898	C	1040800	1057400	16.6
794	C	1042900	1059500	16.6
824	C	1046300	1063500	17.2
856	C	1050200	1066600	16.4
1018	C	1053500	1069500	16.0
1010	C	1051400	1077200	25.8
852	C	1056100	1081200	25.1
905	C	1063700	1084000	20.3
860	C	1059500	1085900	26.4
887	C	1063000	1089100	26.1
993	**B**	**1023500**	**1101900**	**78.4**
1031	C	1084300	1102700	18.4
1029	C	1085900	1109200	23.3

[a] Shaded area represents vehicles which traveled through the system when a bus was present.

Curb-Side Versus Bus Bay/Open Bus Bay

An objective of the computer simulation was to develop criteria as to when a curb-side stop should be converted to a bus bay/open bus bay for midblock and far-side locations. Factors investigated included vehicle speeds and maximum queue length behind stopped buses. To study the trends between these factors and varying traffic volume and bus dwell times, several figures were generated.

Using the travel time data collected from TexSIM, the average speeds of vehicles were computed for the curb-side and bus bay/open bus bay designs. Figure D-33 illustrates the relationship between the speed of vehicles (when a bus was in the system) and through traffic volume (vehicles per hour per lane) for curb-side and bus bay designs at a midblock location. This figure shows that the speeds for the bus bay design are consistently higher than the speeds for the curb-side design, as was expected. Also, for the bus bay design, dwell time did not have an influence on speed because the bus bay minimized the effects of the bus on traffic operations.

Table D-15. Example of TexSIM Output — Queue Data.

Bus ID	Dwell Time Left (sec)	Number of Vehicles in Queue	Bus ID	Dwell Time Left (sec)	Number of Vehicles in Queue
1519	20	0	1519	9	0
1519	19	0	1519	8	0
1519	18	0	1519	7	0
1519	17	0	1519	6	0
1519	16	0	1519	5	0
1519	15	0	1519	4	1
1519	14	0	1519	3	1
1519	13	0	1519	2	1
1519	12	0	1519	1	2
1519	11	0	1519	0	2
1519	10	0			

For the curb-side design, however, dwell time did have an effect on speed. The speeds for the 20-second dwell time were relatively higher than the speeds for the 40- and 60-second dwell times. The speeds for the 40- and 60-second dwell times were very similar. This similarity is most likely due to the timing of the upstream traffic signal, which controls the release of the main street through-traffic volume.

Figure D-33 also shows that for traffic volumes below approximately 350 vphpl, the speeds for the curb-side design decrease at a relatively higher rate for increasing traffic volume than do the speeds for the bus bay design. Above 350 vphpl, the rate of decrease in speed becomes less for the curb-side design.

Figure D-34 was plotted to illustrate the benefits of a bus bay over a curb-side design. This figure shows the difference in vehicle speeds for the bus bay and curb-side designs (i.e., speeds for bus bay design minus speeds for curb-side design). For volumes below 350 vphpl, the difference in speeds increases at a relatively high rate for increasing traffic volume. Above 350 vphpl, the difference in speeds becomes relatively constant.

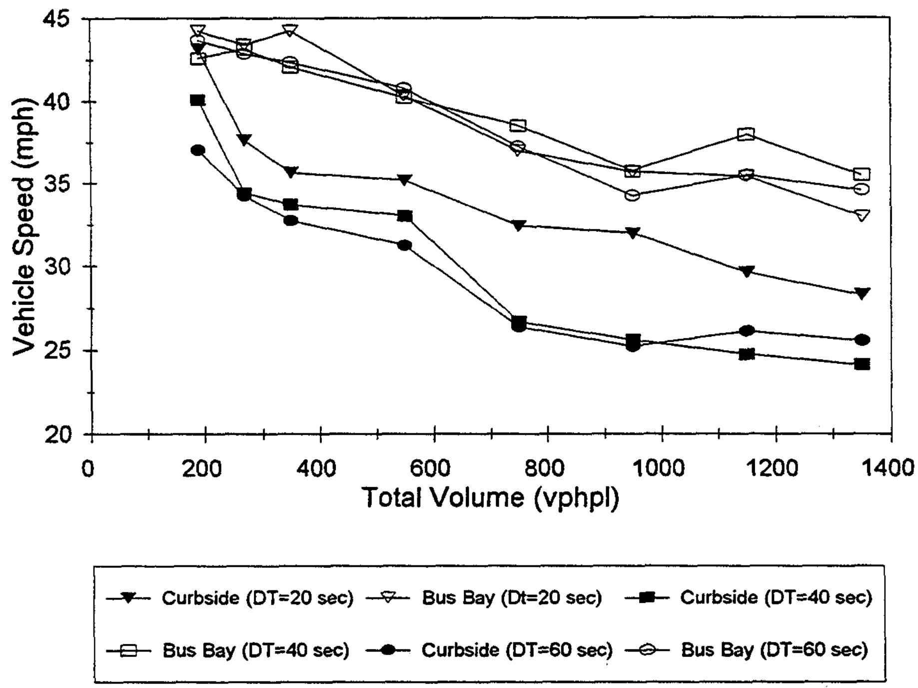


Figure D-33. Relationship Between Speed and Volume for Midblock Location.

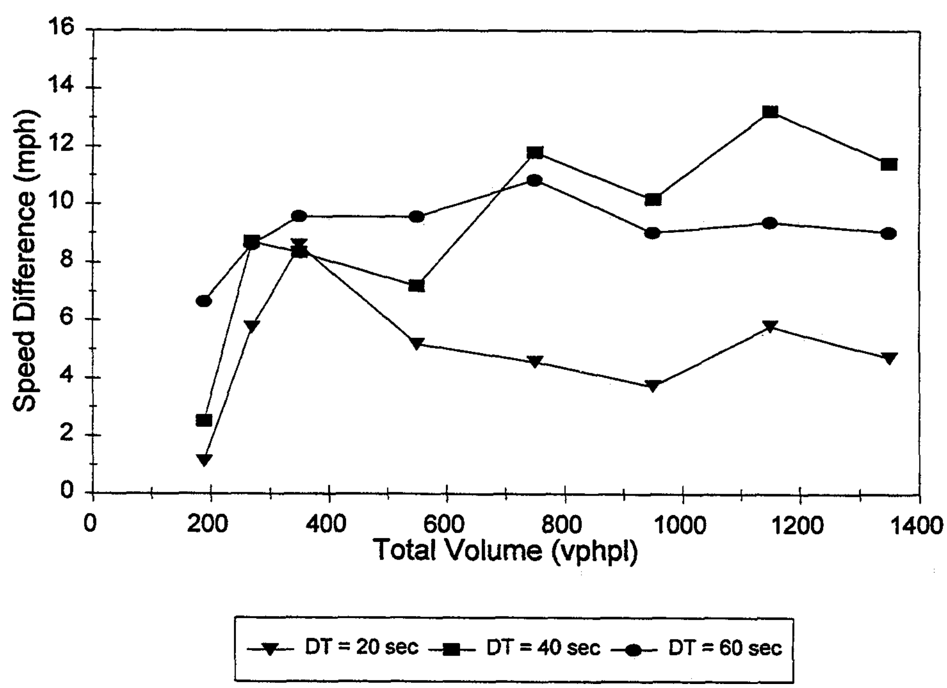


Figure D-34. Speed Difference Between Bus Bay and Curbside Design for Midblock Location.

Figure D-35 illustrates the relationship between vehicle speed and through volume for the far-side location, and Figure D-36 shows the benefits in speed due to a far-side bus bay design as compared to a far-side curb-side design. Similar to the results for the midblock location, Figure D-35 reveals that the rate of decrease in vehicle speed for the curb-side design was greatest for traffic volumes below 350 vphpl. Also, Figure D-36 shows that the difference in speeds between bus bay and curb-side designs reaches a maximum at approximately 350 vphpl. Therefore, these results reveal that the bus bay design provides the greatest benefits to traffic operations at volumes above 350 vphpl.

To further study the effects of the curb-side design on traffic operations, the maximum number of vehicles in queue behind a stopped bus were obtained from the TexSIM output. Figures D-37 and D-38 illustrate the relationship between maximum queue and traffic volume for midblock and far-side locations, respectively. As mentioned earlier, for each combination of traffic volume and bus dwell time, TexSIM was run for 1 hour with a bus headway of 10 minutes (for a total of six bus arrivals). Therefore, the maximum queues illustrated in Figures D-37 and D-38 are the average maximum queues for the six bus arrivals.

Observing Figures D-37 and D-38, for both midblock and far-side locations, the average maximum queue increases at a linear rate for increasing traffic volume for volumes below approximately 950 vphpl. Above 950 vphpl, the rate of increase becomes smaller for the far-side location and is relatively constant for the midblock location. The maximum queues for the observed traffic volumes were approximately four and five vehicles for the midblock and far-side locations, respectively.

From the field studies, the highest number of vehicles in queue was observed at Site S8, which contained a far-side curb-side bus stop (see Table D-2). In the bus stop area at Site S8, there were three through lanes, and the maximum volume observed was approximately 910 vphpl. Figure D-39 shows the maximum queues observed at Site S8 along with the maximum queues predicted by TexSIM for the far-side curb-side design over a range of traffic volumes. Although the field data contain a much higher variation in the maximum queues observed relative to the TexSIM data, there are some similarities between the two data sets. Both the TexSIM output and the field data queues of at least one vehicle occur at approximately 300 vphpl. In addition, queue lengths of three vehicles or more form at traffic volumes of approximately 600 vphpl and above for both the TexSIM data and the field data.

Queue Jumper

The intent of the simulation of the queue jumper bus bay design was to develop recommendations for when to consider a queue jumper bus bay design at a far-side bus stop. Benefits of a queue jumper bus bay were measured in terms of travel time savings and speed increases to the bus when a queue jumper bus bay was present. Factors adjusted during the computer simulation runs included traffic volume (100 to 3000 vph) and right turn percentage (10% and 25%).

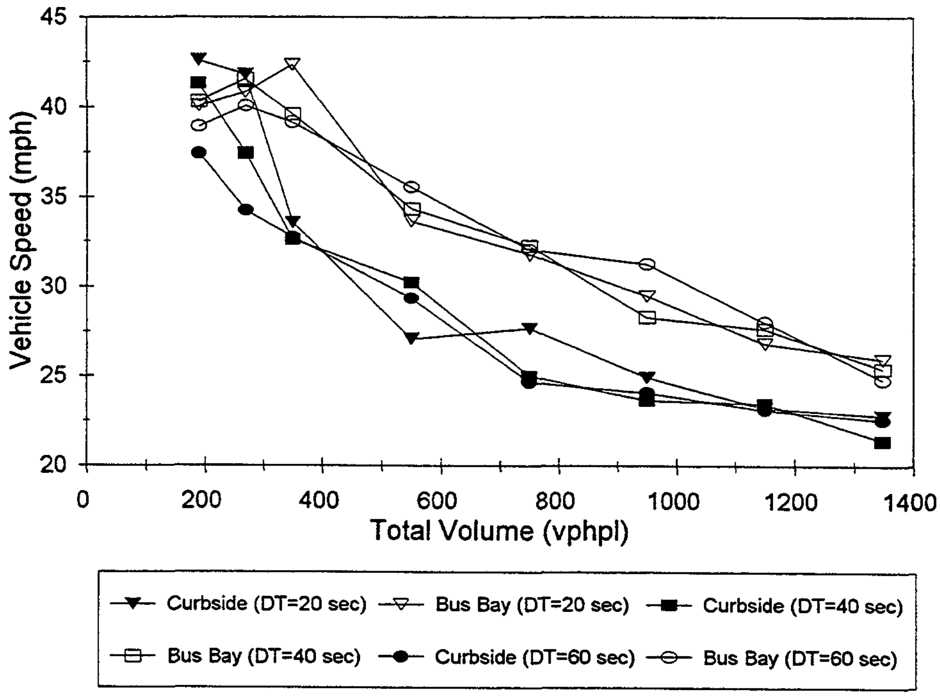


Figure D-35. Relationship Between Speed and Volume for Far-Side Location.

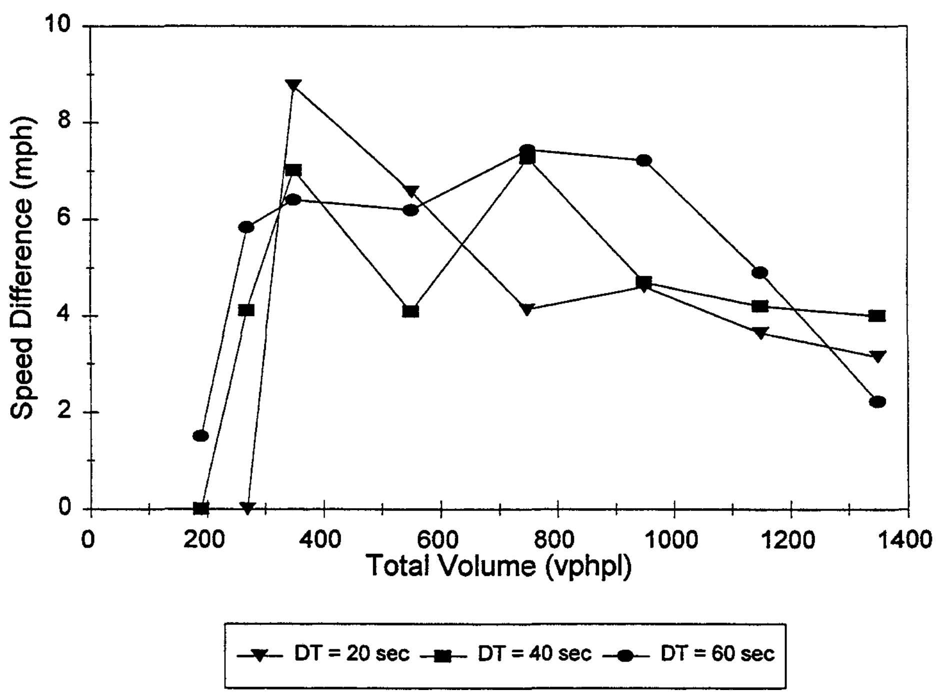


Figure D-36. Speed Difference Between Bus Bay and Curbside Design for Far-Side Location.

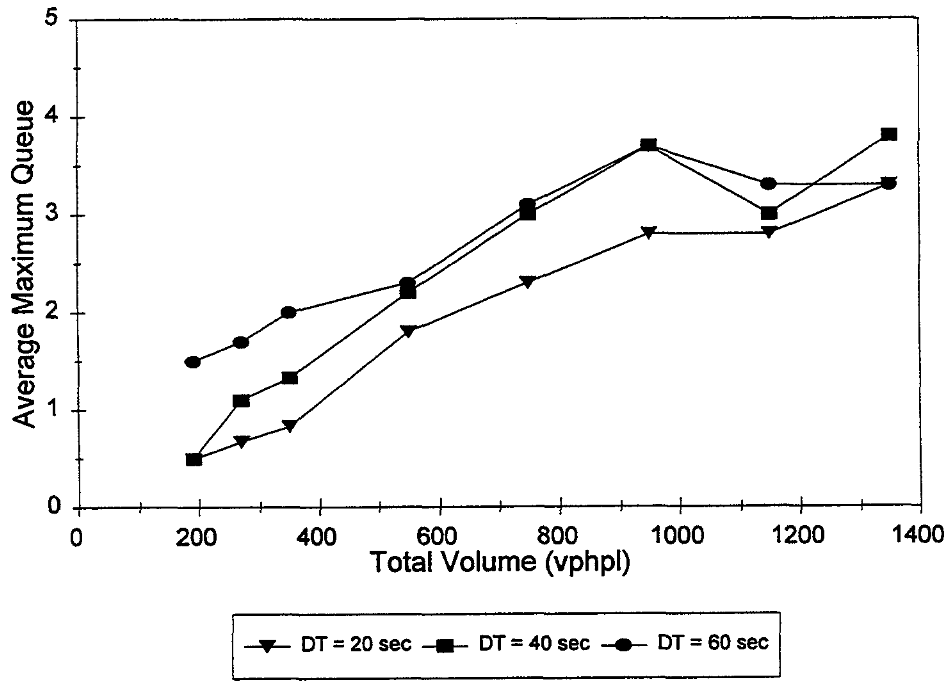


Figure D-37. Relationship Between Maximum Queue and Volume for Midblock Location.

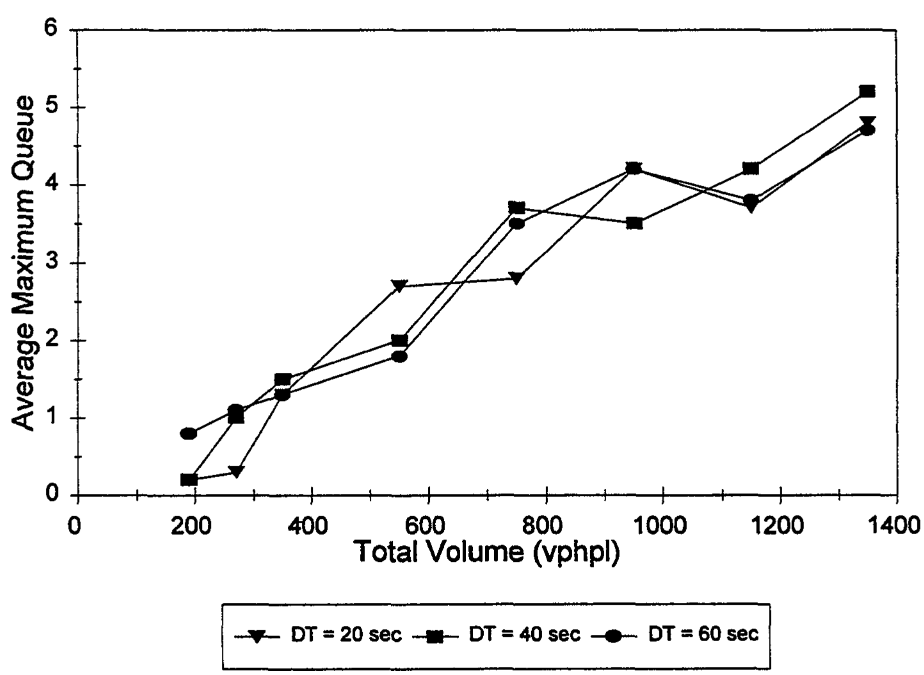


Figure D-38. Relationship Between Maximum Queue and Volume for Far-Side Location

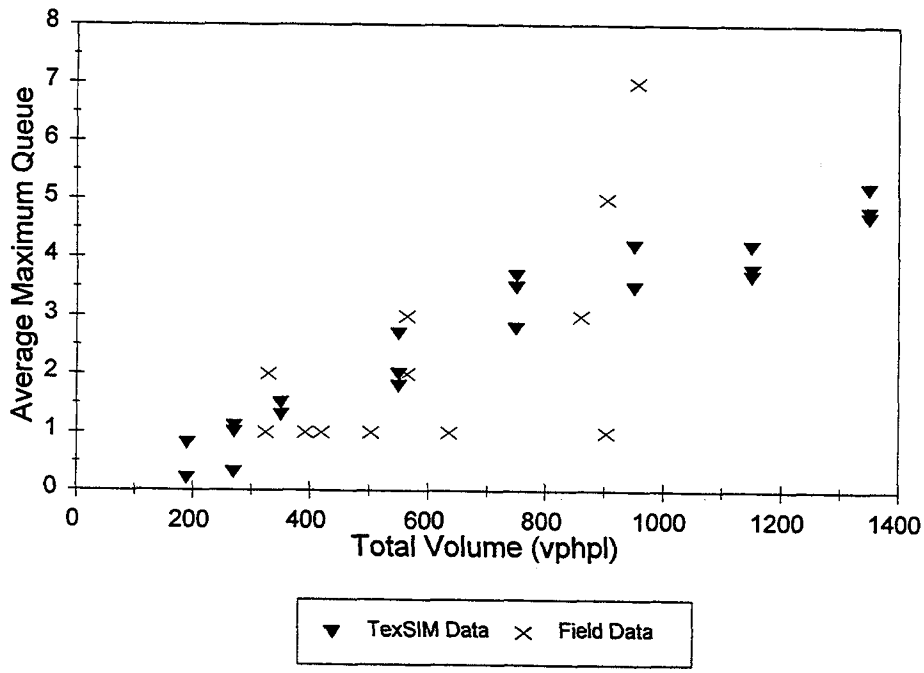


Figure D-39. Relationship Between Maximum Queue and Volume for TexSIM Data and Field Data.

The bus travel times predicted by TexSIM were measured from a point 3300 feet upstream of the intersection to the intersection. This distance included the right turn/queue jumper lane (300 feet in length) and 3000 feet upstream of the queue jumper. Figure D-40 illustrates the relationship between bus travel time and through traffic volume for a far-side open bus bay with and without a queue jumper. As shown in this figure, as the traffic volume increases the bus travel time increases. At traffic volumes above 1000 vphpl, the bus travel time increases significantly for all situations except for a queue jumper with 25% right turns. Above 1000 vphpl, the capacity of the arterial controls the traffic operations and the addition of a right turn bay increases the capacity of the arterial (especially when a heavily-used right turn bay is present, which is the case when right turns = 25%). Increasing the right turn percentage increased the throughput of the arterial because right-turn-on-red was allowed.

Figure D-41 was generated to examine the travel time savings to a bus using a queue jumper bus bay. This figure shows the relationship between travel time savings and through volume for traffic volumes below 1000 vphpl (so that a better view of the operations at lower traffic volumes is available). Observing this figure, the travel time savings were relatively independent of right turn percentage for traffic volumes below 1000 vphpl. For this volume range, the travel time savings varied from approximately 5 seconds to approximately 33 seconds. The travel time savings are relatively constant to approximately 250 vphpl. After 250 vphpl, the travel time savings increase notably.

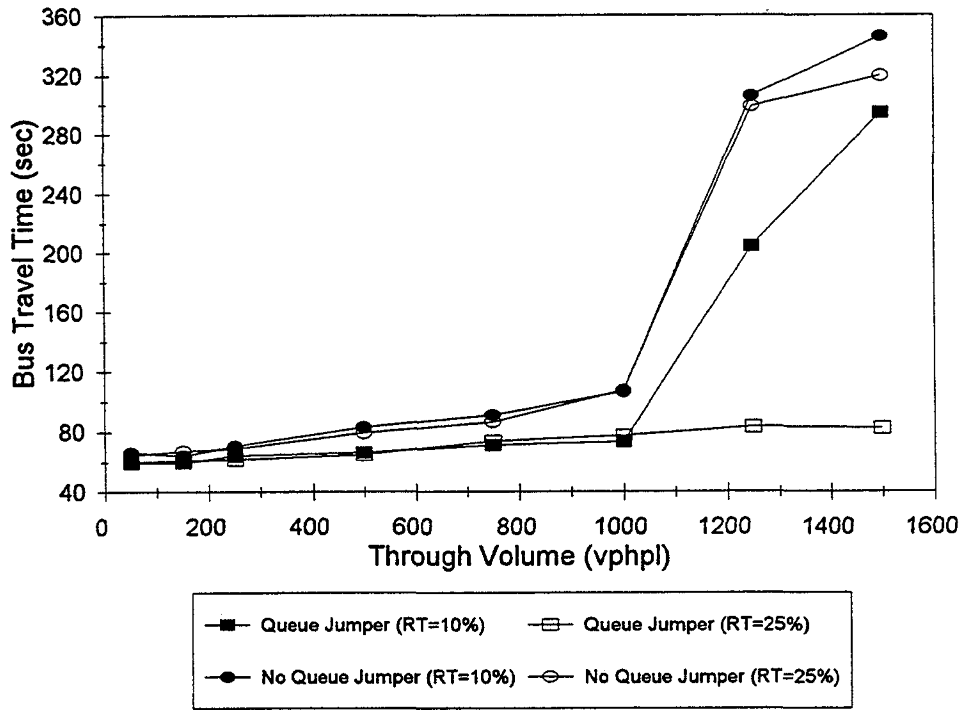


Figure D-40. Relationship Between Bus Travel Time and Volume for Queue Jumper Design.

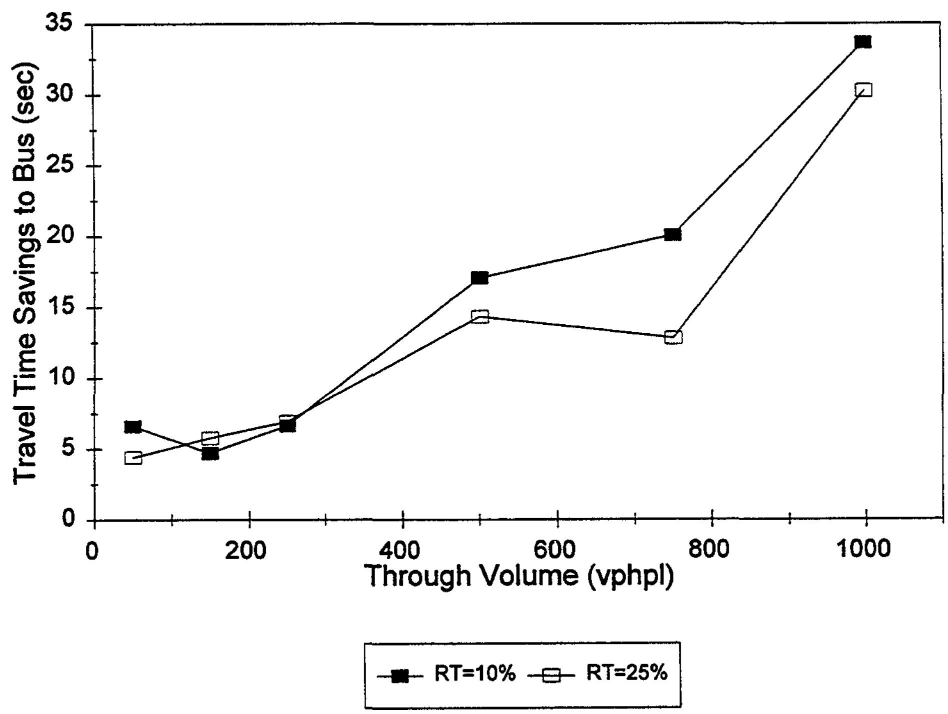


Figure D-41. Relationship Between Travel Time Savings and Volume for Queue Jumper Design.

To further illustrate the benefits of a queue jumper bus bay, the travel time savings were converted to speed. Figure D-42 shows the relationship between traffic volume and the difference in bus speed for bus stops with and without a queue jumper (i.e., bus speeds with queue jumper minus bus speeds without queue jumper). For traffic volumes below 1000 vphpl, the advantages in average speed when a queue jumper was present ranged from approximately 3 mph to 8 mph.

Conclusions

The objective of the computer simulation study was to determine how specific factors, such as volume and bus stop location, influence traffic operations around a bus stop. The conclusions that were made are presented below.

Curb-Side Versus Bus Bay/Open Bus Bay

- For the midblock curb-side and bus bay designs studied, the advantages in average vehicle speed of a bus bay design compared to a curb-side design ranged from approximately 2 mph to approximately 10 mph over the 1000-foot study area (based on traffic volume).

- For the far-side designs studied, the advantages in average vehicle speed of an open bus bay design compared to a curb-side design ranged from approximately 1 mph to 7 mph over the 1000-foot study area.

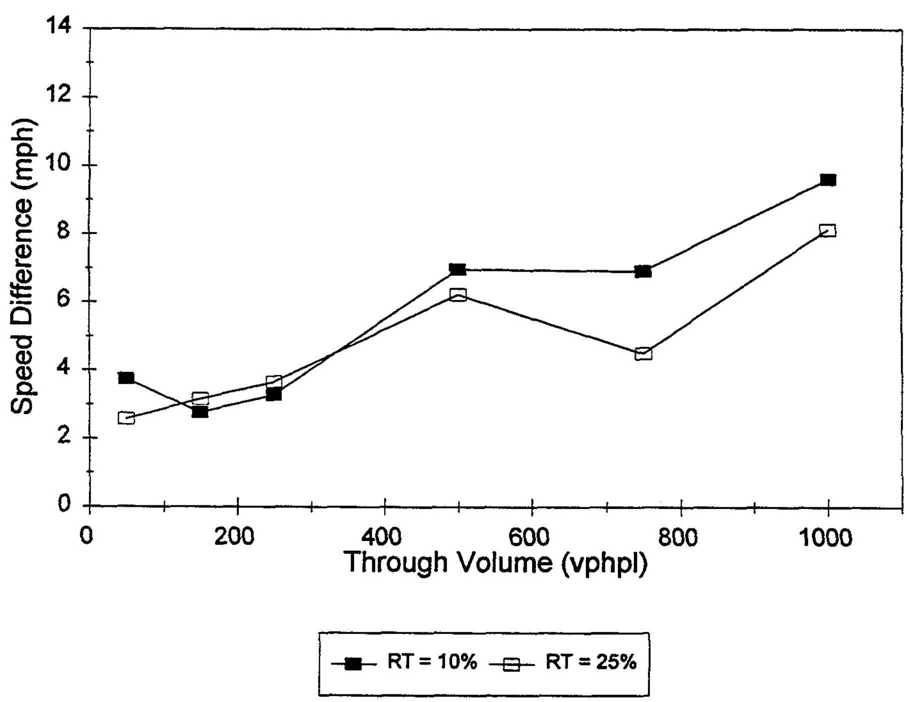


Figure D-42. Speed Difference Between Queue Jumper and No Queue Jumper.

- For the midblock curb-side design, the dwell time of the stopped bus affected traffic operations. The predicted speeds for a 20-second dwell time were from 2 mph to 7 mph higher than the predicted speeds for the 40-second and 60-second dwell times. Speeds for the 40-second and 60-second dwell times were relatively similar.

- For the far-side curb-side design, dwell time had minimal effect on the traffic operations. The relationship between vehicle speed and volume was similar for the 20-, 40-, and 60-second dwell times.

- For both the midblock and far-side bus stop locations, 350 vphpl was the volume at which the advantages in average vehicle speeds due to a bus bay either increased significantly or were near maximum. Notable travel time savings were also observed at 250 vphpl.

Queue Jumper

- For the queue jumper study, the results revealed that traffic operations began to diminish significantly at volumes above 1000 vphpl because of the limited capacity of the arterial (which is to be expected).

- For traffic volumes below 1000 vphpl, the travel time savings to a bus using a queue jumper bus stop ranged from approximately 5 seconds to 33 seconds over the 3300-ft study area (based on traffic volume). The advantages in average bus speed when a queue jumper bus stop was present ranged from 3 mph to 8 mph.

- The queue jumper bus stop design provided notable travel time savings and speed advantages above approximately 250 vphpl.

SUMMARY OF FINDINGS

This appendix documents research that focused on street-side factors affecting the location and design of bus stops. The research included regional visits, field studies, and computer simulation. The findings from each of these studies are summarized below.

Regional Visits

The objective of the regional visits was to explore how different bus stop designs operate. The states visited during the trips included Arizona, Michigan, and California. The efforts during the regional trips included interviewing transit agency staff, visiting several bus stops with different designs and locations, and observing how the stops operated. The findings from the regional visits were as follows:

- Successful design and placement of a bus stop requires coordination between transit agencies and other government agencies (primarily cities but also including neighborhood organizations, etc.).

- Safety considerations include providing adequate sight distances for pedestrians, vehicle drivers, and bus operators and minimizing the number of bus stops near driveways.

- Reinforced bus pads result in reduced pavement deterioration and minimal maintenance costs. Further research is needed to analyze the benefits of bus pads by comparing stops using reinforced bus pads with stops that do not have bus pads.

Field Studies

The objective of the field studies was to observe the operations at existing sites to determine how the location and design of bus stops influence traffic and bus operations. The study sites were divided into suburban sites (traffic speeds greater than 35 mph), and urban sites (traffic speeds less than 35 mph). The locations investigated included near-side, far-side, and midblock. The suburban bus stop designs included curb-side, bus bay, and queue jumper. The urban bus stop designs included curb-side, bus bay, and nub. Following are the findings from these studies:

- For bus bay stops, far-side locations may result in less delay to buses when compared to near-side or midblock locations. One reason for the minimal delays to buses at the far-side stops is due to the breaks in traffic created by the upstream signalized intersection.

- For bus bay stops, delay to buses is minimized for those sites with acceleration lanes. Acceleration lanes provide bus operators with an area to merge smoothly with the through traffic resulting in minimal conflicts.

- For far-side open bus bay stops, a queue jumper can provide significant travel time savings to bus passengers. The travel time savings to buses are dependent upon the queue length at the intersection and the number of right-turning vehicles. The effects on average delay to right-turning traffic due to a bus using a queue jumper is generally assumed to be minimal.

- For nub or curb-side designs, near-side locations may result in less delay to through vehicles when compared to far-side locations. At near-side stops, delay to through traffic due to a bus loading/unloading passengers and delay to a signalized intersection overlap, resulting in less overall delay.

Computer Simulation

The objective of this study was to use computer simulation to determine how different bus stop designs affect traffic and bus operations. Bus stop designs analyzed included curb-side, bus bay, open bus bay, and queue jumper. Both midblock and far-side locations were used in the simulation. Factors varied during the computer simulation included traffic volume and bus dwell time. For the queue jumper design, the percent of right-turning vehicles was also varied. Following are the findings from the computer simulation study:

- For the curb-side design, the dwell time of the stopped bus at the midblock location had an effect on traffic operations; however, dwell time did not affect traffic operations for the farside location.

- For both midblock and far-side locations, 350 vphpl was the volume at which the advantages in average vehicle speeds due to a bus bay either increased significantly or were near maximum. Notable travel time savings were also observed at 250 vphpl.

- The queue jumper bus bay design provided notable travel time savings and speed advantages above approximately 250 vphpl.