APPENDIX C

ROADWAY BEFORE-AND-AFTER STUDY

The benefits to pedestrians and bus patrons are numerous when a bus bay is replaced with a bus bulb. Buses should operate more efficiently at the stop when not required to weave into and out of a bus bay. The bus bulb also provides additional room near the sidewalk to increase walking and/or waiting areas. However, these benefits may be offset by drawbacks to motorists and other buses. In the bus bulb design, the bus loads and unloads passengers while stopped in the travel lane. Being stopped in the travel lane could result in queues forming behind the bus and longer travel times for both vehicles and buses.

STUDY DESIGN

San Francisco anticipated converting several of their stops to bus bulbs during the late 1990s. Stops located on Mission Street from Cesar Chevez to Santa Marina were to be converted as part of a pavement rehabilitation project during 1999. The timing of this TCRP project and the construction schedule for the nine stops on Mission Street allowed the inclusion of the stops as part of a before-and-after study. The before-and-after study would examine the effects of converting a bus stop from a bus bay design to bus bulb design. The goal was to analyze the operations at both farside and nearside bus stops. Specific objectives of the roadside study included determining if the following changed from the before period (bus bay) to the after period (bus bulb):

- bus and vehicle speeds near a bus stop (peak and non-peak time periods),
- bus and vehicle speeds for the corridor (peak time period),
- length of queue behind a bus and driver behavior near the bus stop, and
- bus operations.

Bus speeds represent the speeds for buses stopping at a bus stop of interest. Vehicle speeds represent the speeds of all vehicles in the traffic stream.

A part of the above evaluations included identifying if other events within the area, such as an increase in traffic volume, could have contributed to the observed difference.

The before data collection trip took place in February 1999, while the after data collection trip took place in November 1999. Construction of the bulbs occurred during the summer.

STUDY SITES

Mission Street is a low-speed arterial (less than 30 mph [48.3 km/h]) with heavy commercial development. The surrounding development is primarily shops and restaurants. The corridor has four lanes without a median and is posted with a 25 mph (40.3 km/h) speed limit. Traffic and bus data were collected at six of the nine bus stops converted as part of the construction project and for the corridor. Figure C–1 shows the corridor and the six bus stops studied, while Table C–1 contains the descriptions of each site. Figures C–2 to C–11 are schematics or pictures of the sites.

DATA COLLECTION/REDUCTION

Data were collected using travel time software, palmtop computers, video, photographs, and general observations made in the field. Travel time data for vehicles and buses were collected using synchronized laptop computers and a license plate collection software program (Ttcollec) developed by TTI. Two members of the data collection team were positioned at set locations upstream and downstream of the intersection or corridor being studied. Each member entered the license plates of vehicles and the bus numbers of buses as they passed. The time that a vehicle entered or exited the study zone was automatically recorded in the laptop computer when a license plate or bus number was entered. Figure C–12 shows the locations of the researchers and the distances over which the travel times were collected. It should be noted that the corridor travel times (2380 ft [725.9 m]) were recorded in both the northbound and southbound directions.

The upstream and downstream travel time data files were combined for each study site, and the matches (i.e., the same license plate in both data files) were identified. A software program was then used to compute the travel time and speed for each match. Manual checks of the original files were also completed to ensure that all possible matches had been made. For example, a typo in a license plate number (e.g., RY56 and RYS6) would result in the software not reporting a match when a visual check of the data would indicate that the data were for the same vehicle.

Bus arrival/departure times were collected using the palmtop computers running a program specifically designed for this task. Data available from the palmtop data files include bus dwell times and the delay to buses re-entering the traffic stream. The bus dwell time was defined as the time from when the bus stopped until the doors on the bus closed. The delay to buses re-entering the traffic stream was defined as the time from when the doors on the bus closed until the bus started moving (departed).

Because the study area was located in a dense urban center, the team also used video cameras to collect traffic and bus operations. The data reduced manually from the videos were traffic volumes, bus arrival and departure times, bus position in lane(s) at the stop, the number of queued vehicles behind the bus while stopped, and the number of lane changes associated with the presence of a bus. The bus arrival and departure times were used to compute the time a bus was stopped (i.e., the time from when the bus stopped until the bus departed).

ROADSIDE BEFORE-AND-AFTER STUDIES

The following sections contain a comparison of the before-and-after roadside studies conducted in San Francisco, California.

Traffic Volumes

Evening peak traffic volumes including turning movements for three signalized intersections in the corridor (Cortland, 30th, and 29th) were compared to determine if the volumes changed substantially between the before-and-after study. Table C–2 contains the before-and-after entry volumes and turning percentages for each approach for three intersections.

The percent difference between the before study and the after study values were calculated. It was determined that almost all of the entry volumes increased from the before study; however, several approaches only saw a minimal increase (less than 7 percent). The largest increase in entry volume (20 percent) was seen at the 30th/Eugenia intersection on Mission Street in the northbound direction. The southbound direction experienced almost no change in traffic volume.

With regard to turning percentages, there was no difference in percentages between the before and after studies for the majority of the approaches. However, for two of the approaches (Cortland and 29th) the trend was toward a more even split (e.g., 50/50) with respect to right and left turn movements. Also, the southbound approach on Mission Street at the 29th intersection experienced an increase (8 percent) in right-turn movements. Overall, the turning percentages were relatively the same for the before-and-after study.

Bus and Vehicle Speeds Near a Bus Stop

Travel speed data were available for two blocks. Figure C–12 illustrates the locations of the blocks. For one of the blocks, both peak and non-peak data were collected. Table C–3 presents the findings. The results show that the installation of a bus bulb improved traffic operations along the blocks. During the peak and non-peak periods, the block with the farside stop saw statistically significant increases in vehicle speeds from 11.4 to 20.9 mph (18.4 to 33.6 km/h) in the peak period and from 9.5 to 15.7 mph (15.3 to 25.3 km/h) in the non-peak period. Buses also traveled faster along this block after the bus bulb was installed (increases of 0.2 to 2.2 mph [0.3 to 3.5 km/h]). Improvements in operating speed also occurred for both buses and vehicles on the block with the nearside stop (increase of 4.5 mph [7.2 km/h] for vehicles and 0.9 mph [.4 km/h] for buses). Changes in traffic volumes were checked to determine if they had an influence on the change in travel speeds. Both blocks experienced a slight (between 2 and 4 percent) increase in traffic volumes. This increase would have a marginal, if any, effect on travel speeds.

Bus and Vehicle Speeds for the Corridor

The travel time and speeds of vehicles and buses were recorded from Cortland Ave. to Precita St. (see Figure C–12). In this section of the corridor there were six intersections and seven bus stops, and the distance was approximately 2400 ft (732 m). The data were collected during a peak period. Speeds measured for a block may be heavily influenced by the operations at a traffic signal. Collecting travel time data for a longer distance should provide a better representation of the operating conditions along the entire corridor. A disadvantage to collecting travel time data for the longer distance, however, is that few vehicles travel the entire distance along the corridor. Less than 20 percent of the vehicles observed during the before-and-after study traversed the entire corridor. Most vehicles turn from the corridor or stop at a business along the corridor. Thus, data collection time and effort for the corridor is much greater than for a block. Table C–4 lists the findings for both southbound and northbound traffic within the corridor.

In the northbound and southbound directions the average speed for vehicles increased approximately 3 mph (4.8 km/h) and 7 mph (11.3 km/h), respectively. The increase in speed was statistically significant for the southbound direction. Figure C–13 is a plot of the individual vehicle speeds collected in both directions for both bus stop designs. It demonstrates that much higher speeds are present with the bulb design. Approximately 40 percent of the vehicles observed when the bulbs were present were driving at speeds greater than 19 mph (30.6 km/k), which was the highest speed measured in the before (bay) condition.

The average speed for buses in both directions improved slightly (by about 0.5 mph [0.8 km/h]). The need to not re-enter the traffic stream by a bus should have contributed to the improvement. Figure C–14 is a plot of the individual bus speeds collected in both directions for both bus stop designs. The closeness of the curves in Figure C-14 demonstrates that the speed distribution for bays and bulbs in both directions are similar.

Length of Queue Behind a Bus and Driver Behavior near the Bus Stop

The location and design of a bus stop can affect the operations along a roadway for other buses and vehicles. The following general observations were made by the research team during the data collection effort in San Francisco:

- There were several observed near "sideswipes" between vehicles and buses when the bus tried to re-enter the traffic stream from a bus bay.
- Buses are sometimes caught in the queue created by a traffic signal before reaching the bus stop. This occurred on several occasions during the peak period especially at nearside stops (e.g. Mission at 30th, Southbound).
- Double-parked vehicles or illegally parked vehicles in the bus stop created difficulties for bus drivers with both the bus bay and bus bulb designs (see Figure C–15).

To quantify the vehicle operations around a bus stop, the number of vehicles queued and the number of lane changes that occurred behind a stopped bus were counted at five sites. Table C–5 lists the data collected during non-peak and peak periods. All the sites with non-peak findings were farside stops. One of the sites with peak-period data was a nearside stop (Site 1) with the remaining two sites farside stops.

The non-peak period represents operations between 9:00 am and 3:00 pm. Lower traffic volumes and higher speeds are present during this period. At all four sites, the average number of vehicles in a queue was only one vehicle with a maximum of four vehicles. In the before period when bus bays were present, the buses would frequently stop in the traffic lane. A traffic queue would form behind these buses for every seven to 17 bus arrivals. After the installation of the bus bay, a queue would form for every three to five bus arrivals. Therefore, queues were forming more frequently during the non-peak period with bus bulbs, however, the queue lengths were still fairly short – typically between one to four buses with an average of less than one vehicle for each queue. Most drivers would attempt to change lanes rather than queue behind a stopped bus. For both the bus bay and the bus bulb design, on average, one lane change occurred for each bus arrival. Slightly more lane changes occurred when the bus bulb design was present.

During the peak period traffic volumes are generally higher and speeds lower. In this area of San Francisco, a higher pedestrian volume was also observed during this time period. As expected, vehicle queues behind stopped buses were higher during the peak period than during the non-peak period. When a bay was present, the queues were one to six vehicles long with an average between one and three vehicles. After the bus bulbs were installed, the observed number of vehicles in queue was slightly less, with a maximum length of four vehicles. At the nearside stop (Site 1), queues formed less frequently after the bulb was installed, however, the number of lane changes increased. At the farside stops, queues form more frequently with the bus bulb design. The frequency of lane changes, however, was generally constant.

In summary, queues occur more frequently with the bus bulb designs, however, they are generally short, on average, only one to two vehicles long. During the peak period, the number of lane changes is similar for both designs at the farside stops. The nearside stop had a greater number of lane changes with the bulb design than the bay design.

Bus Operations

During the before study, over 500 bus arrivals at the bus bay were observed. A majority of these buses completely or partially stopped in the outside lane instead of pulling into the bus bay (see Figures C–16 and C–17, respectively). At all of the sites studied except one, more than half of the buses stopped partially or fully in the travel lane (see Tables C–6 and C–7). Site 3 had the highest incident of buses stopping in the lane, with over 72 percent of the buses in the peak period stopping in the lane. Representatives of San Francisco MUNI acknowledged this observation and concluded this behavior is due to two events: bus drivers are wary of the bus re-entry problem and want to avoid this maneuver, and the overhead electrical wires had already been moved for the reconstruction of the bus stops, which can cause the catenary poles from the buses to dislodge from the electrical wire (the data collection team observed several of these events). However, bus patrons are asked to step off the curb and onto the street whenever this maneuver is practiced by bus drivers.

The length of time a bus is present at a stop can influence the operations along the roadway. If the design of the stop causes the length of time to increase noticeably, it will have a negative affect on traffic operations. While in San Francisco, the dwell time for a bus was recorded with the palmtop computers. The time when the bus stopped at the bus stop and the time the doors closed were recorded. Dwell time was computed as the difference between those events. The findings for two sites are listed in Table C–6. Both peak and non-peak data are available. In addition to the palmtop data, the video of several sites could be used to determine the length of time that a bus is at the stop. The video could not provide the time that the bus doors close; therefore, the time that the bus departed the stop was recorded. The “bus stop time” was determined as the length of time between when the bus arrives and when the bus departs. Table C–7 lists these findings.

At the sites where the palmtop computers were used, the amount of delay to buses attempting to re-enter the traffic stream is also available. Table C–6 presents the data for both peak and non-peak time periods. The average delay to the bus was slightly longer in the peak period, and buses at the nearside stop experienced longer delays than buses at the farside stop. Drivers at the farside stop could pull into traffic during the gaps created by a traffic signal. The queues at the signal at the nearside stop limits the opportunity for a bus driver to enter the traffic. Figures C–18 and C–19 are plots of the bus delay collected for both bus stop designs for non-peak and peak time periods, respectively.

The average dwell time at the bulb was in general longer than the average dwell time at the bay. Site 3 during a peak period was the only exception, with the average dwell time being similar for both the bus bay and bus bulb designs (within 2 sec). During the data collection process (both before-and-after studies) researchers noted that supervisors were present at these two stops. On several occasions the driver of a bus would stop and talk to the supervisor, thus increasing the dwell time at the stop. Further review of the notes taken by researchers indicates that this event occurred more often and for longer periods of time during the after study.

The amount of time a bus was stopped at a bus bulb was within three seconds of the amount of time the bus was stopped at a bus bay. Thus, the installation of a bulb did not change the length of time that the bus was at a stop.

CONCLUSIONS

The objective of this study was to analyze the operations at both farside and nearside bus stops before and after the implementation of bus bulbs to determine the advantages/disadvantages to traffic and bus operations in urban areas. The conclusions from this effort are:

- The replacement of a bus bay with a bus bulb improved vehicle and bus speeds on the block. The block with the farside stop saw a statistically significant increase in vehicle travel speed during both the non-peak (9.5 to 15.7 mph [15.3 to 25.3 km/h]) and peak (11.4 to 20.9 mph [18.4 to 33.6 km/h]) periods.

- The average speed for vehicles and buses on the corridor increased with the installation of the bus bulbs. Buses experienced approximately a 7 percent increase (about 0.5 mph [0.8 km/h]) for both northbound and southbound directions. Vehicles' speeds changed from approximately 15 mph (24.2 km/h) to 17 mph (27.4 km/h) (17 percent increase) or 22 mph (35.4 km/h) (46 percent increase), for the northbound and southbound directions, respectively. The finding for the vehicles moving in the southbound direction was statistically significant.

- Queues did occur more frequently with the bus bulb design, however, they were generally short, on average, only one to two vehicles long.

- During the peak period, the number of lane changes is similar for both designs at the farside stop. The nearside stop had a greater number of lane changes with the bulb design than the bay design.
- Even though an area was provided for removing the bus from the travel lane, the majority of the buses completely or partially stopped in the outside lane instead of pulling into the bus bay.

- The average delay to buses when re-entering the travel stream was constant from the before period to the after period at the farside stop. The nearside stop, which experienced higher delays to buses, saw a reduction in the average delay with the installation of the bus bulbs. With a bus bay design, the queues at the signal limited the opportunity for a bus driver to enter the traffic.

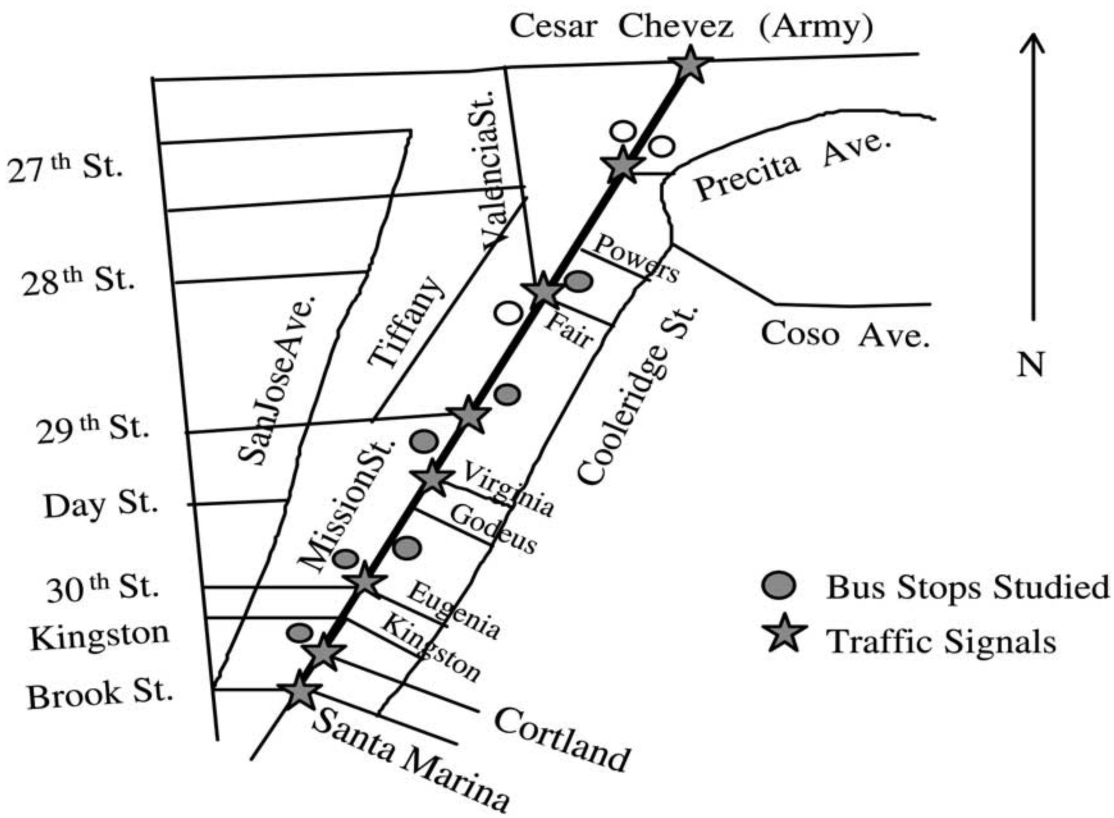
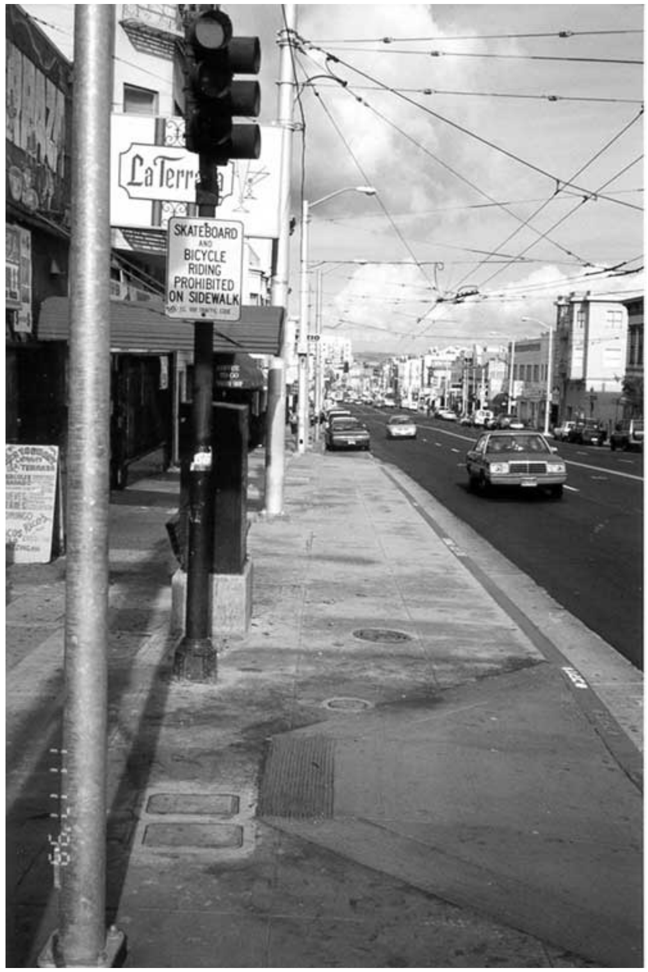


Figure C-1. Study Location.

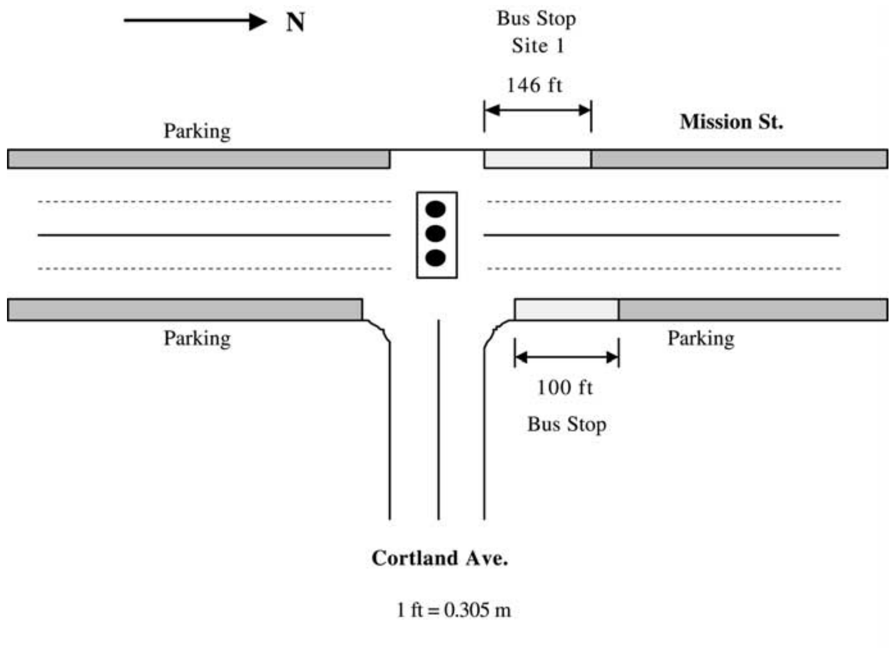
(a) Bus Bay

Figure C-2. Bus Stop 1: Southbound on Mission Street at Cortland Avenue.



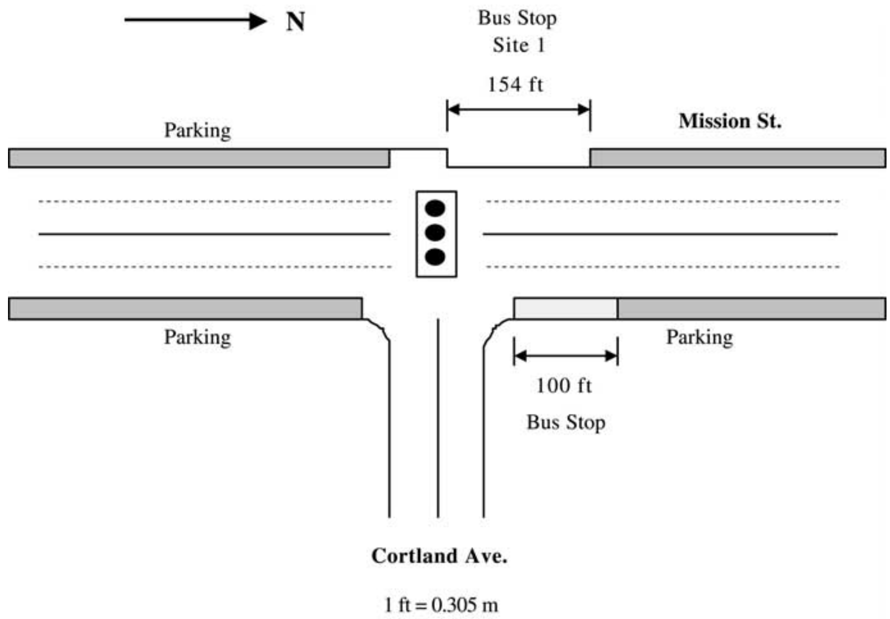
(b) Bus Bulb

Figure C-2. Bus Stop 1: Southbound on Mission Street At Cortland Avenue (continued).



(a) Bus Bay

Figure C-3. Site 1: Mission Street at Cortland Avenue.



(b) Bus Bulb

Figure C-3. Site 1: Mission Street at Cortland Avenue (continued).

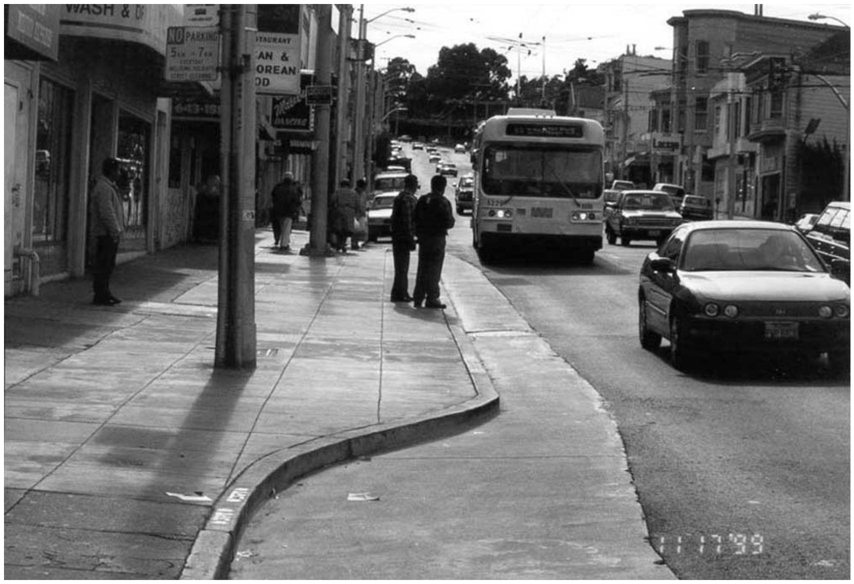
Figure C-4. Bus Stop 2: Southbound on Mission Street at 30th Street.

(b) Bus Bulb

Figure C-4. Bus Stop 2: Southbound on Mission Street at 30th Street (continued).

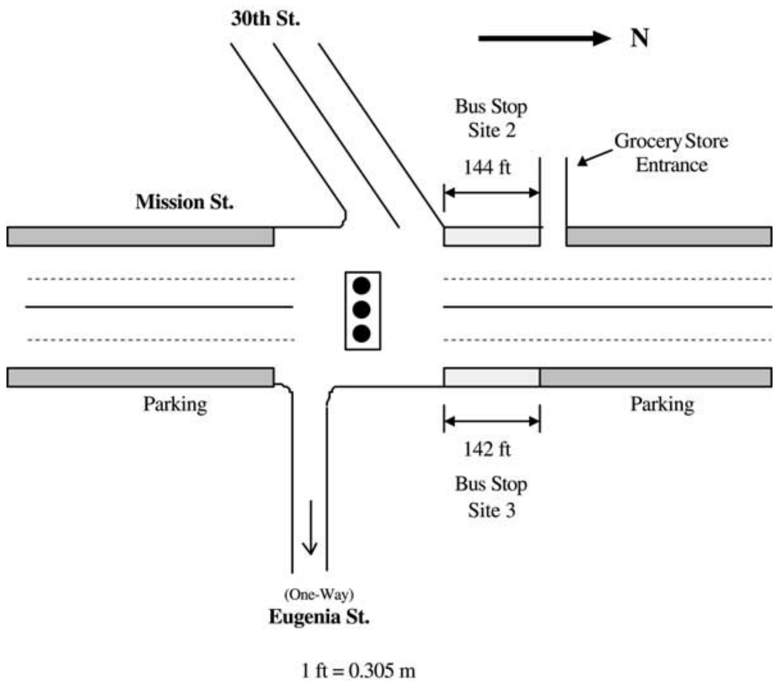
(a) Bus Bay

Figure C-5. Bus Stop 3: Northbound on Mission Street at 30th Street.



(b) Bus Bulb

Figure C-5. Bus Stop 3: Northbound on Mission Street at 30th Street (continued).



(a) Bus Bay

Figure C-6. Site 2 and Site 3: Mission Street at 30th Street.

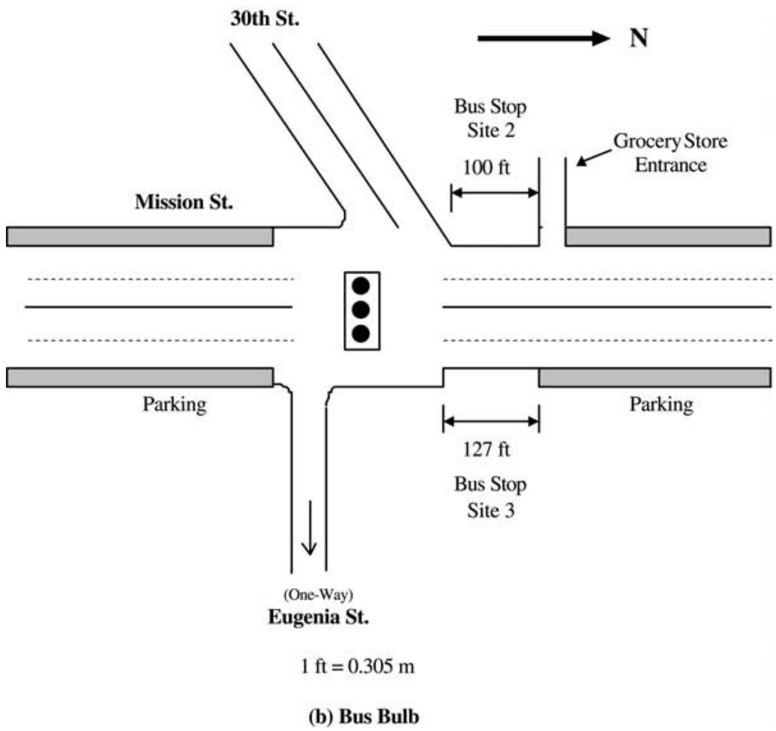


Figure C-6. Site 2 and Site 3: Mission Street At 30th Street (continued).

(a) Bus Bay

Figure C-7. Bus Stop 4: Northbound on Mission Street at 29th Street.

(b) Bus Bulb

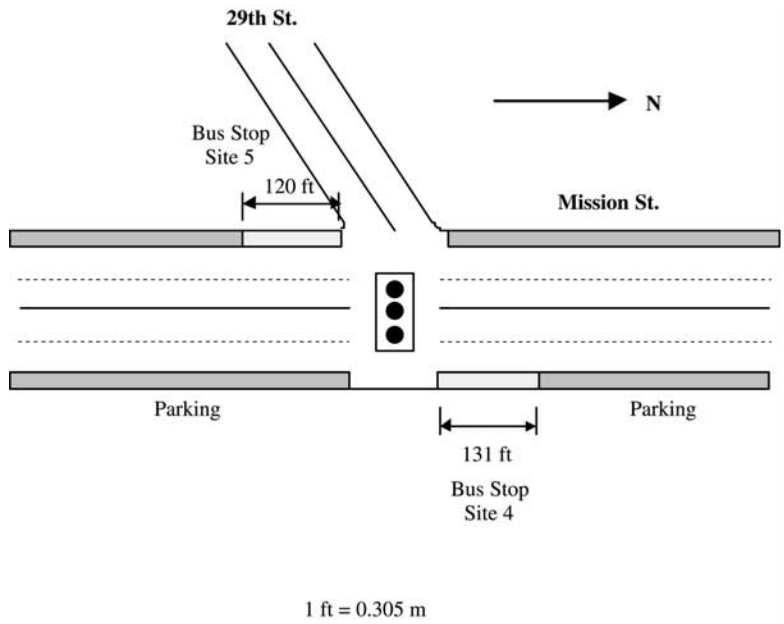
Figure C-7. Bus Stop 4: Northbound on Mission Street at 29th Street (continued).

(a) Bus Bay

Figure C-8. Bus Stop 5: Southbound on Mission Street at 29th Street.

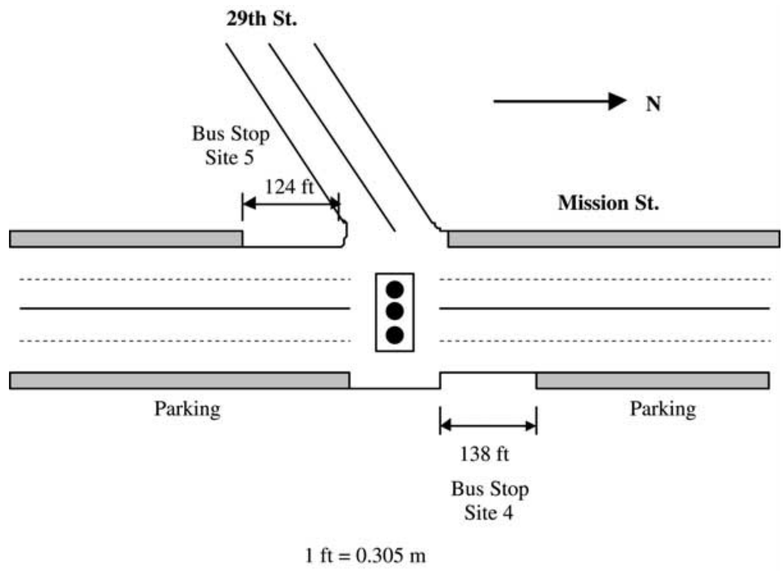
(b) Bus Bulb

Figure C-8. Bus Stop 5: Southbound on Mission Street at 29th Street (continued).



(a) Bus Bay

Figure C-9. Site 4 and Site 5: Mission Street at 29th Street.



(b) Bus Bulb

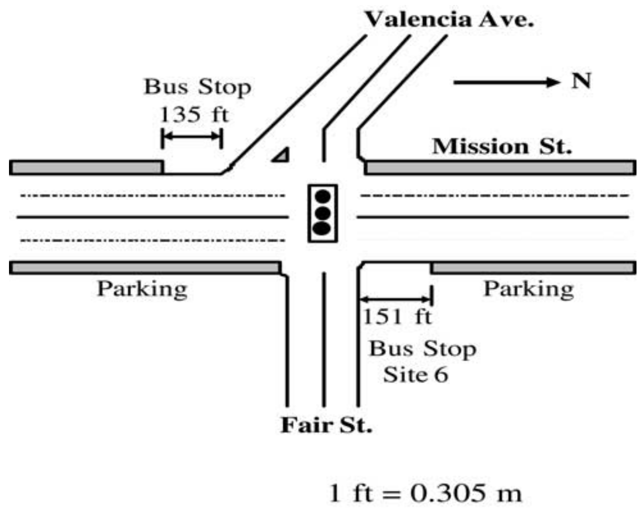
Figure C-9. Site 4 and Site 5: Mission Street At 29th Street (continued).

(a) Bus Bay

Figure C-10. Bus Stop 6: Northbound on Mission Street at Valencia Street.

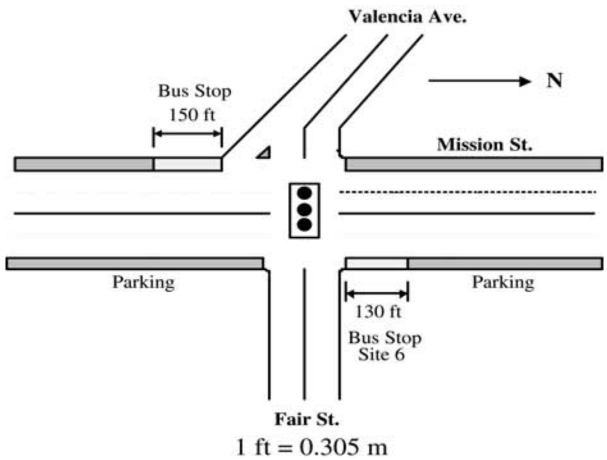
(b) Bus Bulb

Figure C-10. Bus Stop 6: Northbound on Mission Street at Valencia Street (continued).



(a) Bus Bay

Figure C-11. Site 6: Mission Street at Valencia Street.



(b) Bus Bulb

Figure C-11. Site 6: Mission Street at Valencia Street (continued).

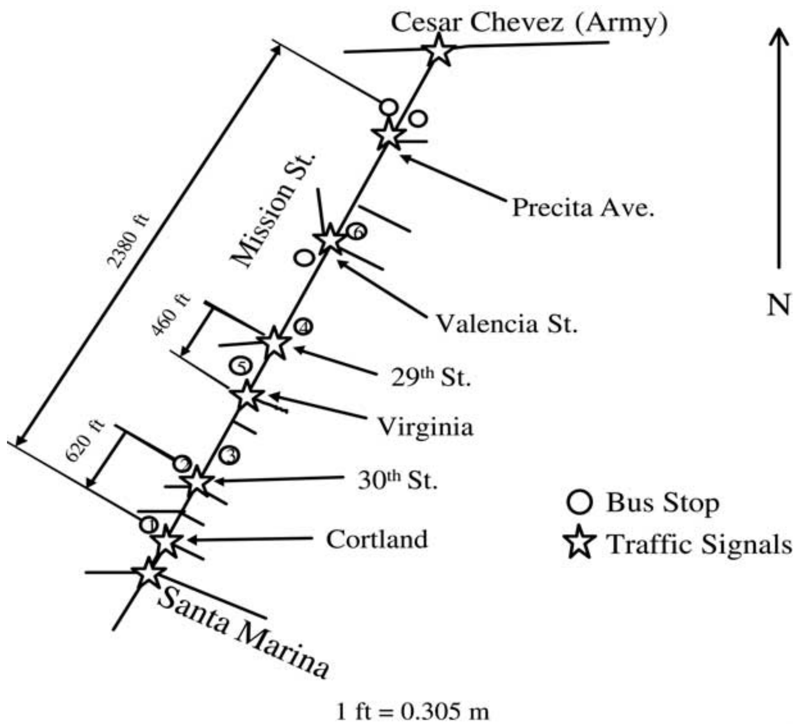


Figure C-12. Travel Time Collection Locations.

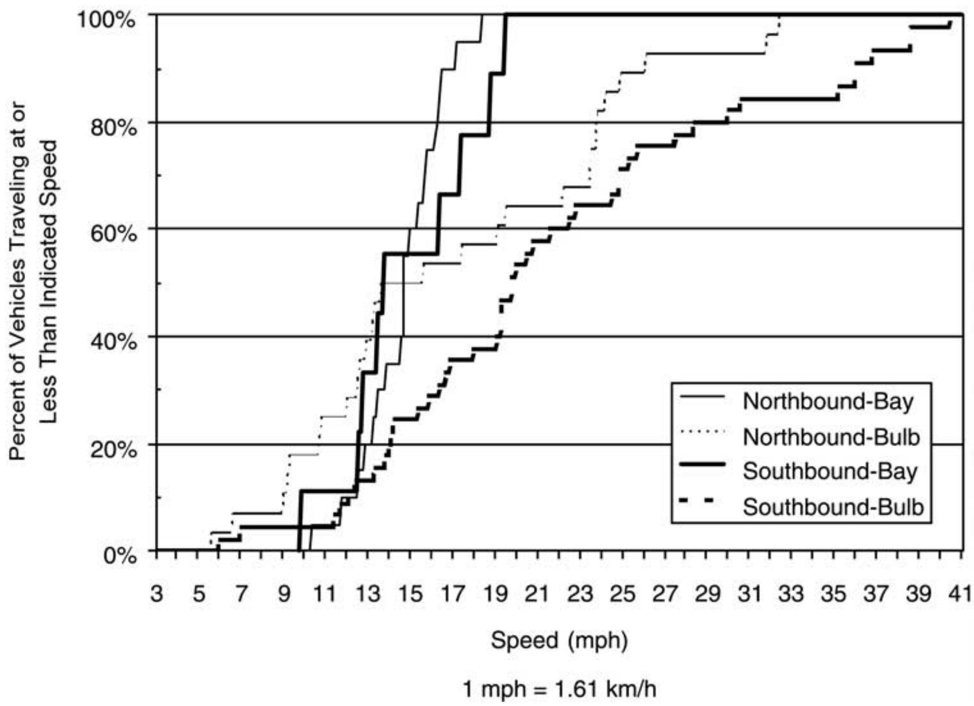


Figure C-13. Vehicle Travel Speeds in Corridor.

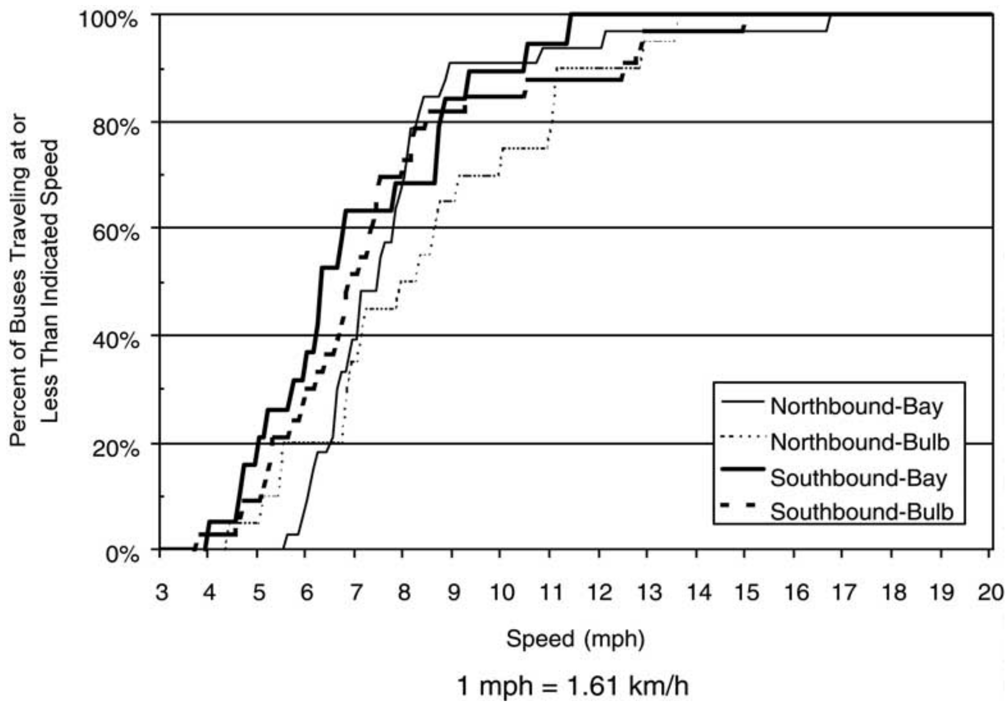


Figure C-14. Bus Speeds in Corridor.

(a) Bus Stop 3 with Bus Bay Design

Figure C-15. Examples of Vehicles Hindering Bus Operations.

(b) Bus Stop 5 with Bus Bay Design

Figure C-15. Examples of Vehicles Hindering Bus Operations (continued).

(c) Bus Stop Northbound on Mission St. at Precita Ave.

Figure C-15. Examples of Vehicles Hindering Bus Operations (continued).

Figure C-16. Bus Completely Stopped in Lane.

Figure C-17. Bus Partially Stopped in Lane.

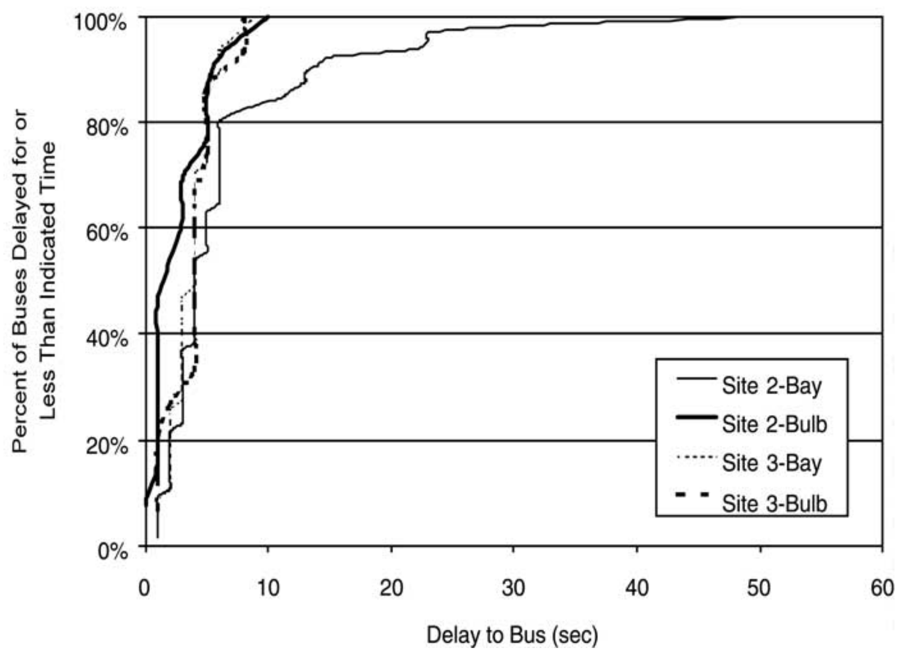


Figure C-18. Non-Peak Bus Delay.

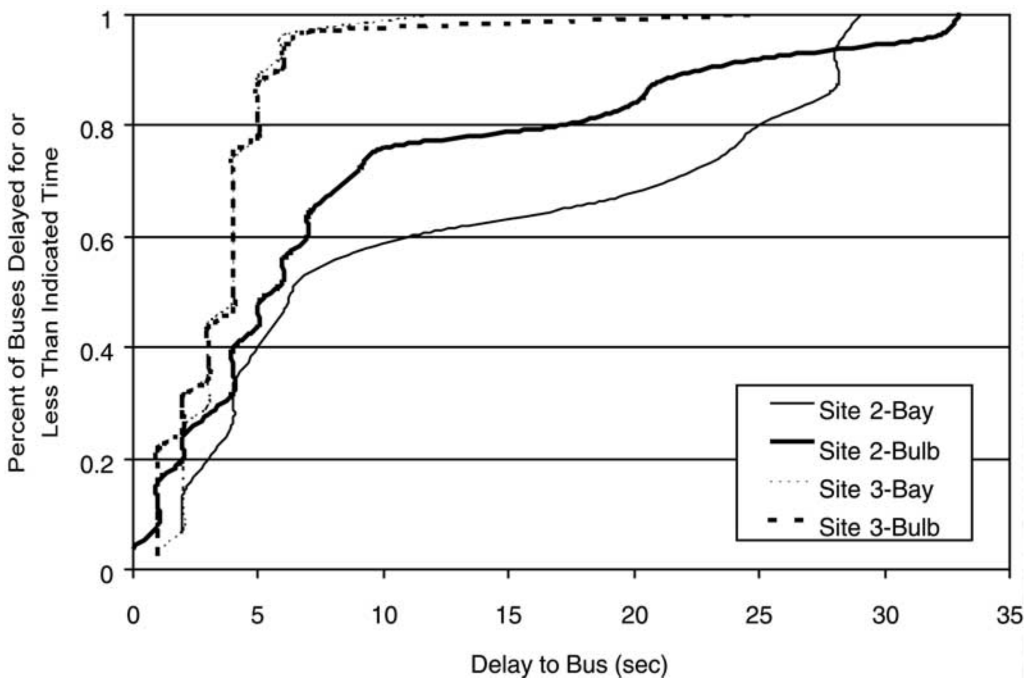


Figure C-19. Peak Bus Delay.

Table C-1. Description of Bus Stops Studied.

Site	Location Mission at	Direction	Bus Stop Location
1	Cortland Avenue	Southbound	Nearside
2	30th Street	Southbound	Nearside
3	30th Street	Northbound	Farside
4	29th Street	Northbound	Farside
5	29th Street	Southbound	Farside
6	Valencia Street	Northbound	Farside

Table C–2. Evening Peak Traffic Volumes.

Intersection	Time Period	Street	Entry Volume (vph)/ Percent Difference [a]	Turning Percentages		
				Left	Thru	Right
	Before	Mission-Northbound	606	--	80 %	20 %
	After	Mission-Northbound	650 (7 % +)	--	82 %	18 %
	Before	Mission-Southbound	779	16 %	84 %	--
	After	Mission-Southbound	796 (2 % +)	18 %	82 %	--
	Before	Cortland	268	46 %	--	54 %
Cortland	After	Cortland	271 (1 % +)	52 %	--	48 %
	Before	Mission-Northbound	617	10 %	89 %	1 %
	After	Mission-Northbound	768 (+ 20 %)	8 %	90 %	2 %
	Before	Mission-Southbound	859	1 %	90 %	9 %
30th/Eugenia [b]	After	Mission-Southbound	863 (0 %)	1 %	91 %	8 %
	Before	Mission-Northbound	550	6 %	94 %	--
	After	Mission-Northbound	630 (+13 %)	6 %	94%	--
	Before	Mission-Southbound	786	--	81 %	19 %
	After	Mission-Southbound	817 (+4 %)	--	73 %	27 %
	Before	29th	167	53 %	--	47 %
29th	After	29th	142 (-18 %)	49 %	--	51 %

[a] The percent difference is based on the after study (i.e., [after-before]/after). The "+" and "-" sign represents an increase or decrease, respectively.

[b] Eugenia is a one-way street in the eastbound direction; thus, there was no traffic entering the intersection via this road. The before traffic volumes on 30th could not be accurately counted because of the camera view; thus, there is no comparison of the traffic entering the intersection from 30th.

Table C-3. Speed on Block with Bus Stop.

Block	Stop Location	Period	Type	Measure	Bay	Bulb	Change in Speed
29th to Virginia (460 ft)	farside	Non peak	Vehicle	Average Speed (mph)	9.5	15.7	65 %*
				Observations	27	17	
			Bus	Average Speed (mph)	6.1	6.3	3 %
				Observations	27	9	
30th to Cortland (620 ft)	nearside	Peak	Vehicle	Average Speed (mph)	16.0	20.5	28 %
				Observations	13	65	
			Bus	Average Speed (mph)	5.3	6.2	17 %
				Observations	15	33	
29th to Virginia (460 ft)	farside	Peak	Vehicle	Average Speed (mph)	11.4	20.9	83 %*
				Observations	41	27	
			Bus	Average Speed (mph)	6.4	8.6	34 %
				Observations	22	13	

1 mph = 1.61 km/h, 1 ft = 0.305 m
Non-peak = between 9:00 am and 3:00 pm
Peak = after 3:00 pm
* Change in speeds from the bay to bulb condition was significantly different at alpha = 0.05

Table C-4. Speed for Corridor (Evening Peak).

Site	Type	Measure	Bay	Bulb	Change in Speed
NB Corridor	Vehicle	Average Time Average Speed Observations	114 sec 14.5 mph 21	116 sec 17.0 mph 29	17 %
	Bus	Average Time Average Speed Observations	219 sec 7.8 mph 33	212 sec 8.4 mph 20	8 %
SB Corridor	Vehicle	Average Time Average Speed Observations	114 sec 14.9 mph 9	89 sec 21.7 mph 45	46 %*
	Bus	Average Time Average Speed Observations	252 sec 7.0 mph 19	238 sec 7.5 mph 33	7 %

1 mph = 1.61 km/h
* Change in speeds from the bay to bulb condition was significantly different at alpha = 0.05

Table C-5. Driver Behavior Around the Stopped Buses at Sites 1, 4, 5, and 6.

Site [a]	Design	Number of Vehicles in Queue (Min to Max, Average)	Number of Bus Arrivals Observed	Traffic Queue [b]		Lane Changes [c]	
				Number [d]	Rate [e]	Number	Rate
NON-PEAK PERIOD							
3 FS	Bay	1 to 2, 1	70	4	1/17.5	97	1/0.7
	Bulb	1 to 3, 1	88	30	1/2.9	125	1/0.7
4 FS	Bay	0 to 1, 1	59	9	1/6.6	--	--
	Bulb	1 to 3, 1	117	24	1/4.9	--	--
5 FS	Bay	0 to 0, 0	25	0	0	14	1/1.8
	Bulb	1 to 3, 1	164	54	1/3.0	169	1/0.97
6 FS	Bay	1 to 2, 1	50	7	1/7.1	49	1/1.0
	Bulb	1 to 4, 1	100	22	1/4.5	123	1/0.8
PEAK PERIOD							
1 NS	Bay	2 to 6, 3	20	11	1/1.8	3	1/6.7
	Bulb	1 to 4, 2	18	8	1/2.3	11	1/1.6
3 FS	Bay	1 to 2, 1	56	7	1/8.0	106	1/0.5
	Bulb	1 to 4, 2	35	19	1/1.8	82	1/0.4
5 FS	Bay	1 to 2, 1	37	10	1/3.7	40	1/0.9
	Bulb	1 to 4, 1	32	13	1/2.5	42	1/0.8

Non-peak = 9:00 am to 3:00 pm, peak = after 3:00 pm
[a] NS=Nearside, FS=Farside
[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] Total number of driver behaviors for the number of bus arrivals observed
[e] Number of driver behaviors / number of bus arrivals
-- Signifies that the driver behavior was not measured

Table C-6. Bus Operational Characteristics of Sites 2 and 3.

Site [a]	Design	Bus Position		Dwell Time [b] (sec)			Delay to Bus [c] (sec)			Obser-vations
		Obser-vations	% Stopping in Lane	Min.	Max.	Avg.	Min.	Max.	Avg.	
NON-PEAK PERIOD										
2 NS	Bay	154	66	6	95	22	1	52	7	65
	Bulb	--	--	8	156	43	0	10	3	13
3 FS	Bay	83	66	4	55	18	1	9	4	47
	Bulb	--	--	9	196	28	1	8	4	15
PEAK PERIOD										
2 NS	Bay	95	62	8	32	17	2	29	13	15
	Bulb	--	--	7	101	33	0	33	9	25
3 FS	Bay	65	72	4	38	16	1	12	4	27
	Bulb	--	--	2	53	18	1	25	4	32

[a] NS=Nearside, FS=Farside

[b] Dwell time is the time from when the bus stops at the bus stop until the doors on the bus close

[c] Delay to bus is the time from when the doors on the bus close until the bus starts moving (i.e., departs)

-- Signifies that the operational characteristic was not measured

Table C-7. Bus Operational Characteristics of the Sites.

Site [a]	Design	Bus Position		Bus Stop Time [b] (sec)			
		Observations	% Stopping in Lane	Observations	Min.	Max.	Avg.
NON-PEAK PERIOD							
4 FS	Bay	59	63	57	6	39	17
	Bulb	--	--	113	3	50	19
5 FS	Bay	25	68	25	5	43	17
	Bulb	--	--	163	2	56	19
6 FS	Bay	50	48	50	8	44	19
	Bulb	--	--	100	7	52	22
PEAK PERIOD							
1 NS	Bay	20	70	19	14	40	23
	Bulb	--	--	18	8	43	21
5 FS	Bay	37	60	36	8	31	18
	Bulb	--	--	30	2	28	16

[a] NS=Nearside, FS=Farside
[b] Bus stop time is the time from when the bus arrives until the bus departs
[c] Signifies that the operational characteristic was not measured

APPENDIX D

COMPUTER SIMULATION

Traffic simulation programs have been used for many 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 as compared to collecting data in the field.

OBJECTIVE

Computer simulation was used to study the effects of bus stop design on traffic and bus operations. The two bus stop designs analyzed were bus bay and bus bulb. Farside and nearside locations were used in the simulation. The results from the computer simulation are intended to 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 part of the study, the following tasks were performed:

- Select a *traffic simulation program* to be used.
- Use *field data* to aid in the *development and calibration of model*.
- *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 a given bus stop location and traffic characteristics.

STUDY DESIGN

After selecting the simulation program, field data were used to calibrate the computer simulation model. The simulation program was then used to study traffic and bus operations under various traffic volumes and bus dwell times. The evaluation of the bus stop designs used two approaches: 1) effect on speeds within a *corridor* containing a series of bus stops and 2) performance at an *isolated intersection*.

Traffic Simulation Program

Traffic simulation programs have been used effectively for many operations-related traffic studies and research projects. These programs have been used to analyze the effects that a wide range of roadway, traffic, and bus characteristics have on the operations of a system. This extensive range of data is very difficult to collect in the field; however, it can be easily studied using computer simulation. NETSIM was selected as the traffic simulation program to be used for this study because of its national acceptance and its capability to allow the user to modify text files for multiple runs.

NETSIM is a software system that consists of several macroscopic and microscopic simulation programs that 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 TSIS package and is a microscopic model of urban street traffic. For NETSIM, each vehicle is a distinct object that 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 based on a random seed).

NETSIM can evaluate the effects of adding lanes or turn pockets, moving the location of a bus stop, or installing a new signal. Its objective is to evaluate the effect of traffic control on the system's operational performance, as expressed in terms of measures of effectiveness (MOEs), which include average vehicle speed, vehicle stops, delays, vehicle-hours of travel, vehicle miles of travel, fuel consumption, and pollution emissions. The MOEs provide insight into the effects of the applied strategy on the traffic stream, and they also provide the basis for optimizing that strategy.

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 that the bus follows as it travels through the network. The bus route is the sequence of bus stops that the bus services. The bus flow rate is the mean headway for buses that 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 (bus bulbs), respectively.

Field Data

Figure D–1 shows the corridor and bus stops included in the computer simulation. Field data from the six sites studied during the before field study were used to calibrate the traffic simulation model. Data at each site were collected with video cameras and laptop computers. The data collected with the laptop computers were used to determine the travel times and travel speeds of vehicles and buses. Traffic volumes including turning movements for four signalized intersections in the corridor (Cortland, 30th, Virginia, and 29th) were reduced manually from the videos for use in coding the network. The bus arrival and departure times were also reduced manually from the videos and were used to compute bus dwell times. A summary of the data collection and data reduction efforts is presented in Appendix C. A seventh bus stop (farside) at Mission St. and Valencia St. (southbound) was also included in the computer simulation. The traffic volumes and turning movements for this additional intersection were obtained from the city engineering office, and the bus dwell time was estimated. Signal timing information for the intersections was also obtained from the city engineering office and verified in the field.

Development and Calibration of Model

A NETSIM model was developed using the characteristics of the intersections in the corridor shown in Figure D–1. The hourly traffic volumes, turning movements, travel speeds, bus dwell times, and parking activity observed in the field were coded. Because outcome from NETSIM is stochastic, the output may not be the same for a given input. For this reason, each run was simulated for one hour with a bus arriving every five minutes. Therefore, for each run a total of 12 bus arrivals were included. Vehicle and bus travel times were averaged over the hour period and compared to the observations made in the field.

Table D–1 shows the comparison between field observations and output from the NETSIM model developed. The percent difference between the average vehicle and bus speeds measured in the field and those predicted by NETSIM was below 20 percent for both the northbound and southbound directions.

Several aspects of the simulation that might have affected the average speeds computed by NETSIM were identified. In NETSIM the average travel times are computed by link (i.e., intersection to intersection). However, when the research team collected travel times in the field, they were positioned at bus stops. This accounts for the difference (53 ft [16.2 m]) in the distances noted in Table D–1. As mentioned earlier, the traffic volumes and turning movements at the Mission St. and Valencia St. intersection were obtained from the city engineering office instead of being collected during the before field study. Also, the average bus dwell time at the farside bus stop in the southbound direction at this intersection was estimated. In the before field study (see Appendix C) it was noted that the majority of the buses completely or partially stopped in the outside lane instead of pulling into the bus bay. Thus, the travel times collected in the field were affected by this type of maneuver. However, NETSIM is only capable of having the buses stop in a bus bay or in the outside lane (i.e., bus bulb) during a run, not both in the same run.

To further calibrate NETSIM, the graphical interface was used to compare vehicle and bus operations on the corridor and around the bus stop area to the field observations. Maneuvers observed from NETSIM that were compared to field observations included vehicles changing lanes to avoid vehicles that were parking, buses entering the bus stop, and buses re-entering the traffic stream after completing a stop.

Performing the Simulation

The two bus stop designs studied were bus bay and bus bulb. NETSIM was used to compare the two bus stop designs at both farside and nearside locations. This was accomplished by performing multiple simulation runs on the corridor (which included farside and nearside locations) and on two isolated intersections (one with farside locations and one with nearside locations).

Schematics of the isolated intersection models used to study bus bay and bus bulb designs for both farside and nearside locations are shown in Figures D–2 and D–3, respectively. The models consisted of a single signalized intersection with four approaches. The main street approach consisted of two through lanes in each direction. The bus stop under investigation was located on a main street approach either at the farside or at the nearside of the intersection. 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 the range of traffic volumes studied.
Specific inputs required by NETSIM included speed, traffic volumes, turning percentages, bus headways, bus dwell times, and signal timings. To perform the simulations, variables to be adjusted and their increment size were selected. Tables D–2 and D–3 contain the variables that were altered during the simulation process for the corridor and isolated intersections, respectively. The variables adjusted included main street entry volume (400 to 2000 vph) and bus dwell time (20 to 60 sec). Again, because outcome from NETSIM is stochastic, each run was simulated for one hour with a bus arriving every five minutes. Therefore, a total of 12 bus arrivals was included for each run.

Data Reduction and Analysis

After each simulation run, the necessary data were retrieved from the NETSIM output and graphical interface. The data retrieved included vehicle and bus speeds, the number of vehicles in the outside lane that pass by a stopped bus (bus bay design only), and the number of vehicles in the outside lane that are delayed by a stopped bus (bus bulb design only).

Average vehicle and bus speeds are computed by NETSIM for each movement (right, through, left) on each link. For the corridor study, the through movement average speed for vehicles and buses on each link in the corridor were averaged to determine an overall average speed for vehicles and buses along the corridor. This overall average speed was then used to evaluate the corridor data. For the isolated intersection studies, the through movement average speed for vehicles and buses on the link that contained the bus stop (farside or nearside) was used in the evaluation. In the analysis of the data, the average speeds for the bus bay designs were compared to the average speeds for the bus bulb designs for the range of volumes and dwell times studied.

The number of vehicles in the outside lane that passed by a stopped bus (bus bay design only) and the number of vehicles in the outside lane that were delayed by a stopped bus (bus bulb design only) were determined manually using the graphical interface. Since each simulation run contained 12 buses, the average number of vehicles in the outside lane that passed by a stopped bus or that was delayed by a stopped bus were used in the analysis.

RESULTS

The calibrated NETSIM models for bus bay and bus bulb designs were run for the combinations of traffic volumes and bus dwell times shown in Tables D–2 and D–3. The following sections of this report contain a discussion of the results from the bus bay versus bus bulb study.

Corridor

Figure D–4 is a screen capture of the corridor graphical interface. The intent of the corridor computer simulation was to evaluate the effect of bus stop design (i.e., bus bay and bus bulb) on traffic and bus operations (i.e., vehicle and bus speeds) within a corridor. The variables adjusted included main street entry volume (400 to 1000 vph) and bus dwell time (20 to 60 sec). The maximum main street entry volume was determined to be 1000 vph, since volumes higher than 1000 vph caused the corridor to become too congested to collect accurate data (see Figure D–5).

Northbound Corridor

The northbound direction (from Cortland Ave. to Precita Ave.) contained three farside bus stops and six signalized intersections (see Figure D–1). Table D–4 contains the average speed of the vehicles and buses for the bus bay and bus bulb designs for the associated main street entry volumes and dwell times.

The average vehicle speeds within the corridor for both designs range from 12 to 17 mph (19.3 to 27.3 km/h). In general, the average vehicle speeds decrease as the main street entry volume increases for a given dwell time, as was expected. The dwell time did not have an effect (≤1 mph [≤ 1.6 km/h]) on the average vehicle speed for main street entry volumes at and below 800 vph; however, for both designs the dwell time did have an influence (>1 mph [> 1.6 km/h]) on the average vehicle speed above 800 vph.

Figure D–6 shows the difference in the average vehicle speeds for the bus bay and bus bulb designs (i.e., average vehicle speed for bus bay design minus average vehicle speed for bus bulb design). For a 20 sec dwell time, the difference in the average vehicle speed is relatively constant at and below 900 vph (less than a 1 mph [1.6 km/h] difference). However, at 1000 vph the difference in the average vehicle speed decreases (≥-2 mph [≥-3.2 km/h]); thus, the average vehicle speed for the bus bay design (11.9 mph [19.2 km/h]) is lower than the average vehicle speed for the bus bulb design (14.1 mph [22.7 km/h]). For the 40 and 60 sec dwell times, the difference in the average vehicle speed remains relatively constant (less than a 1 mph [1.6 km/h] difference) over all of the main street entry volumes. Overall, the data indicate that the bus bulb design does not negatively affect the traffic operations (i.e., vehicle speed) compared to the bus bay design.

The average bus speeds within the corridor for both designs range from 6 to 12 mph (9.7 to 19.3 km/h) (see Table D–4). In general, the average bus speeds decrease as the main street entry volume increases for a given dwell time, as was expected. For both bus stop designs, dwell time did have an influence on the average bus speed over the range of main street entry volumes. This was also anticipated since an increase in dwell time increases the travel time of the bus along the corridor; which in turn decreases the average bus speed through the corridor.
Figure D–7 shows the difference in the average bus speeds for the bus bay and bus bulb designs (i.e., average bus speed for bus bay design minus average bus speed for bus bulb design). For the 20 sec dwell time, the difference in the average bus speed at 500 and 1000 vph is greater than 1 and 2 mph (1.6 and 3.2 km/h), respectively. Thus, the average bus speeds for the bus bay design (10.4 and 8.0 mph [16.7 and 12.9 km/h] , respectively) are lower than the average bus speeds for the bus bulb design (11.9 and 10.1 mph [19.2 and 16.3 km/h], respectively). The difference in the average bus speed for the 60 second dwell time at 1000 vph was also greater than 2 mph (3.2 km/h), with the average bus speed for the bus bay design (6.5 mph [10.5 km/h]) being less than the average bus speed for the bus bulb design (8.6 mph [13.9 km/h]). For the 40 second dwell

time, the difference in the average bus speed is relatively constant (less than a 1 mph [1.6 km/h] difference) over all of the main street entry volumes. Overall, these results reveal that the bus bulb design may provide the greatest benefit to bus operations at higher volumes (> 900 vph).

Southbound Corridor

The southbound direction (from Precita Ave. to Cortland Ave.) contained two farside bus stops, two nearside bus stops, and six signalized intersections (see Figure D–1). Table D–5 contains the average speed of the vehicles and buses for the bus bay and bus bulb designs by main street entry volumes and dwell times.

The average vehicle speeds within the corridor ranged from 14 to 18 mph (22.5 to 29 km/h). In general, the average vehicle speeds increase from 400 to 600 vph and then decrease from 600 to 1000 vph for a given dwell time. For both designs, the dwell time did not have an effect (≤ 1 mph [≤ 1.6 km/h]) on the average vehicle speed for main street entry volumes below 900 vph; however, at 900 vph for the bus bulb design and at 1000 vph for the bus bay design the dwell time did have an influence (>1 mph [> 1.6 km/h]) on the average vehicle speed.

Figure D–8 shows the difference in the average vehicle speeds for the bus bay and bus bulb designs (i.e., average vehicle speed for bus bay design minus average vehicle speed for bus bulb design). In almost all cases, the difference in vehicle speed between the two designs was less than 1 mph (> 1.6 km/h). The data indicate that only at higher volumes may the bus stop design affect vehicle speed (more than 1 mph [1.6 km/h] difference).

The average bus speeds within the corridor for both designs range from 7 to 11 mph (11.3 to 17.7 km/h) (see Table D–5). In general, the average bus speeds remain relatively constant as the main street entry volume increases for a given dwell time. For both designs, as the dwell time increased the average bus speed decreased, as was expected. This result occurred over all main street entry volumes.

Figure D–9 shows the difference in the average bus speeds for the bus bay and bus bulb designs (i.e., average bus speed for bus bay design minus average bus speed for bus bulb design). For all of the dwell times, the difference in the average bus speed is relatively constant (less than 1 mph [1.6 km/h] difference) for all of the main street entry volumes. Overall, these results reveal that there is no difference between the bus bay and bus bulb designs with respect to bus operating speed within the corridor.

Comparison of NETSIM and Field Results

To determine how well NETSIM was simulating the actual conditions in the corridor, the simulation results were compared with the data collected in the field for each of the bus stop designs. Based on the traffic volumes and dwell times observed in the before-and-after field studies, it was determined that the comparison should be for 600 vph with a 20 sec dwell time. Table D–6 contains the average vehicle and bus speeds in both directions collected in the field during peak periods and computed using simulation for the bus bay and bus bulb designs. For both the before-and-after data (i.e., bay and bulb) in the northbound direction the difference between the simulation results and the field results is less than 3 mph (4.8 km/h), while in the southbound direction the difference was less than 4 mph (6.4 km/h).

The field results indicate that the installation of the bus bulbs notably improves the travel speed for vehicles and slightly improves the travel speed for buses. Appendix C provides additional information on these findings. The computer simulation program, however, did not show such improvements in travel speeds. The addition of subroutines within NETSIM to evaluate buses were added to the program in recent years. The findings from this comparison indicate that the subroutines may not be sensitive enough to the nuances of how the bus stop design affect operations. Therefore, the design of the bus stop may have greater impact on travel speed than found in the computer simulation study.

Isolated Intersections

The objective of the computer simulation was to develop recommendations that could aid in the selection of a preferred bus stop design (bus bay or bus bulb) for a given bus stop location (farside and nearside). Thus, in addition to the corridor study, simulation was used to study the operations around an isolated intersection. This approach allowed for the counting of the number of vehicles in the outside lane that passed by a stopped bus (bus bay design only) and the number of vehicles in the outside lane that are delayed by a stopped bus (bus bulb design only).

Farside Location

The variables adjusted included main street entry volume (1000 to 1700 vph) and dwell time (20 to 60 sec). The maximum main street entry volume was determined to be 1700 vph, since volumes higher than 1700 vph caused the intersection to become too congested to collect accurate data. Table D–7 contains the average speed of the vehicles and buses for the bus bay and bus bulb designs and the associated main street entry volumes and dwell times.

The average vehicle speeds on the link that contained the bus stop for both designs ranged from 24 to 26 mph (38.6 to 49.9 km/h). In general, the average vehicle speeds remain relatively constant as the main street entry volume increases for a given dwell time. For the bus bay design, the dwell time did not have an effect (≤ 1mph [≤ 1.6 km/h]) on the average vehicle speed; however, for the bus bulb design as the dwell time increased, the vehicle speed decreased (> 1 mph [> 1.6 km/h]). This result was expected because with the bus bulb design the bus stops in a lane of traffic. Thus, the longer the bus is stopped the more effect it has on traffic.

Figure D–10 shows the difference in the average vehicle speeds for the bus bay and bus bulb designs (i.e., average vehicle speed for bus bay design minus average vehicle speed for bus bulb design). For the 20 and 40 sec dwell times, the difference in the average vehicle speed is relatively constant (less than a 1 mph [1.6 km/h] difference) over all of the main street entry volumes. For the 60 sec dwell time, the difference in the average vehicle speed is also relatively constant, but at a slightly higher difference than the shorter dwell times. This was expected due to the longer stopping time for the bus in the lane of traffic, which affects (i.e., decreases) the speed of the vehicles. Thus, the data indicate that at higher volumes and larger dwell times the bus bulb design on the farside of the intersection may have greater effects on traffic operations (i.e., decrease vehicle speeds) as compared to the bus bay design at the same location.

To further study the effects of the bus stop design on traffic operations, the average number of vehicles in the outside lane that pass a stopped bus (bus bay design only) and the average number of vehicles in the outside lane that are delayed by a stopped bus (bus bulb design only) were graphed with respect to the main street entry volume (see Figure D–11). In general, both factors increased as the main street entry volume increased, as was expected. However, the average number of vehicles that are delayed by a stopped bus is consistently lower than the average number of vehicles that pass a stopped bus for a given dwell time. The average number of vehicles delayed by a stopped bus ranged from 2 to 14, with a majority of the averages ranging from 2 to 6. The average number of vehicles that pass a stopped bus ranged from 6 to 16.

The average bus speeds within the corridor for both designs ranged from 4 to 10 mph (6.4 to 16.1 km/h). In general, the average bus speeds remain relatively constant as the main street entry volume increases for a given dwell time. For both bus stop designs, dwell time did have an influence on the average bus speed over all of the main street entry volumes, as was expected. The trend was for the average bus speed to decrease as the dwell time increased.

Figure D–12 shows the difference in the average bus speeds for the bus bay and bus bulb designs (i.e., average bus speed for bus bay design minus average bus speed for bus bulb design). For all of the dwell times, the difference in the average bus speed is relatively constant (less than a 1 mph [1.6 km/h] difference) over all of the main street entry volumes. Overall, these results reveal that there is no difference between the bus bay and bus bulb designs with respect to bus operations when the bus stop is located on the farside of the intersection.

Nearside Location

The operations at a bus stop sited on the nearside location of an intersection were also studied. The variables adjusted included main street entry volume (1000 to 1600 vph) and dwell time (20 to 60 sec). The maximum main street entry volume was determined to be 1600 vph, since volumes higher than 1600 vph caused the intersection to become too congested to collect accurate data. Table D–8 contains the average speed of the vehicles and buses for the bus bay and bus bulb designs and the associated main street entry volumes and dwell times.

The average vehicle speeds on the link that contained the bus stop for both designs range from 10 to 21 mph (16.1 to 33.8 km/h). In general, the average vehicle speeds decrease as the main street entry volumes increase for a given dwell time, as was expected. For the bus bay design, the dwell time did not have an effect (≤ 1mph [≤ 1.6 km/h]) on the average vehicle speed for main street entry volumes at and below 1300 vph. However, at 1400 and 1500 vph the difference in the average vehicle speed was greater than 1 mph (1.6 km/h).

For the bus bulb design, as the dwell time increased, the vehicle speed decreased (> 1 mph [> 1.6 km/h]) over all the main street entry volumes. This result was expected because with the bus bulb design the bus stops in a lane of traffic and has a greater effect on traffic. The greatest effect in average vehicle speed occurs at 1500 vph where the 20 sec dwell time average vehicle speed (17.4 mph [28 km/h]) is approximately 7 mph (11.3 km/h) higher than the 60 sec dwell time average vehicle speed (10.2 mph [16.4 km/h]).

Figure D–13 shows the difference in the average vehicle speeds for the bus bay and bus bulb designs (i.e., average vehicle speed for bus bay design minus average vehicle speed for bus bulb design). For all of the dwell times, the trend is for the difference in the average vehicle speed to increase as the main street entry volume increases. This increase in the difference in the average vehicle speed is greatest for the 60 second dwell time. Overall, these results reveal that for a nearside location the bus bay design provides the greater benefit to traffic operations.

As with the farside data, to further study the effects of the bus stop design on traffic operations, the average number of vehicles in the outside lane that pass a stopped bus (bus bay design only) and the average number of vehicles in the outside lane that are delayed by a stopped bus (bus bulb design only) were graphed with respect to the main street entry volume (see Figure D–14). In general, both factors increased as the main street entry volume increased, as was expected. However, the average number of vehicles that are delayed by a stopped bus is consistently lower than the average number of vehicles that pass a stopped bus for a given dwell time. The average number of vehicles delayed by a stopped bus ranged from two to nine, while the average number of vehicles that pass a stopped bus ranged from three to 13.

The average bus speeds for both designs range from 5 to 10 mph (8.1 to 16.1 km/h) (see Table D–8) and for the 20 sec dwell time, the average bus speeds decrease as the main street entry volumes increase. This decrease in average bus speed also occurs for the bus bulb design with a 40 sec dwell time. In contrast, the average bus speeds for a dwell time of 40 sec for the bus bay design and 60 sec for both designs remain constant as the main street entry volumes increase. For both designs, as the dwell time increased the average bus speed decreased, as was expected. This trend occurred over all of the main street entry volumes.

Figure D–15 shows the difference in the average bus speeds for the bus bay and bus bulb designs (i.e., average bus speed for bus bay design minus average bus speed for bus bulb design). For the 20 sec dwell time, the difference in the average bus speed is relatively constant (less than a 1 mph [1.6 km/h] difference) at and below 1200 vph; however, at 1300 vph the average bus speed for the bus bulb design (9.1 mph [14.7 km/h]) is greater than the average bus speed for the bus bay design (7.7 mph [12.4 km/h]). In contrast, at and above 1400 vph the trend is for the bus bay design to result in better bus operations (i.e., higher average bus speeds). For example, at 1600 vph the average bus speed for the bus bay design (8.4 mph [13.5 km/h]) is greater than the average bus speed for the bus bulb design (6.5 mph [10.5 km/h]).

For a 40 sec dwell time, the difference in the average bus speed is relatively constant over all of the main street entry volumes except at 1600 vph. At 1600 vph, the difference in the average bus speed increases; thus, the average bus speed for the bus bay design (6.5 mph [10.5 km/h]) is higher than the average bus speed for the bus bulb design (4.9 mph [7.9 km/h]). The average bus speeds for the 60 sec dwell time remained relatively constant (less than a 1 mph [1.6 km/h] difference) over all of the main street entry volumes. Overall, the data indicate that only at very high volumes and the smaller dwell times will the bus bay design provide slightly greater benefit with respect to bus operations when the bus stop is located on the nearside of the intersection.

CONCLUSIONS

The conclusions made for the corridor and isolated intersections are presented below.

Corridor

The intent of the computer simulation for the corridor was to evaluate the effect bus stop design has on traffic and bus operations for a series of intersections that closely represent a real-world environment. A corridor in San Francisco was used as a base for the study. Both farside and nearside locations and bus bays and bus bulbs were used in the simulation. Variables varied during the computer simulation included traffic volume and bus dwell time. Vehicle and bus speeds were the factors evaluated.

The computer simulation runs showed that at lower volumes (≤ 900 vph) there is no practical difference between the bus bay and bus bulb designs with respect to traffic operations. However, at higher traffic volumes (> 900 vph) a difference between the two designs was found. For smaller dwell times (i.e., 20 sec), the bus bulb design had a 1 to 2 mph (1.6 to 3.2 km/h) speed advantage for vehicles, while for larger dwell times (i.e., ≥ 40 sec), there was no practical difference (near or less than a 1 mph [1.6 km/h] difference) between the two designs.

The northbound bus data showed that the bus bulb design may provide a benefit over the bus bay design with respect to bus operations during higher volumes (above 900 vph). However, since traffic volumes higher than 1000 vph caused the corridor to become too congested to collect accurate data, higher volumes could not be studied to verify the potential benefit. Also, the southbound bus data revealed that there was no difference between the bus bay and bus bulb designs with respect to bus operations. Therefore, the computer simulation runs indicate that the two designs have minimal effect on bus speeds within a corridor.

The simulation results (600 vph and 20 sec dwell time) were compared with the data collected in the field during the peak period to determine how well NETSIM was simulating the actual conditions in the corridor. The field results indicate that the installation of the bus bulbs notably improves the travel speed for vehicles and slightly improves the travel speed for buses. The findings from this comparison indicate that NETSIM may not be sensitive enough to the nuances of how the bus stop design affects operations. Therefore, the design of the bus stop may have greater impact on travel speed than found in the computer simulation study.

Isolated Intersections

The objective of the computer simulation for the isolated intersections was to develop recommendations that could aid in the selection of a preferred bus stop design for a single bus stop location. Bus stop designs analyzed included bus bay and bus bulb at both farside and nearside locations. Variables varied during the computer simulation included traffic volume and bus dwell time. Vehicle and bus speeds, the number of vehicles in the outside lane that passed by a stopped bus (bus bay design only), and the number of vehicles in the outside lane that are delayed by a stopped bus (bus bulb design only) were the factors investigated.

Farside stop

Based on the vehicle and bus speed data, it was determined that there is no practical difference between the bus bay and bus bulb designs when the bus stop is located on the farside of the intersection. The difference in speed was near or less than 1 mph (1.6 km/h) for all combinations.

Nearside stop

Based on the traffic data, it was determined that the bus bay design provides a benefit over the bus bulb design with respect to traffic operations at higher volumes (above 1000 vph) regardless of the dwell time when the bus stop was located on the nearside of the intersection. The advantages in average vehicle speed of a bus bay design compared to a bus bulb design ranged from approximately 1 to 8 mph (1.6 to 12.9 km/h). However, as with the farside data, the average number of vehicles that are delayed by a stopped bus (i.e., bus bulb design) was consistently lower than the average number of vehicles that passed by a stopped bus (i.e., bus bay design) for a given dwell time.

Based on the bus data, it was concluded that only at very high volumes is there a potential difference between the two designs when the bus stop is located on the nearside of the intersection. For most combinations of main street volumes and dwell times, the difference in average bus speed was less than 1 mph (1.6 km/h). The bus bay design had a 1 to 2 mph (1.6 to 3.2 km/h) speed advantage for buses with volumes greater than 1500 vph and a 20 sec dwell time.

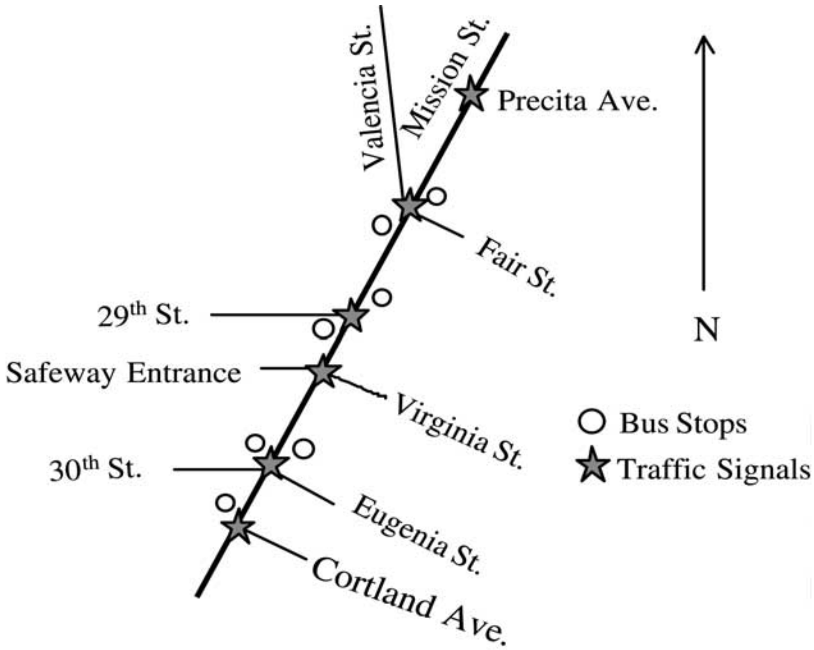
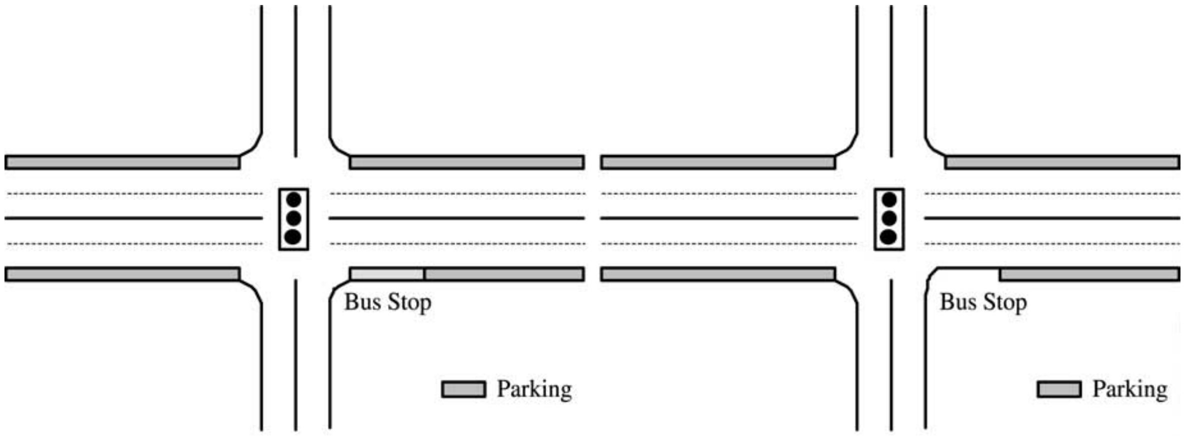
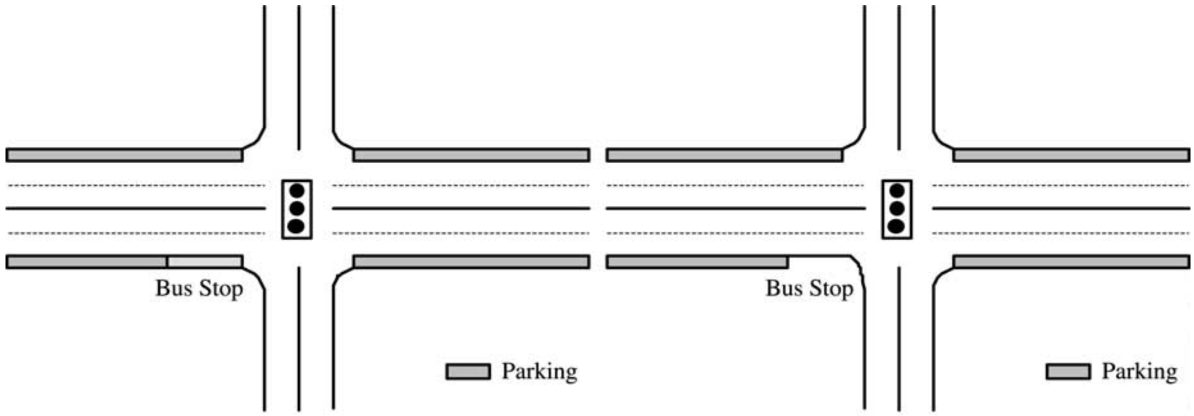


Figure D-1. Corridor and bus Stops Included In the Computer Simulation.



(a) Farside, Bus Bay **(b) Farside, Bus Bulb**

Figure D-2. Farside Bus Stop



(a) Nearside, Bus Bay **(b) Nearside, Bus Bulb**

Figure D-3. Nearside bus Stop Designs.

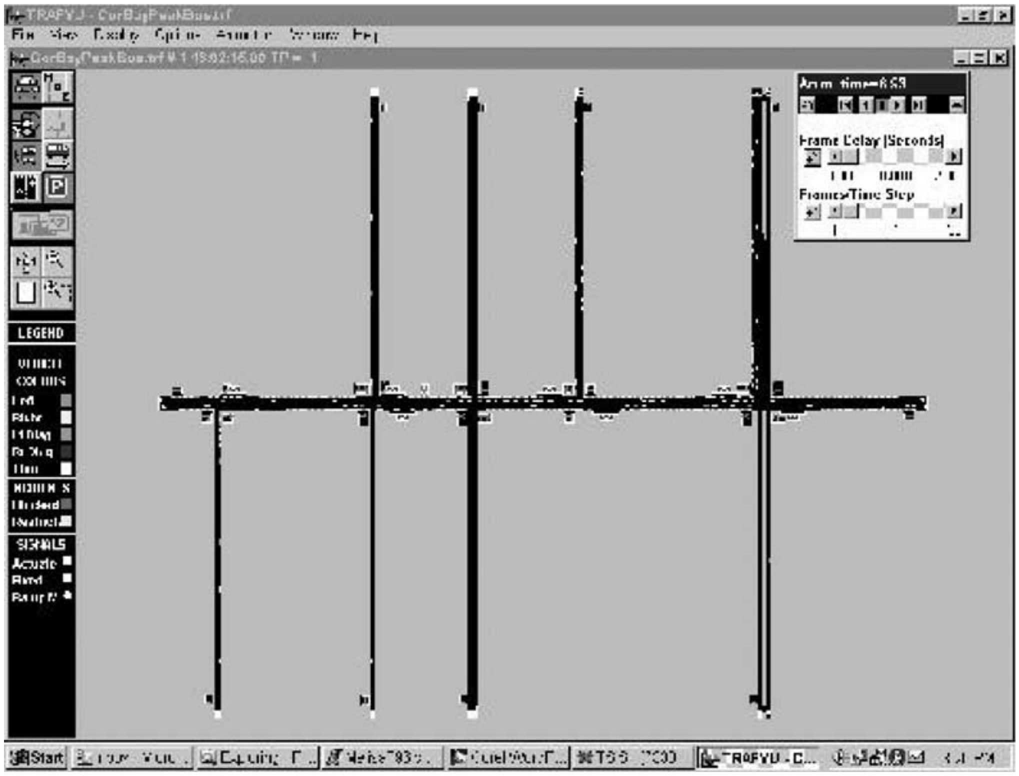


Figure D-4. Corridor Graphical Interface.

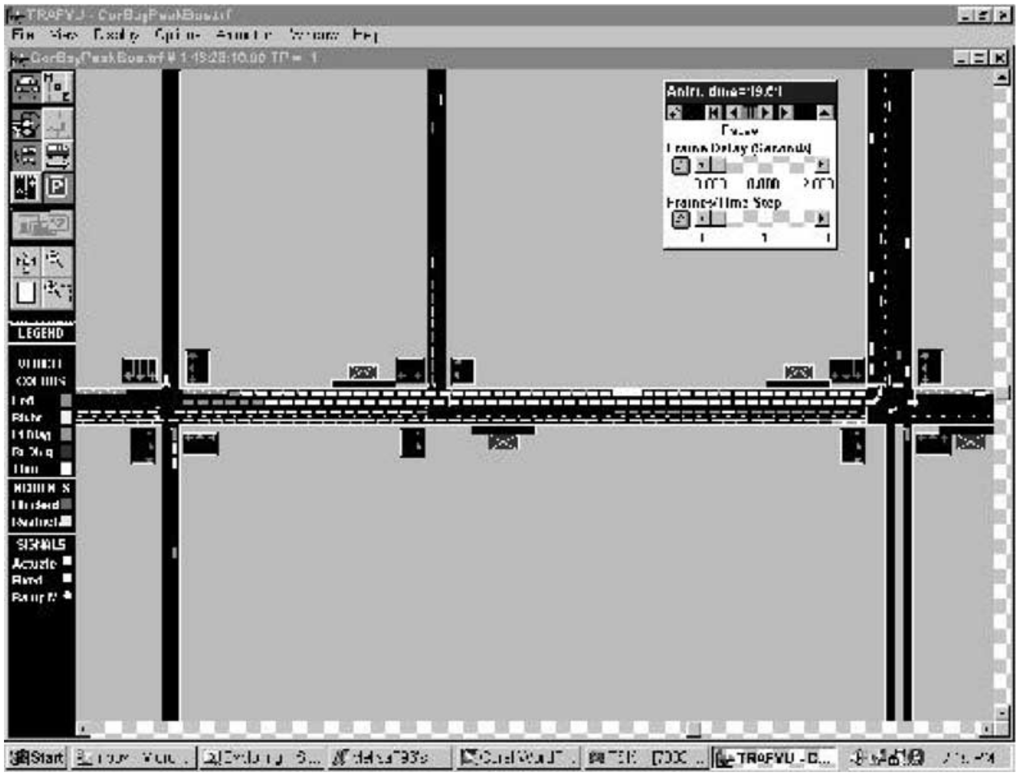
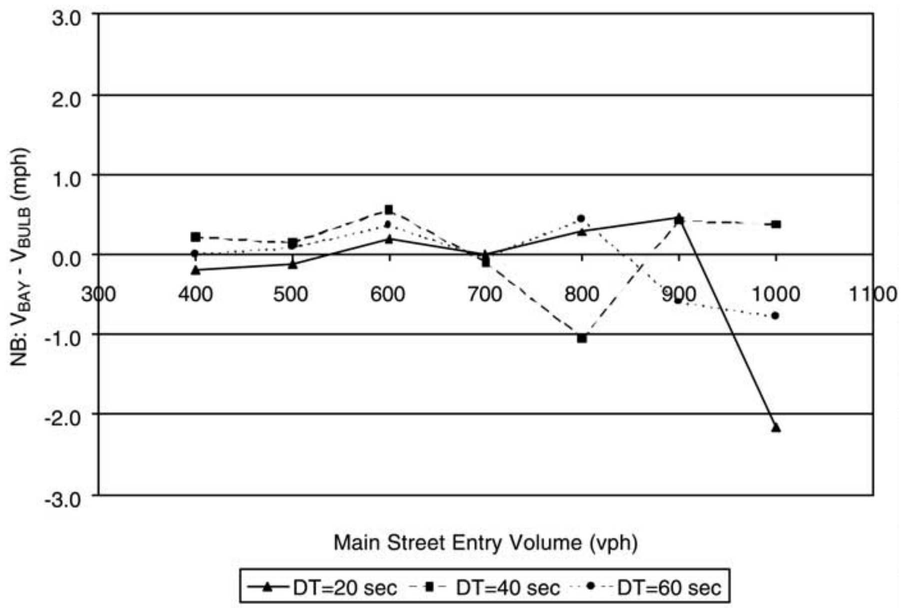


Figure D-5. NETSIM Graphical Interface at 1100 vph.



1 mi = 1.61 km/h

Figure D-6. Northbound Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design.

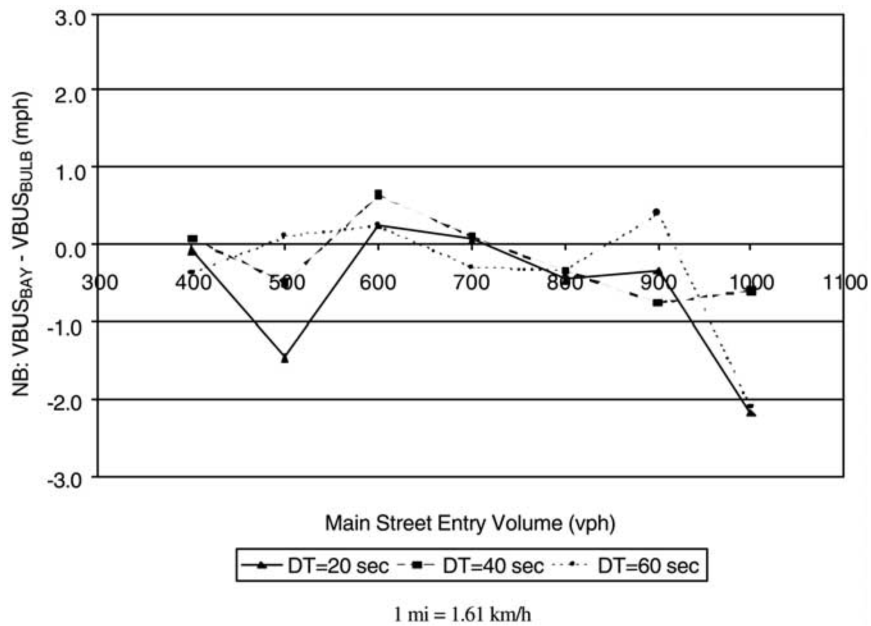
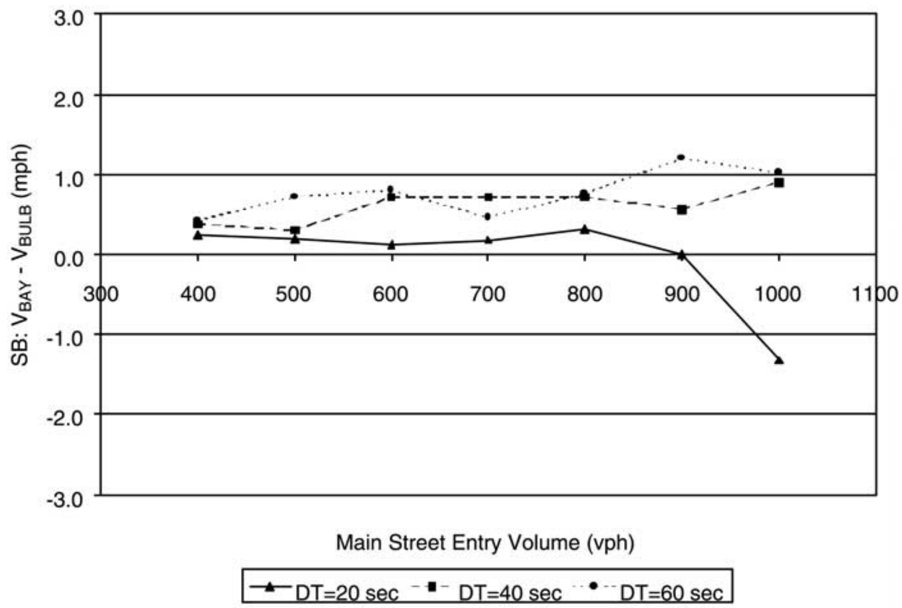
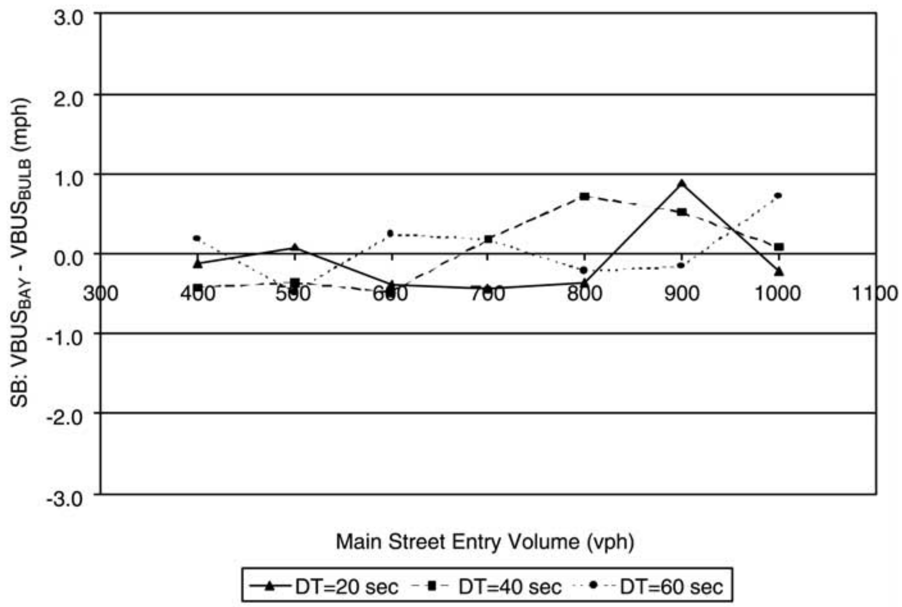


Figure D-7. Northbound Average Bus Speed Difference Design Between Bus Bay and Bus Bulb.



1 mi = 1.61 km/h

Figure D-8. Southbound Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design.



1 mi = 1.61 km/h

Figure D-9. Southbound Average Bus Speed Difference Between Bus Bay and Bus Bulb Design.

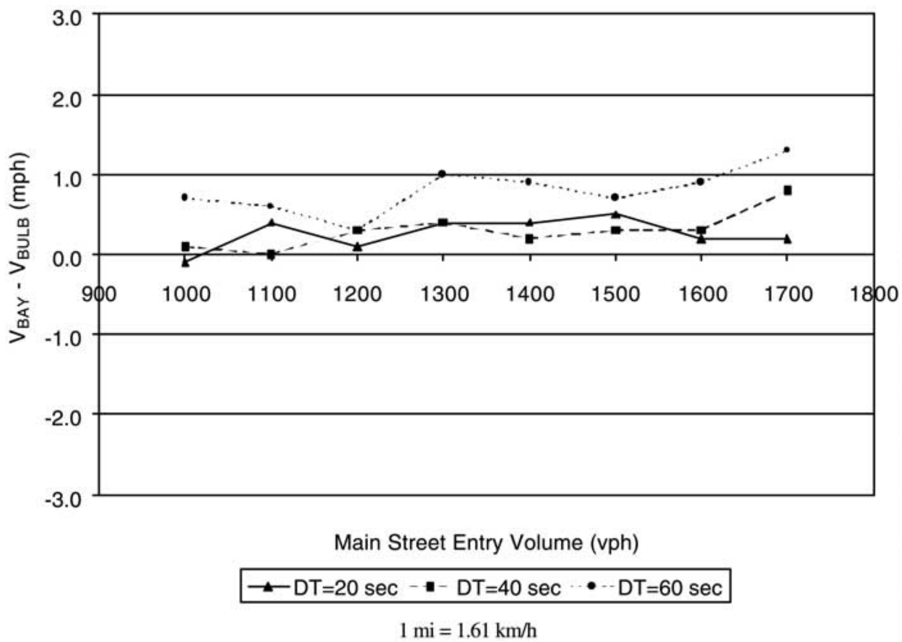


Figure D-10. Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design for a Farside Location.

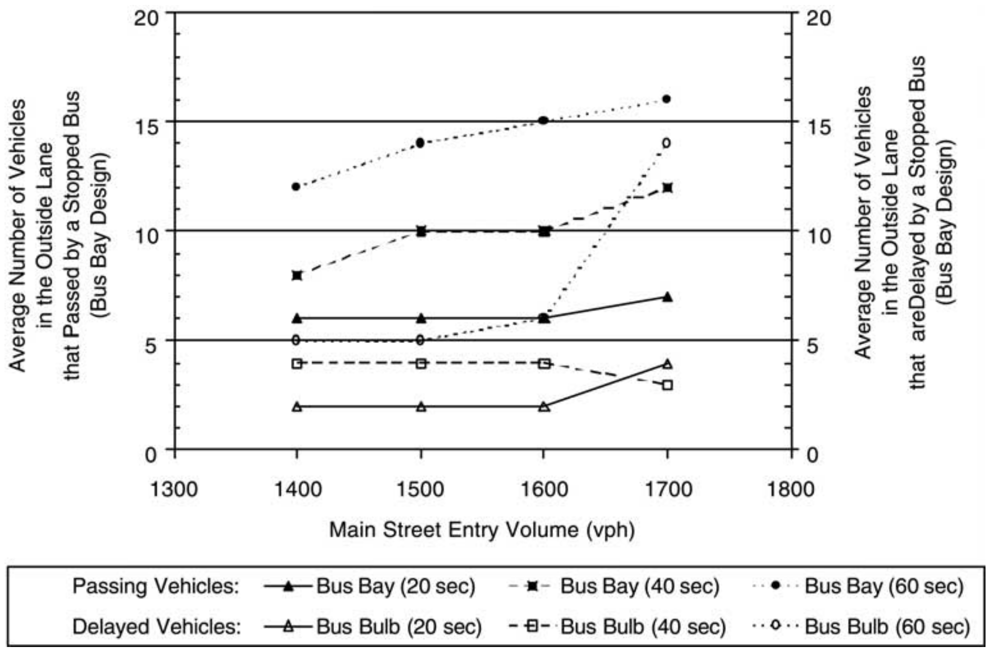


Figure D-11. Relationship Between the Average Number of Vehicles that Passed by a Stopped Bus and the Average Number of Vehicles that Are Delayed by a Stopped Bus for a Farside Location.

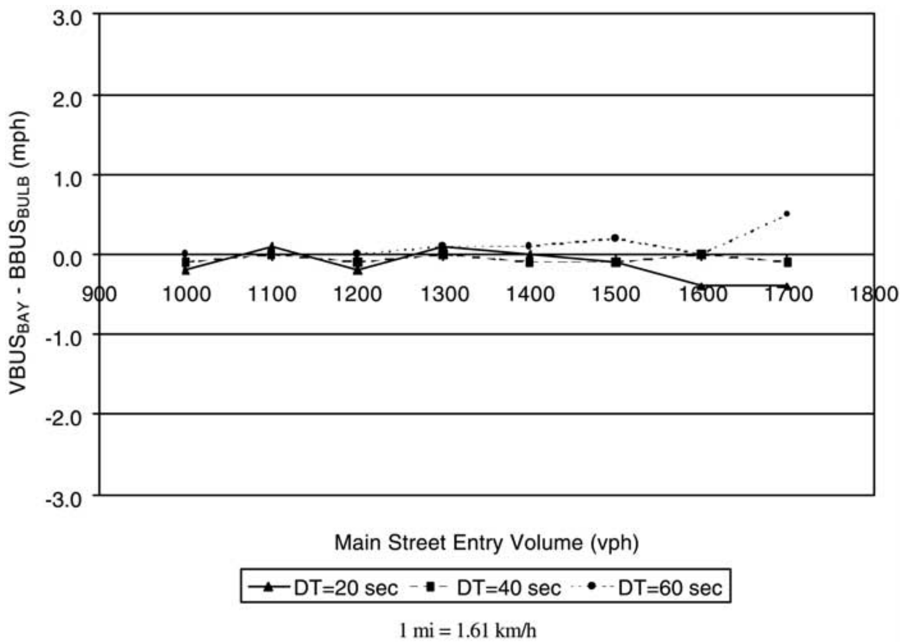


Figure D-12. Average Bus Speed Difference Between Bus Bay and Bus Bulb Design For a Farside Location.

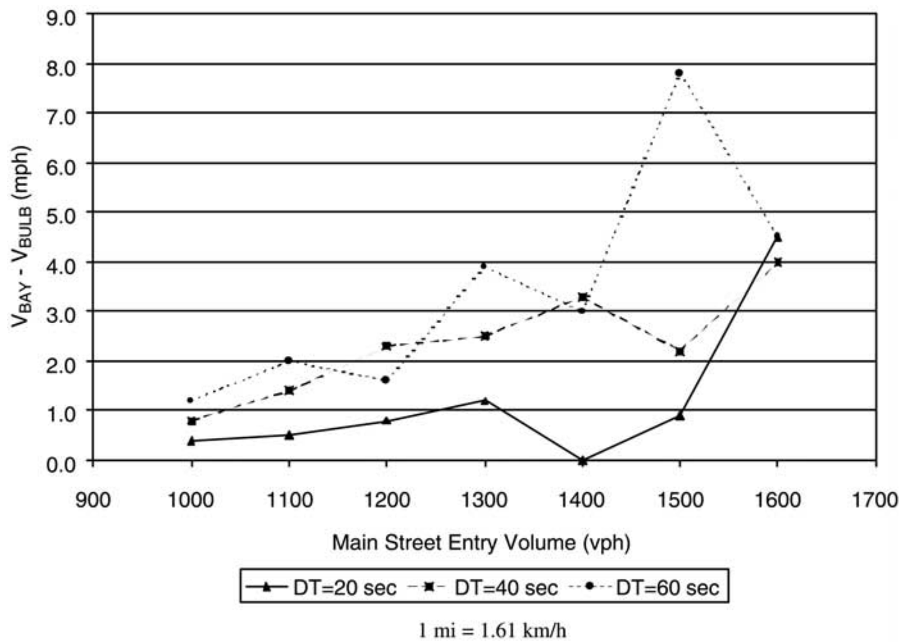


Figure D-13. Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design for a Nearside Location.

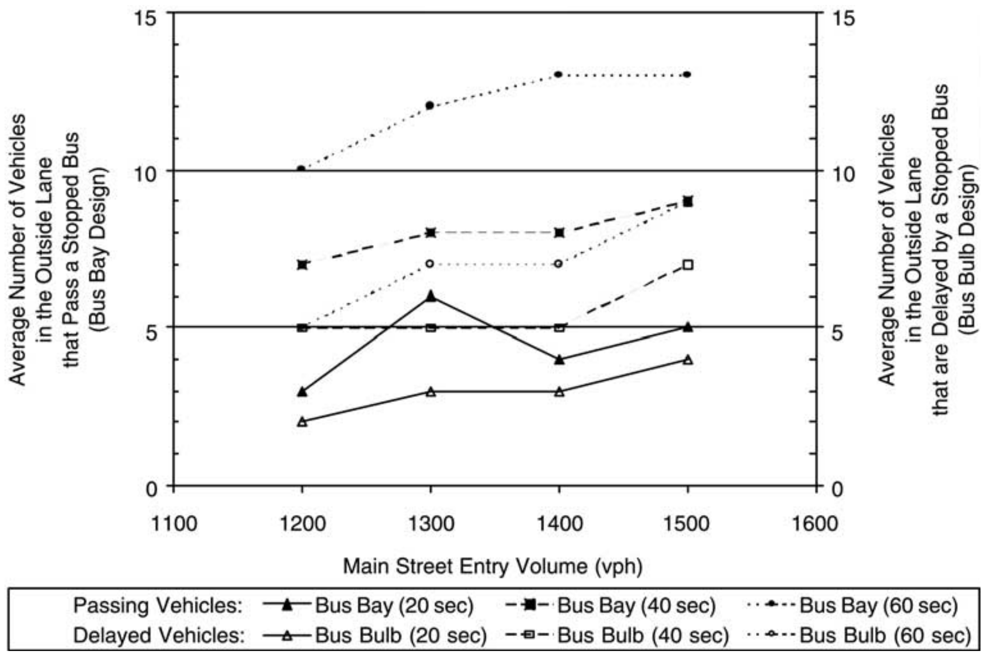


Figure D-14. Relationship Between the Average Number of Vehicles that Pass a Stopped Bus and the Average Number of Vehicles that Are Delayed by a Stopped Bus for a Nearside Location.

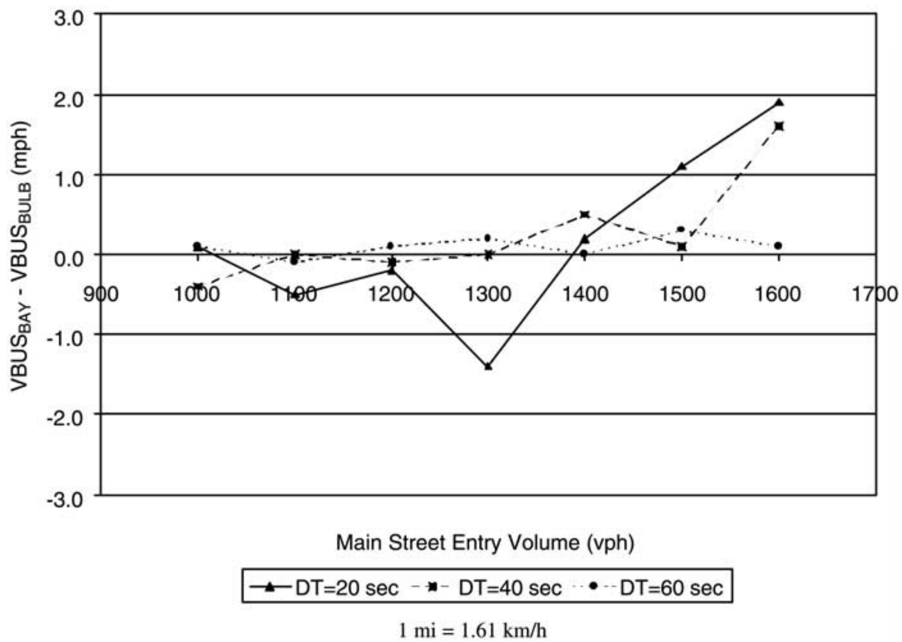


Figure D-15. Average Bus Speed Difference Between Bus Bay and Bus Bulb Design for a Nearside Location.

Table D-1. Comparison of Field Data to NETSIM Output.

Type	Site	Average Speed (mph)		Percent Difference
		Field (2380 ft) [726 m]	NETSIM (2327 ft) [710 m]	
Vehicle	Northbound on Mission St. from Cortland Ave. to Precita St.	14.2	12.4	13 %
Bus	Northbound on Mission St. from Cortland Ave. to Precita St.	7.4	8.1	10 %
Vehicle	Southbound on Mission St. from Precita St. to Cortland Ave.	14.2	11.7	18 %
Bus	Southbound on Mission St. from Precita St. to Cortland Ave.	6.4	7.0	9 %

Table D-2. NETSIM Model Variables for the Corridor.

Variables	Values
Desired Speed	30 mph (48.3 km/h)
Main Street Entry Volumes	400, 500, 600, 700, 800, 900, 1000 vph
Main Street Turning Percentages	Determined from before field data
Cross Street Entry Volumes	Determined from before field data (% of Main)
Cross Street Turning Percentages	Determined from before field data
Bus Headway	5 min
Bus Dwell Time	20, 40, 60 sec
Time of Day (Related to Main St. Entry Vol.)	Non-peak and Peak
Location of Stop	Mixed (Farside and Nearside)

Table D-3. NETSIM Model Variables for the Isolated Intersections.

Variables	Values
Desired Speed	30 mph (48.3 km/h)
Main Street Entry Volumes	1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, vph
Main Street Turning Percentages: Left Through Right	 10 % 80 % 10 %
Cross Street Entry Volume	30 % of Main (vph)
Cross Street Turning Percentages: Left Through Right	 20 % 60 % 20 %
Bus Headway	5 min
Bus Dwell Time	20, 40, 60 sec
Time of Day (Related to Main St. Entry Vol.)	Peak
Location of Stop	Farside and Nearside

Table D-4. Comparison of Northbound Average Vehicle and Bus Speeds for Bus Bay and Bus Bulb Designs.

Main Street Entry Volume (vph)	Dwell Time (sec)	Average Vehicle Speed (mph)		Average Bus Speed (mph)	
		Bus Bay	Bus Bulb	Bus Bay	Bus Bulb
400	20	17.0	17.2	12.1	12.2
	40	16.8	16.5	11.3	11.2
	60	16.3	16.3	10.0	10.3
500	20	16.6	16.7	10.4	11.9
	40	16.7	16.6	10.1	10.6
	60	16.5	16.4	9.8	9.7
600	20	17.0	16.8	10.6	10.4
	40	16.8	16.3	10.2	9.5
	60	16.4	16.0	9.8	9.6
700	20	16.5	16.5	10.8	10.8
	40	16.4	16.5	10.4	10.3
	60	16.1	16.2	9.6	9.9
800	20	16.3	16.1	9.7	10.1
	40	14.9	16.0	9.2	9.6
	60	15.8	15.4	9.2	9.6
900	20	13.6	13.2	8.5	8.8
	40	15.1	14.7	8.3	9.0
	60	13.9	14.5	8.1	7.7
1000	20	11.9	14.1	8.0	10.1
	40	13.8	13.4	8.4	9.0
	60	11.8	12.6	6.5	8.6
1 mi = 1.61 km/h					

Table D-5. Comparison of Southbound Average Vehicle and Bus Speeds for Bus Bay and Bus Bulb Designs.

Main Street Entry Volume (vph)	Dwell Time (sec)	Average Vehicle Speed (mph)		Average Bus Speed (mph)	
		Bus Bay	Bus Bulb	Bus Bay	Bus Bulb
400	20	16.4	16.2	9.5	9.6
	40	16.1	15.8	7.8	8.2
	60	15.7	15.3	6.9	6.8
500	20	15.8	15.6	9.9	9.8
	40	15.6	15.3	8.3	8.7
	60	15.3	14.6	7.1	7.6
600	20	17.9	17.8	10.4	10.8
	40	18.1	17.4	8.4	8.8
	60	17.7	16.9	8.2	8.0
700	20	17.3	17.1	10.3	10.7
	40	17.4	16.7	8.8	8.7
	60	16.9	16.5	8.0	7.8
800	20	16.6	16.3	10.0	10.3
	40	16.4	15.7	8.8	8.0
	60	16.2	15.5	7.2	7.4
900	20	16.1	16.1	10.5	9.6
	40	16.2	15.6	7.8	7.3
	60	16.0	14.8	7.0	7.2
1000	20	13.8	15.2	9.7	9.9
	40	15.6	14.7	8.5	8.4
	60	15.3	14.3	8.1	7.3
1 mi = 1.61 km/h					

Table D-6. Comparison of NETSIM and Field Results.

Direction	Bus Stop Design	Method	Average Vehicle Speed (mph)	Average Bus Sped (mph)
Northbound	Bay	Field	14.5	7.8
		NETSIM	17.0	10.6
	Bulb	Field	17.0	8.4
		NETSIM	16.8	10.4
Southbound	Bay	Field	14.9	7.0
		NETSIM	17.9	10.4
	Bulb	Field	21.7	7.5
		NETSIM	17.8	10.8
1 mi = 1.61 km/h				

Table D-7. Comparison of Farside Average Vehicle and Bus Speeds for Bus Bay and Bus Bulb Designs.

Main Street Entry Volume (vph)	Dwell Time (sec)	Average Vehicle Speed (mph)		Average Bus Speed (mph)	
		Bus Bay	Bus Bulb	Bus Bay	Bus Bulb
1000	20	26.1	26.2	9.3	9.5
	40	25.8	25.7	6.4	6.5
	60	25.6	24.9	4.9	4.9
1100	20	26.2	25.8	9.3	9.2
	40	25.8	25.8	6.4	6.4
	60	25.6	25.0	4.8	4.8
1200	20	26.3	26.2	9.4	9.6
	40	26.0	25.7	6.4	6.5
	60	25.4	25.1	4.9	4.9
1300	20	26.3	25.9	9.3	9.2
	40	25.8	25.4	6.4	6.4
	60	25.4	24.4	4.8	4.7
1400	20	26.1	25.7	9.4	9.4
	40	25.7	25.5	6.4	6.5
	60	25.5	24.6	4.9	4.8
1500	20	26.1	25.6	9.2	9.3
	40	25.7	25.4	6.4	6.5
	60	25.2	24.5	4.9	4.7
1600	20	25.9	25.7	9.1	9.5
	40	25.5	25.2	6.4	6.4
	60	25.3	24.4	4.9	4.9
1700	20	25.8	25.6	8.8	9.2
	40	25.8	25.0	6.4	6.5
	60	25.4	24.1	4.9	4.4

1 mi = 1.61 km/h

Table D-8. Comparison of Nearside Average Vehicle and Bus Speeds for Bus Bay and Bus Bulb Designs.

Main Street Entry Volume (vph)	Dwell Time (sec)	Average Vehicle Speed (mph)		Average Bus Speed (mph)	
		Bus Bay	Bus Bulb	Bus Bay	Bus Bulb
1000	20 40 60	21.1 20.9 20.5	20.7 20.1 19.3	10.2 6.6 5.0	10.1 7.0 4.9
1100	20 40 60	20.3 20.4 19.9	19.8 19.0 17.9	9.4 6.7 5.0	9.9 6.7 5.1
1200	20 40 60	19.7 19.7 19.5	18.9 17.4 17.9	9.4 6.4 5.0	9.6 6.5 4.9
1300	20 40 60	18.6 19.2 18.8	17.4 16.7 14.9	7.7 6.1 5.0	9.1 6.1 4.8
1400	20 40 60	17.2 19.0 17.2	17.2 15.7 14.2	9.2 6.8 5.0	9.0 6.3 5.0
1500	20 40 60	19.3 17.3 18.0	17.4 15.1 10.2	9.3 6.2 4.9	8.2 6.1 4.6
1600	20 40 60	14.1 14.4 15.0	9.6 10.4 10.5	8.4 6.5 4.7	6.5 4.9 4.6
1 mi = 1.61 km/h					