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An Evaluation of Bus Bulbs on Transit, Traffic, and Pedestrian Operations

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ABSTRACT

Bus bulbs are a section of sidewalk that extends from the curb of a parking lane to the edge of the through lane. A major advantage of using bus bulbs is the creation of additional space at a bus stop for shelters, benches, and other bus patron improvements when the inclusion of these amenities would otherwise be limited without the additional space. The primary motivators for installing bus bulbs are to reduce congestion on sidewalks and to eliminate the bus-weaving maneuver into a bus bay stop. Bus bulbs are appropriate at sites with high patron volumes along crowded city sidewalks and where parking along the curb is permitted. An evaluation of pedestrian operations found that the average amount of available space for pedestrians and transit patrons improved after the bulb had been constructed. Vehicle and bus speeds also increased on the block and in the corridor. The average delay to buses attempting to re-enter the travel stream was constant from the before to 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 bulb.

The executive summary and body of the contractor's final report, along with Appendix A, has been published separately as *TCRP Report 65,* "Evaluation of Bus Bulbs."

APPENDIX B

CURBSIDE BEFORE-AND-AFTER STUDY

Transit activities can place great demands on sidewalks that are already crowded with pedestrians, street furniture, store front displays and/or transit shelters. Bus stop areas can become instantly undersized with the intermittent surges created by boarding and alighting activities. Therefore, bus stops become unintended bottlenecks or points of congestion on crowded urban sidewalks. With the typical arrangement of a bus stop on a sidewalk, there is limited space to segregate transit activities (e.g., boarding and alighting, waiting patrons) from normal pedestrian movement on the sidewalk. Bus bulbs appear to be the most logical strategy for improving pedestrian congestion in narrow or small areas. By extending the curb toward the outside travel lane through an on-street parking area, transit agencies can provide a defined waiting area for bus patrons away from the flow of pedestrian traffic on the sidewalk and can store amenities, such as bus shelters, off of the sidewalk altogether. The benefits, on the surface, appear to be rather obvious.

STUDY DESIGN

A total of nine bus stops were converted from bus bays to bus bulbs during the summer of 1999 along south Mission Street between Cesar Chavez and Cortland Avenue. The bus bulbs were a part of a greater street reconstruction project. San Francisco MUNI used the reconstruction project as an opportunity to extend the curbs from the sidewalk through the parking lane and directly adjacent to the outside travel lane. The newly created space provided much needed storage area for waiting bus patrons off and away from the busy sidewalks. The road reconstruction project created an opportunity to compare pedestrian operations in and around a bus stop zone between a bus bay and a bus bulb. Bus bay stops are a very common design configuration in San Francisco. In this configuration, a section of a parking lane is marked for buses servicing a particular stop. Bus bulbs exist when the sidewalk is extended into the parking lane to the edge of the travel lane. The major objectives of the pedestrian field studies were to:

- determine if the space available per pedestrian increases with the construction of the bus bulb, thereby improving walking speeds, reducing conflict points, and increasing storage area for waiting patrons;
- determine if the effective walkway width of the sidewalk improves with the addition of the bus bulb;
- determine if the corner operates at a higher level of service (LOS) with the additional room created by the bus bulb; and
- determine boarding and alighting characteristics on the available sidewalk space.

The before data collection trip when the bus bay configuration was present occurred in February 1999, and the after data collection trip when the bus bulb configuration was present took place in November 1999.

NEIGHBORHOOD CHARACTERISTICS

South Mission Street is an extension of the Mission District (South of Cesar Chavez/Army Street). The Mission District is a multi-cultural residential and shopping district in San Francisco. The community has evolved into an Hispanic center within the city. The area is characterized by three to five story buildings that contain street-level stores and single-room apartments/hotels or residential spaces above. Figure B–1 is a picture of south Mission Street looking towards downtown San Francisco. Note the dense urban pattern that is characteristic of the neighborhood.

Because of the residential density and shopping opportunities in the district, the sidewalks can become extremely congested with pedestrians. During the week, the highest pedestrian volumes along Mission Street coincide with the release of children from local schools. The period begins in the mid-afternoon with the release of elementary and middle school children and ends after the release of high school students later in the afternoon. However, the greatest demand occurs on Saturday mornings when residents do weekly errands in the neighborhood stores. It is not uncommon to see sidewalks completely saturated with pedestrians carrying multiple shopping bags on mid-afternoons and on Saturday mornings. There is no morning pedestrian peak period to note since neighborhood stores do not generally open before 10 o'clock in the morning.

In addition to the normal local pedestrian movement, the bus stops along Mission Street can cause tremendous surges of additional people onto the sidewalk. Bus stops can, in effect, become bottlenecks to pedestrian flow along the sidewalks in the Mission District. Transit ridership numbers along Mission Street are the highest west of the Mississippi. Six routes either serve all or part of the study corridor (14, 14L, 49, 67, 26, and Sam Trans). In fact, the Mission @ 20th Street location has the highest boardings in the city.

The boarding and alighting activities can cause bottlenecks when patrons form queues that block sidewalks. The mingling of boarding and alighting passengers with pedestrian movement on the sidewalk can cause temporary and intermittent points of congestion in and around the bus stops. Waiting patrons can also serve to restrict the flow of pedestrian movement along sidewalks. Along crowded settings such as the bus stops in San Francisco, waiting patrons choose to either stand along the edge of the curb or wait against storefronts. This type of behavior tends to restrict or funnel pedestrians into increasingly limited space at bus stops. This is especially true during peak periods when bus patronage is at its highest, and pedestrian flow is at its greatest. The surges of alighting passengers can also place great demands on the capacity of street corners and crosswalks. Crossing delays may incur by the large amount of pedestrians that are suddenly placed at the crosswalks.

The existing sidewalk width is further limited by the presence of street furniture (e.g., light poles, street signs, parking meters, and benches) and store front displays. Displays in front of stores are a common characteristic of the Mission District shopping culture. The presence of bus stop amenities, such as a bus shelter, also removes available sidewalk space for normal pedestrian operations.

Consequently, the justification for additional sidewalk space is clearly evident. However, the city cannot widen the sidewalk along the entire length of the road because the sidewalk is bounded by buildings on one side and curbside parking on the other. The existence of parking spaces in front of the store is believed to be critical for the health of the businesses. Since the bus stops represent the highest level of pedestrian bottlenecks along Mission Street and curbside parking is not permitted in the bus stop zone, the bus stops are the most logical location to extend or widen the sidewalk. The inclusion of a bus bulb will, hypothetically, create additional storage space for waiting bus patrons, increase the available sidewalk width for pedestrians, segregate bus boarding and alighting activities from sidewalk flow, create the necessary space for bus stop amenities (e.g., bus shelters), and reduce the exposure time of pedestrians crossing the intersection.

STUDY SITE CHARACTERISTICS

Only one of the bus stops along Mission Street has sufficient pedestrian activity for a pedestrian study—the southbound approach at the intersection of Mission Street and 30th Street. The site is a nearside stop with a bus shelter for waiting patrons. This site was chosen because it has the highest pedestrian and boarding and alighting volumes of any of the sites on South Mission Street where bus bulbs are being constructed. The high pedestrian and bus patronage volumes were confirmed by officials at MUNI and by observations made during the data collection trips. The high pedestrian volumes are created by a Safeway grocery store and Walgreens pharmacy directly adjacent to the bus stop zone, a variety of restaurants and retail establishments in close proximity to the bus stop, and the high volume of children that ride the bus to and from school. Further adding to the pedestrian traffic at the site is the location of another bus stop on 30th Street, which serves as a transfer point from the Mission Street bus routes onto the Divisadero bus route. Another parallel bus route is available on San Jose Street, which is in close proximity of Mission Street.

Figures B–2 and B–3 show the configuration/layout of the entire intersection prior to and after the construction of a bus bulb. An interesting feature to this site is the position of the Safeway driveway relative to the bus stop. The bus stop zone actually extends beyond the upstream entrance to the driveway at this site. Presumably, this is to prevent parking near the bus stop zone. The proximity of the driveway actually reduces the length of the bus stop zone. When multiple buses arrive at the bus stop (bunching), only two buses can actually board and alight passengers directly from the curb and this is with quite a bit of maneuvering on behalf of the bus drivers. The zone extension was maintained even after the construction of the bus bulb. The bulb reduced the crossing distance of Mission Street but did not significantly impact the distance across 30th Street. A curb extension into 30th Street was probably infeasible because of the acute angle that 30th Street has with Mission Street. Additional parking was not removed for the purposes of constructing the bulbs.

Figures B–4 and B–5 are detailed dimensioned drawings of the area immediately adjacent to the bus shelter for both the bus bay and bus bulb configurations. The bus shelter is present in both bus stop configurations, however the placement was slightly changed when the bulb was constructed. The bus shelter was moved slightly downstream on the bulb but away from the Walgreens storefront and placed closer to the edge of the curb in the bulb. The location of the streetlight and transit supervisor storage bin did not change. Therefore, the distance between the edge of the shelter and these existing features is reduced in the bus bulb configuration. The trash receptacle was moved to the upstream side of the bus shelter, presumably to increase the space between the bus shelter and the street light. This area between the bus shelter and the streetlight is where a majority of the boarding and alighting activities occur. Consequently, it needs to be free of any unnecessary features in order to provide unencumbered movement through this space.

Figure B–6 is a photograph of the Mission @ 30th Street bus bay taken during the before trip, and Figure B–7 shows the resulting space created by the bus bulb during the after trip. The pictures were taken from a similar position in order to illustrate the increased sidewalk area for pedestrians.

DATA COLLECTION/REDUCTION

The pedestrian studies focused on the southbound side of Mission Street at the intersection of 30th Street where a nearside bus stop is located. Additional bus arrival/departure information was collected on the northbound, farside stop. To study the pedestrian and transit operations around this particular bus stop in an urban area, data were collected on multiple days both prior to and after construction of the bus bulb.

Pedestrian data were primarily collected using palmtop computers with programs specifically created for the project. The palmtop computers were used to collect pedestrian and bus arrival and departure information. The TransLINK Data Collection unit of the Texas Transportation Institute developed the programs using Visual Basic software for use on the palmtop computers. The palmtop computers run on a Windows CE operating system that is compatible with Windows 95 or greater operating systems. The palmtops have a stylus and touch-screen as well as a mini-keyboard for manually entering text and/or numbers. Figure B–8 provides an example of the palmtop screen utilized during the bus arrival/departure data collection effort.

Table B–1 highlights the specific information that was identified as being required for the data collection effort. For each task, there are specific fixed data that remain the same for the entire data collection session, information pertinent to each individual record, and additional fields. The output of the programs is a comma-delimited text file that can be easily imported into a spreadsheet, and subsequently analyzed.

The data collection efforts were greatly enhanced with the introduction of the palmtop computers. For example, data were entered directly into a computer with an automatic time stamp for each observation. The data are then easily disaggregated into time segments to account for the presence of the bus at the bus stop. The effects of the bus arrival/departure sequence were captured in far greater detail then would have otherwise been possible without the palmtop computers. For pedestrian studies, it is critical to capture the intermittent surges of boarding and alighting passengers from the bus to determine the impact of this activity on sidewalk operations.

Still photographs were taken with a digital camera and standard lens camera to capture general attributes of the site as well as any notable events (e.g., cars parked in bus stop zone, articulated buses not fully in the bus stop zone, etc.) that may have occurred. The photographs, when appropriate, were also used to document pedestrian behavior in and around the bus stop zone (e.g., common waiting areas, boarding and alighting activities, and points of congestion).

For the analysis of pedestrian operations at the street corner, video cameras were used to capture peak-hour pedestrian movements at the northwest corner of the intersection of Mission Street and 30th Street. Two weekday afternoon peak periods were videotaped for approximately two hours each during both the before and after data collection trips. During the after data collection trip, video cameras were placed in identical locations in an effort to capture similar information.

Since the corner study needed signal cycle information, signal timing data were also collected during the before and after study trips. Signal timings were checked using stop watches, and detailed drawings were made of the sidewalk area adjacent to the bus stop zone at Mission Street and 30th Street.

PEDESTRIAN SPACE STUDY

A significant indicator of change for the benefit of pedestrians and transit patrons is available pedestrian space. Available space is determined by measuring the space per pedestrian or square feet per pedestrian in a defined area. Space utilized per pedestrian is the inverse of pedestrian density and is typically used since density has fractional values (pedestrians per square foot). Pedestrians adapt to the path of least resistance and greatest comfort, whether it is in motion (e.g., walking through the bus stop zone) or standing still (e.g., waiting for the next available bus). Similar to vehicular movement, as the available space is reduced and the density increases, pedestrian flow and comfort decreases. In this manner, pedestrian space can be quantified in Levels-of-Service by using readily developed criteria.

Significant studies of pedestrian flow indicate that as the space available per pedestrian decreases to a range of 5 to 9 sq ft (0.5 to 0.8 sq m) per pedestrian, the capacity of the sidewalk or area is attained. [1,2] Any available space with a value of 4 sq ft (0.4 sq m) per pedestrian or less causes significant interruptions to pedestrian movement and in some cases, movement ceases to exist. In fact, some literature suggests that available space between the 5 to 9 sq ft (0.5 to 0.8 sq m) range causes significant intrusion into the natural “buffer” zone that unfamiliar pedestrians will create between them and other strangers. [3] Studies into the relationship between pedestrian speed and space show thresholds at 6, 15, and 40 sq ft (0.6, 1.4, and 3.7 sq m) per pedestrian. [1,2] Similar to the 5 to 9 sq ft (0.5 to 0.8 sq m) per pedestrian range noted above, it appears that in some cases at 6 sq ft (0.6 sq m) per pedestrian, the maximum capacity of a sidewalk to handle uninterrupted movement of pedestrians is attained. At 15 sq ft (1.4 sq m) per pedestrian, slow walkers are forced to change their pace in order to adjust for pedestrian congestion. The fastest pedestrian can reach a comfortable speed at 40 sq ft (3.7 sq m) per pedestrian. Observations made from photographic studies indicate that free flow is not truly achieved until the space available per pedestrian is at least 100 sq ft (9.3 sq m). [4] Unchallenged movement is not attained until a pedestrian encounters a space that provides at least 130 sq ft (12.1 sq m) per pedestrian.

Another important consideration at bus stops is the ability to cross streams of traffic. This type of behavior commonly occurs at the point where buses board and alight. The ability to cross bi-directional traffic has been studied and similar threshold values have been developed. For example, at 15 sq ft (1.4 sq m) per pedestrian, almost all crossing movements are negatively impacted by pedestrian crowding. [(3)] Additional research by anthropologists indicates that pedestrians that are in an unfamiliar setting with strangers would prefer a spacing of at least 12 ft (3.7 m), which would be unrealistic at a crowded bus bay stop. [(4)] The values noted above may appear to be rather large, but as stated above, pedestrians, especially in strange settings with unfamiliar people, will naturally try to provide the greatest level of separation unless they are with friends or family. People that travel through a space on a regular basis will also gravitate to the same paths. Bus stops provide a unique setting for studying the change in available space. Bus stops, at times, are practically devoid of waiting patrons, while at other times, they experience tremendous surges of alighting patrons and have large groups of people waiting to board, either in informal congregations or slightly developed queues. Therefore, it is important to quantify the relationship of available pedestrian space between a bus bay and a bus bulb in order to definitively define the true value of a bus bulb versus a bus bay.

Data Collection Methodology

Using the palmtop computers and a program written specifically for this task, measurements were taken of the number of people in a specified area for the following three time intervals:

- one minute prior to a bus arriving in the bus stop zone (*prior* to bus stopping),
- while the bus was present in the stop zone with patrons boarding and alighting (bus is *present*), and
- one minute after the bus had left the bus stop zone (*following* the bus departure).

The three time intervals were adopted in order to analyze the impact on the sidewalk LOS for the pedestrian surge created by a bus loading and alighting. The area utilized in this study is located on the sidewalk adjacent to the bus stop zone between the bus shelter and the corner of the Walgreens store because a majority of the boardings and alightings occur in the area. Figure B–9 shows the study area and dimensions of the bus bay stop configuration, and Figure B–10 shows the study area and dimensions with the bus bulb configuration. The total square footage of the study area was determined by accounting for the effective walkway width of the study area in the bus stop zone. The effective walkway width is essentially the width of the sidewalk minus the width of any features that cause pedestrians to avoid or move around them. Pedestrians will naturally provide a buffer between objects or other pedestrians in order to establish a "comfortable" distance to pass. The total area of available pedestrian space for the bus bay configuration was 308 sq ft (28.6 sq m) and 462 sq ft (43 sq m) for the bus bulb configuration. Within the adjacent area around the bus stop, it is immediately evident that the bus bulb configuration provides additional square footage to the study area.

The available space per pedestrian is determined by dividing the number of observed pedestrians during each of the above time intervals by the resulting total square footage of the selected study area. The resulting available space per pedestrian is then associated to defined Levels of Service. Table B–2 shows the LOS categories by square feet per pedestrian as presented in the *Highway Capacity Manual*.[(1)]

Bus Bay Configuration

A total of 20 bus arrival/departure cycles were collected on the first day, and eight were collected on the second day when the bus stop was configured as a bus bay. Table B–3 lists the resulting space per pedestrian and accompanying LOS for the period prior to the bus, when the bus was present, and following the departure of the bus for each cycle during the two-day bus bay data collection effort. The initial set of calculations shows that the bus bay is functioning at a fairly acceptable LOS for most cycles. Twenty-six of the total 28 cycles had a space per pedestrian that was lowest while the bus was present at the bus bay stop. Understandably, this can be expected since the amount of pedestrian traffic in the bus stop area is highest when the bus is in the zone. The average space per pedestrian while a bus was at the bus bay stop was reduced by over 50 percent.

The average space per pedestrian per cycle is 71 sq ft (6.6 sq m) in the prior phase, 33 sq ft (3.1 sq m) in the present phase, and 80 sq ft (7.4 sq m) in the following phase. These numbers correlate to an average LOS B for the prior phase, LOS C for the present phase, and LOS B for the following phase.

Prior to the bus arriving to the site, when it is likely to find patrons congregating in groups or developing informal queues, the LOS dropped below a C only once. However, there were six events when the bus stop had an available pedestrian space between 16 to 40 sq ft (1.5 to 3.7 sq m) per pedestrian. At this range, pedestrians have to adjust their stride to move through the site and as the space degrades closer to the lower end of the range, pedestrians are forced to make greater changes to their paths and speeds. The greatest number of events that fell in this range occurred while the bus was boarding and alighting passengers. A total of 19 boarding and alighting events caused the bus bay's available space to fall between the range of 16 to 40 sq ft (1.5 to 3.7 sq m) which represents 68 percent of the observations. Table B–3 summarizes the initial findings from the bus bay configuration by aggregating the data into LOS categories that are defined by available space. The impact of the bus boarding and alighting is evident in the number of events that occur below a LOS B.

The findings only consider the impact that existing features, such as the bus shelter, store front, and benches may have on the available space at the bus stop. However, the bus stop is never completely devoid of waiting patrons, passing pedestrians, or congregating groups of pedestrians. In reality, there are really two different sets of effective walkway conditions that exist at each site. The first effective walkway condition is the sidewalk width minus any perceived "safe passage" zones around fixed objects. The resulting area shows the available space that might be present if there were no other bus patrons or congregating pedestrians in the site. However, this type of condition rarely exists, especially during peak travel times when children are walking home from school with friends and family, people are toting copious amounts of grocery bags, people are congregating in groups, and several people are passing each other on the sidewalk.

Therefore, to represent typical conditions at a site, common bus patron and pedestrian congregation areas are figured into the calculation.

For the bus stop site at Mission and 30th Street, the research team observed a number of common areas where people tended to congregate thereby reducing the available space for pedestrians to pass through the bus stop zone. The most common areas were around the bus shelter, leaning against the light pole and MUNI supervisor storage bin, and against the Walgreens store. Typically, no more than three to four bus patrons simultaneously utilize the bus shelter to wait for the next available bus. If the shelter is full, people stand along the wall of the Walgreens store or behind/next to the shelter. The Walgreens store has an overhang that provides ample protection from the elements for pedestrians and waiting bus patrons alike. This adopted use of the overhang by waiting patrons effectively reduces the area available for pedestrians to travel through the zone. It was a fairly common condition to have people stop and chat behind the bus shelter or wait against the storefront with their bags of grocery. Another common occurrence was to have people standing two deep along the wall talking to each other. This further reduces the sidewalk width and overall available pedestrian space at the bus stop. The bus bay configuration was already confined by the limited sidewalk width in relationship to use and by the presence of a bus shelter at the stop.

Figure B–11 provides a graphical representation of the common waiting areas that were observed at the bus bay configuration. Dimensions of the reduced effective walkway width are also included in the figure. When waiting pedestrians/patrons are included in the space calculation, the available area in the bus bay is reduced from 308 to 173 sq ft (28.6 to 16.1 sq m). This is a fairly realistic inclusion since the bus stop zone is never completely void of waiting patrons, passing pedestrians, or people congregating in groups during the afternoon peak period.

The dimensions from Figure B–11 were used to determine a second set of LOS and available area calculations. Table B–5 compares the resulting available space per pedestrian and LOS between the two different sets of calculations. The data in the left side of the table were determined by only considering the existing street furniture. Calculations developed in order to account for waiting patrons and congregating pedestrians in the available space are shown in the far right side of Table B–5.

Figure B–12 compares the available space observed when the bus is present with only street furniture considered and when both street furniture and standing pedestrians are considered. Consideration of waiting patrons and pedestrians notably decreases the amount of space available for each pedestrian.

Figure B–13 graphically shows the available pedestrian space comparison between each phase of the bus arrival/departure episode at the bus bay zone for one of the data collection days. The figure was developed using the calculations with street furniture and waiting pedestrians. The impact of the boarding and alighting activities on available pedestrian space is clearly evident in the *present* phase when the bus is boarding and alighting passengers. The best example of the pedestrian surge created by boarding and alighting activities is evident in cycle 16. The bus stop zone is nearly empty prior to and following the departure of the bus but when the bus boards and alights, the LOS that pedestrians and patrons encounter drops dramatically from an A to an E. This figure highlights the intermittent characteristics associated with pedestrian operations in and around bus stops.

Similar to the previous analysis of the bus bay, the available space per pedestrian drops by at least 50 percent when the bus is present at the zone. The bus bay stop zone experienced a total of 11 events when the LOS dropped to E when a bus was present and there were congregating pedestrians and/or waiting patrons. An additional 10 periods of boardings and alightings caused the LOS to be only a D. Consequently, approximately 75 percent of the time a bus boarded and alighted during the peak period at the bus bay stop, the LOS was at or below D.

More interestingly though, there were a total of 14 cycles during all three of the bus arrival/departure events that had an available space of less than 15 sq ft (1.4 sq m). At this size, almost every crossing maneuver encounters some kind of obstacle to movement. A majority of these events, nearly 80 percent, took place while the bus was boarding and alighting. During the highest moments of the peak period, all three doors were often used for boarding and alighting. It was also common to have more than one bus arrive at the stop at the same time. Boarding and alighting patrons were often faced with multiple streams of flow and crisscrossing patrons trying to either exit the site or board a bus. Twice, the available space per pedestrian in the bus stop zone dropped to only 7 sq ft (0.7 sq m) during the present phase. According to extensive research on pedestrian comfort, 7 sq ft (0.7 sq m) is the minimum level of comfort before crowding becomes intrusive and carrying capacity of the space is reached.

At 7 sq ft (0.7 sq m), lateral passage between standing pedestrians becomes extremely restricted. Another seven cycles yielded an available space of only 16 sq ft (1.5 sq m), which is barely above the 15 sq ft (1.4 sq m) threshold when crossing through pedestrian traffic becomes difficult.

The resulting average LOS for the prior phase and following phase was a B. The average space per pedestrian for these two phases was 40 and 45 sq ft (3.7 and 4.2 sq m), respectively. However, the average pedestrian space is only 19 sq ft (1.8 sq m) when the bus is boarding and alighting at a crowded bus bay, which equates to a LOS of D. At this level-of-service, pedestrian movements are restricted and the probability for conflicts are high. Table B–6 shows the total number of events that occurred at certain level-of-service during the bus arrival/departure sequence when waiting pedestrians are factored into the available space calculation.

Therefore, when typical conditions exist at a bus bay stop configuration, such as the presence of bus shelters, street furniture, waiting patrons, passing pedestrians, and congregating pedestrians, the bus stop reaches a critical level of saturation during boarding and alighting activities in peak conditions.

The impact of the boarding and alighting activities is also evident in common walkway paths that pedestrians choose in order to avoid areas with high levels of congestion. Pedestrians and patrons alike seek the path of least resistance, which sometimes involves people moving out onto the street pavement. One particular route that was chosen by pedestrians was passing between the bus shelter and the curb or even on the street in front of the shelter. This creates conflicts with those bus patrons that are in the bus shelter waiting to board the bus and with any queues that are forming at the bus stop. Another potential danger exits with any unintentional interaction between the bus and walking pedestrians. One of the reasons MUNI constructs bus bulbs is to help limit any accidental sideswipes by the side mirrors on the bus with pedestrians. When a bus pulls into and out of a bus bay, the bus may have to take a strong entry angle into the zone, thereby causing the mirrors to overhang the sidewalk. If pedestrians are forced to use the space between the curb and shelter or to actually use the street to by pass pedestrian congestion, this can cause greater chances for the bus and pedestrians to interact. Common pedestrian walking paths that were observed at the bus bay stop configuration are shown in Figure B–14.

Bus Bulb Configuration

During the after data collection trip when the bus bulb configuration was present, a total of 13 cycles were collected on the first day, and 19 cycles were collected on the second day. Figure B–15 provides a graphical representation of the common waiting areas that were observed at or near the bus bulb. The dimensions of the reduced study area are also included in the figure.

The waiting or congregation patterns did not change significantly from the bay to the bulb configuration, but the change in available space is quite evident in the figure. The total area of the bus bulb that was studied was 462 sq ft (43 sq m). However, the reduced size is 284 sq ft (26 sq m) when areas that are prone to have waiting patrons are removed from the available space in the bulb.

Table B–7 lists the resulting space per pedestrian and accompanying LOS for the period prior to the bus, when the bus was present, and following the departure of the bus for the 32 cycles when street furniture and waiting pedestrians are considered. The average space per pedestrian on the bus bulb is 44 sq ft (4.1 sq m) in the prior phase, 44 sq ft (4.1 sq m) in the present phase (boarding and alighting), and 63 sq ft (5.9 sq m) in the following phase. These numbers correlate to a LOS of B for all phases.

Figure B–16 illustrates the average available pedestrian space for the second day of data collection at the bus bulb. Cycles 11 through 15 represent the period of greatest pedestrian congestion in and around the bus bulb. Even with the additional space afforded by the bulb, the area including the bulb and adjacent sidewalk only functions at a LOS of C or D during these five events. At only one time did the average space equate to a LOS above a C, which was a period immediately following the departure of a bus from the stop. The average available space available to waiting patrons and pedestrians during these five cycles is only 30 sq ft (2.8 sq m). This represents a degradation of approximately 250 sq ft (23.3 sq m) per pedestrian from the base case of 284 available sq ft (26.4 sq m), which is an 89 percent reduction in available space. This highlights the magnitude of patrons and pedestrians that use this space during peak periods as well as the basic need for additional space in and around the bus stop to accommodate the demand.

Comparison of Bus Bay to Bus Bulb

Similar to the bus bay, the presence of a bus (boarding and alighting patrons) in the zone has the greatest impact on available space within the bus bulb configuration. On the first day, nine of the 13 cycles had an available space per pedestrian that is the lowest while the bus is in the bus stop zone. On the second day, 12 of the 19 cycles showed a similar result. In comparison, though, the bus bulb reduces the percentage of times that boarding and alighting activities cause the available space to deteriorate to its lowest levels-of-service. When the bus stop was configured as a bus bay, the bus stop's available space dropped to its lowest levels all but two times when the bus boarded and alighted passengers. The bulb is clearly an improvement in this category.

Table B–8 shows the total number of events that a particular LOS occurs on the bus bay and bus bulb configurations. The table also shows the percentage of each event by bus arrival/departure sequence (prior, present, following).

Based on Table B-8, the bus bulb operates more efficiently than the bus bay configuration. Approximately 72 percent of events operate at a level-of-service of C or greater in the bus bulb configuration as compared to 60 percent for the bus bay design. More importantly, some of the greatest benefits in levels-of-service are evident in the present bus phase. Nearly 26 percent of the total observations made at the bus bulb when a bus was boarding and alighted operated at LOS greater than or equal to B. In comparison, only 4 percent of the observations made at the bay during the similar period operated at this level. At no time did the bay have a period when the LOS was an A during the present phase. Similar improvements are in the period after the bus has departed the stop. Level-of-service, though, does not adequately capture the true value of the bus bulb when analyzing pedestrian operations and space availability.

Table B–9 shows a direct comparison between the average space per pedestrian per cycle between the bus bay and bus bulb configurations. In almost every bus arrival/departure scenario, the bus bulb provides addition square footage for transit patrons and passing pedestrians in the bus stop zone (see also Figure B–17). The most dramatic differences occur during the boarding and alighting phase when the average available space increases from 19 sq ft (1.8 sq m) in the bay configuration to 44 sq ft (4.1 sq m) in the bus bulb configuration. This increase amounts to a difference of 132% or a factor greater than 2 when comparing available square footage. At approximately 19 sq ft (1.8 sq m), the average condition at the bay, walking speeds and paths need to be adjusted because of crowding, crossing through bi-directional traffic is difficult, and passing another pedestrian is close to the minimum threshold of 18 sq ft (1.7 sq m) per pedestrian. Conversely, at 44 sq ft (4.1 sq m), passing slower pedestrian traffic is easier, crossing through bi-directional traffic is nearly unimpaired, and traveling through the zone is dramatically less impacted by other walking or standing pedestrians.

Similarly, there is a fairly significant difference in available space in the period immediately following the departure of a bus(es) from a bus stop, when a site may experience lingering delays caused by the queues of boarding and alighting passengers. The space available for pedestrians increased from 45 to 63 sq ft (4.2 to 5.9 sq m), which amounts to a 40 percent increase in available area for patrons and pedestrians to pass each other.

As expected the second lowest reading among the three events is the period prior to the arrival of a bus, when patrons are standing along the sidewalk, using the shelter, or leaning against store fronts. The average space available changed slightly from 40 to 44 sq ft (3.7 to 4.1 sq m) when the bulb was added to the bus stop. This finding may be related to the desire to use the overhang of the Walgreens as protection against the elements, regardless of the additional space created by the bus bulb. People still seek relief from the elements when they are waiting for their bus. If the bus shelter is full, people will naturally adapt to the next best available shelter, whether it's the shelter of a building overhang or a threshold to a door. Because of this, the capacity of the sidewalk is still impacted by the adaptive use practices of waiting patrons despite the additional space provided by the bulb. In a dense urban environment, such as San Francisco, this type of adaptive practice is unavoidable.

The bus bulb is clearly an improvement in available space per pedestrian for most observations. This finding is important since it was not uncommon to have more than one bus board and alight simultaneously (bunching). The greatest challenge to the capacity of the bus stop to adequately serve large amounts of people is when more than one bus is boarding and alighting. Patrons and pedestrians are most likely to encounter the greatest mix of multiple streams of traffic, queuing areas, and passing pedestrians during the boarding and alighting of buses. As previously mentioned, areas that have less than 15 sq ft (1.4 sq m) per pedestrian cause pedestrians to change their stride and make it difficult, at best, to cross different streams of pedestrian traffic. The bus bay configuration had a total of 14 events when the available space per pedestrian was at or below 15 sq ft (1.4 sq m) per pedestrian. Approximately 79 percent of these events occurred when the bus was present. Therefore, nearly 40 percent of the boarding and alighting activities that were observed at the bus bay stop configuration had densities that were significant enough to impact pedestrian behavior, comfort, and patterns. Not unlike the bus bay, the bus bulb had a total of 14 observed events when the bulb design had less than 15 sq ft (1.4 sq m) per pedestrian available. Approximately 64 percent of these events occurred, again, when the bus(es) were boarding and alighting. However, the percentage of times that crowding would be encountered when a bus was at the stop was reduced by nearly 28 percent, which represents a notable difference between the bay and bulb designs.

More importantly, the total number of events, regardless of the bus arrival/departure sequence, where crowding was significant enough to impact pedestrian movement (e.g., one pedestrian passing another pedestrian) dropped between the two designs. Below 35 sq ft (3.3 sq m) per pedestrian, studies have shown that it becomes progressively difficult to cross streams of traffic or to pass a slower pedestrian.[3] In 63 events, bus bays had an available space less than or equal to 35 sq ft (3.3 sq m). Conversely, exiting transit riders and pedestrians encountered this type of crowding about half of the time after the bulb had been constructed. Table B–10 summarized the total number of events that occur at various conditions of pedestrian crowding between the two bus stop designs.[3] The table also presents the total number and percentage of crowding conditions that occur while the bus was present. The impact of a bus boarding and alighting at a bus stop on pedestrian crowding, regardless of design, is quite evident.

The widening of the sidewalk caused by the presence of a bus bulb had a significant impact in reducing the number of people passing between the bus stop shelter and the curb, or even walking in the street in front of the shelter. Figure B–18 illustrates common pedestrian walking paths observed during the after data collection trip. The reconfiguration of the site also produced other positive results, one of them being the noticeable improvement in the number of people that stay within the crosswalk boundaries when approaching the site. Previously, pedestrians would "cut the corner" and not completely cross the street within the lines.

Another positive result was the significant reduction in the number of people walking into the street to see the arrival of the next bus. In the old site configuration, the primarily empty curbside lane provided the bus patrons a seemingly safe place to walk into in order to look downstream to see the location of the next bus. However, the bus bay zone was used by cars making right turns onto 30th Street. With the new configuration, the sidewalk is extended to the edge of traffic, and patrons do not need to step into the street to see the next bus.

SIDEWALK LEVEL-OF-SERVICE STUDY

Pedestrian flow levels on sidewalks are similar to those of vehicles on roadways. The freedom to choose a desired speed as well as the ability to bypass others are important elements. A method for quantifying the efficiency of a sidewalk is determining the pedestrian flow rate. Pedestrian flow rate is the total number of people passing a particular point in a specified period of time. The resulting value is in terms of pedestrians per minute per foot (ped/min/ft) and this value correlates to a specific level-of-service.

Sidewalk LOS data were collected at the Mission Street and 30th Street (southbound direction) site during two afternoon peak periods for both trips. With the bay configuration, pedestrian volumes were collected for an hour and a half on the first day and one hour the second day. Information was also collected for an hour and a half on the first day and two hours the second day after the site was reconfigured. The data were subsequently verified by videotape. In order to conduct an analysis as specified in the *Highway Capacity Manual*, bi-directional pedestrian volumes in 15-minute increments, as well as the effective walkway width of the sidewalk, are needed.

The effective walkway width is essentially the width of the sidewalk minus the width of any fixed features that cause pedestrians to avoid or move around them. Using only the effective walkway width provides one interpretation of the data. Another interpretation is to include common bus patron and pedestrian congregation areas in the calculation. These mobile features, while not fixed in a particular location, have a constant effect on the ability to comfortably travel on the sidewalk. For example, in Figure B–19 the effective walkway width of the empty curbside bus bay is 6 ft (1.8 m). However, if common waiting areas and congregation points are accounted for, the effective walkway width available for passage through the site is essentially reduced to 3 ft (0.92 m). Based on the research team's observations of the frequency that this area contained waiting patrons, the most realistic conditions (with waiting patrons and congregating pedestrians) are presented in the findings.

The sidewalk level-of-service study relied primarily on the use of palmtop computers. Data were collected by positioning a member of the research team at a pre-determined spot near the end of the bus stop zone at approximately the same location for each bus stop configuration. As pedestrians and bus patrons passed a certain location in the zone, the research team member would enter a data point by clicking on a counter on the palmtop computer by using a stylus pen. Each entry is automatically recorded with a time stamp for the purpose of analyzing the impact of boarding and alighting activities on the sidewalk flow. The arrival and departure of a bus is recorded by the research team with another automatic time stamp that is available on the palmtop window screen.

The area between the corner of the Walgreens store and the light post at the far end of the bus stop zone was selected as the sidewalk LOS study area. This area represents the greatest level of pedestrian flow for the entire bus stop zone. As observed during the data collection trips, a majority of the boarding and alighting bus patrons typically used the sidewalk between the Walgreens store and the light post. The bus patrons are either moving from this bus stop to the adjacent bus stops (transfer point) on 30th Street or are going to the 30th Street or Mission Street crosswalks. A large number of school children with their book bags use the bus stop on Mission Street to go home in the evening. Pedestrians also utilize this space to move through the site. Most pedestrians are carrying shopping bags from the Safeway store and are usually traveling in groups (e.g., families and friends). Therefore bus patrons and pedestrians alike usually arrive and depart in groups and are a part of intermittent surges that place varying demands on this area to provide adequate space for unobstructed pedestrian movement.

Bi-directional pedestrian flow data were collected along the line between the Walgreens and the light pole to capture movement in both the northbound and southbound directions. The data were collected during the afternoon peak hours when school children were leaving school and parents were running errands with their children.

Figure B–19 shows the resulting walkway width of the bus bay configuration while Figure B–20 provides a cross section of the effective walkway width between the bus shelter and the Walgreens store. Figure B–21 shows the resulting walkway width of the bus bulb after construction and Figure B–22 provides a cross-section of the improved effective walkway width between the bus shelter and the Walgreens in the new configuration. Although the walkway width increased by the bus shelter, the effective walkway width did not change at the measuring point when the bus bulb was constructed because the street lights, signs, and supervisor storage bin did not move during the reconfiguration of the site. The movement of the shelter did increase the sidewalk width upstream of the intersection. The linear distance between the storefront and the back of the bus shelter changed from a width of 6 ft (1.8 m) in the bus bay configuration to a width of 10.5 ft (3.2 m) with the addition of the bus bulb. This change represents an improvement of approximately 75 percent for this specific area. At this stop, a majority of pedestrians and exiting bus patrons do not utilize this space. Therefore, this improvement would have minimal effect on the sidewalk performance at the choke point for this particular bus stop. At other locations where the directional traffic is more evenly split between the two sides of the bus stop zone, the relocation of the shelter would have a dramatic improvement in available sidewalk space. The overall width of the sidewalk increased from 14 to 20.25 ft (4.3 to 6.2 m) for an improvement of approximately 45 percent.

Flow rate is measured in pedestrians per minute per foot, and the rate is used to determine the LOS on the sidewalk. As the flow rate increases, pedestrian speeds decrease and there are less opportunities for them to bypass other pedestrians. Consequently, the level-of- service will be degraded. The formula for determining sidewalk LOS in 15-minute increments is:

$$v = V_p / 15W_E \qquad (1)$$

where:

v = pedestrian unit flow rate (ped/min/ft)
V_p = peak 15-minute bi-directional pedestrian count (ped/15-min)
W_E = effective walkway width (ft)

The flow rates for four 15-minute peak time periods were determined for both the bus bay and bulb configurations. The results of the data are provided in Table B–11.

The flow rates for all analysis periods fall between 2.9 and 4.8 ped/min/ft (9.5 and 15.7 ped/min/m) and all equate to LOS B. While the highest flow rate was measured with the bulb configuration, when the four highest flow rates are averaged an improvement in sidewalk performance was found between the bay and bulb configuration. The average flow rate for the bay configuration is 4.0 ped/min/ft (13.1 ped/min/m), while the average for the bus bulb is 3.6 ped/min/ft (11.8 ped/min/m). Although this may seem like a minor improvement, it represents an 11 percent increase in the sidewalk flow level.

In addition to the 15-minute counts, the data were divided into one-minute increments. This was made possible by the time-stamps that were associated with the palmtop program developed for this data collection task. Having the data reduced into smaller segments provides a more complete view of the minute-by-minute conditions of the sidewalk. Using one-minute increments and an adjustment to the formula in the *Highway Capacity Manual*, the pedestrian flow rate and LOS were determined for all of the sidewalk LOS data that were collected. The modification of the formula used to calculate LOS in one-minute increments simply removes the factor of 15 used in the original formula and is as follows:

$$v = V_p / W_E \qquad (2)$$

Using the data for November 12, 1999, from 2:53-3:08 pm, pedestrian flow rates were determined in one-minute increments for the bus bulb. Figure B–23 provides a summary of the sidewalk flow rates for this period. The figure also shows the periods when buses are and are not present in the bus stop zone for a particular one-minute increment. The highest pedestrian flows are typically experienced when a bus is in the bus stop zone. After the bus departs the stop, there is a gradual decrease in the flow rate until the next bus enters the zone.

All of the data collected were reduced into one-minute increments, and the resulting flow rates are plotted in Figure B–24. The figure shows the cumulative frequency of all measured flow rates in addition to providing the level-of-service ranges. Table B–12 provides a summary of the flow rate values in terms of the number of observations (one-minute increments) and a percent of the total number of observations per configuration for each level-of-service. Over 90 percent of the level-of-services were in the A or B range. However, there are instances when the LOS drops to C and occasionally even D. The average flow rate for all one-minute increments in the bus bay configuration was 3.1 ped/min/ft (10.2 ped/min/m), while the average for the bus bulb was 2.8 ped/min/ft (9.2 ped/min/m). This equates to an 11 percent improvement in the flow on the sidewalk.

In order to account for the surges created when buses are boarding and alighting, the one-minute counts were divided into two scenarios: 1) when a bus was present and 2) when a bus was not present at the stop. The one-minute counts not only provided more individual determinations of LOS than using 15-minute counts, they also provided the analysis with a better interpretation of the impact of boarding and alighting activities on the level-of-service that might be encountered by a pedestrian.

The calculations considered whether a bus was present in the bus stop zone during the minute increment time period. Figure B–25 is a plot of the flow rates for bay and bulb configurations for scenarios when buses are and are not present during the minute time period. Intuitively, the average flow rate was better when buses were not present in the bus stop zone in both the bay and bulb configurations. The average flow rate when buses were not present improved in the bulb configuration, decreasing from an average of 2.8 to 2.4 ped/min/ft (9.2 to 7.9 ped/min/m). This equates to an improvement of nearly 17 percent. However, when buses were present, the average flow rate showed a small increase (approximately 2 percent). The flow rate changed from an average of 4.0 to 4.1 ped/min/ft (13.1 to 13.4 ped/min/m). However, as shown in Figure B–25, only on rare occasions does the LOS of the sidewalk drop below a C in either configuration. Table B–13 summarizes the total one-minute increments that were at or above a LOS D for both the bus bay and bus bulb configuration, taking into account whether or not a bus was present in the bus stop zone. The table also provides a percent value relative to the number of observations for each LOS as compared to the total number of observations for when a bus is in the bus stop zone and when it is not present in the zone.

The distribution of LOS observations is nearly identical when comparing the bay and bulb configurations when a bus is present in the bus stop zone. However, when a bus is not present in the bus stop zone, the percent of LOS readings that were A decreased from 52 percent in the bay configuration to 39 percent in the bulb. Subsequently, the number of LOS readings that were B in the bulb stop increased, meaning that there was a degradation in the level-of-service.

As previously mentioned, the critical dimension in the analysis was the distance between the Walgreens store and the MUNI supervisor storage box. This dimension did not change during the reconfiguration of the site. Therefore, the change in level-of-service from the bay to bulb configuration can be misleading. According to the level-of-service calculations, the sidewalk adjacent to the bus stop functions at a rather consistent and high LOS. The findings showed minor improvements in most cases. This finding includes the peak period 15-minute counts, the individual one-minute counts, as well as when buses boarding and alighting were considered. Despite the fact that the physical dimensions of the data collection point did not change, the bus bulb provided a slightly improved flow rate in most instances.

CORNER LEVEL-OF-SERVICE STUDY

There are several reasons to study the LOS at a corner near a bus stop. Pedestrians will typically queue in random fashions at the corner while waiting for the "Pedestrian Walk" phase of the traffic light. Once the light changes, people will form several informal queues as they cross the street. Depending on the number of people that have been waiting at the corner, delay may or may not be experienced by pedestrians as they cross the street. If there are large numbers of pedestrians in the storage area of the corner, the likelihood of conflicts or people adjusting their paths to preserve a buffer between them and the next person increases.

For corners near bus stops (both farside and nearside), the area may experience large intermittent surges of alighting and boarding bus patrons. The boarding and alighting activities may or may not coincide with the "Walk" or "Do Not Walk" phase of the traffic signal. If alighting patrons are caught in the "Do Not Walk" phase, the corner could potentially become overcrowded with alighting bus patrons and pedestrians. The construction of a bus bulb provides additional storage area in and around the corner. Bus bulbs also provide additional room by the adjustment of the location of light poles, traffic signal poles, and vending machines.

Another advantage of constructing bus bulbs at the intersection is the reduced crossing width of the street. Although the width was reduced at the Mission Street at 30th Street location, the "Walk" phase was not changed between the bus bay configuration and the bus bulb configuration.

The afternoon peak period between 3:00 pm and 5:30 pm was selected for the corner level-of-service study due to the high pedestrian volumes that occurred during that time. After 3:00 pm, there is a significant increase in pedestrian activity due to children traveling home from school. Additionally, the two bus stops located on 30th Street are transfer points for transit riders. These factors, coupled with the location of the Walgreens store and the Safeway grocery store, helped generate significant pedestrian activity along the sidewalk adjacent to the bus stop zone.

A video camera mounted on a traffic sign directly across the street from the bus stop was used to collect pedestrian volumes at the corner of Mission Street and 30th Street. In accordance with Chapter 13 of the *Highway Capacity Manual,* [1] the data were reduced by viewing the videotape and documenting specific information. This information included:

- total signal cycle length,

- green and red signal times for both the major (Mission) and minor (30th) streets,
- pedestrian volumes crossing the major street in both the inbound and outbound direction,
- pedestrian volumes crossing the minor street in both the inbound and outbound direction, and
- pedestrians passing through the corner sidewalk area but not crossing either street.

Figure B–26 is a picture looking upstream toward the curbside bus bay at Mission Street and 30th Street. The site is rather constrained by the narrow sidewalk and the presence of street furniture. Figure B–27 is a plan view of the curbside corner study area.

Conversely, Figure B–28 is a picture showing the corner after the bulb has been constructed. The picture is taken at the same location for comparative purposes. The corner is noticeably larger with the addition of the bus bulb, which extends 6 ft (1.8 m) beyond the old curbside location. The actual increase in corner area is 32 percent, increasing from 100 sq ft (9.3 sq m) in the bay configuration to 132 sq ft (12.3 sq m) in the bulb configuration. Figure B–29 is the plan view of the bulb configuration.

The "Street Corner Analysis Worksheet" provided in the *Highway Capacity Manual*, served as the basis for the corner LOS evaluation. An example worksheet is shown in Figure B–30. The "Street Corner Analysis Worksheet" provides output in terms of square feet per pedestrian that can subsequently be translated into a LOS using the values listed in Table B–2. Each resulting LOS determination is for one complete signal cycle.

Using the three highest pedestrian crossing data from both the bus bay and bulb configurations, the research team was able to determine the corner space available per pedestrian. Table B–14 provides a summary of the corner LOS analysis. It should be stressed that the corner functions as a time-space zone. Pedestrians waiting to cross a street occupy the corner for longer periods of time, but they require less standing space, while circulating pedestrians require more space for shorter periods of time. The space element is strictly a function of the area, while the time element relates to the signal phasing and cycle length.(1)

An initial review of the data in Table B–14 shows little, if any, improvement. All of the peak cycles are in the LOS B range. Another approach to examining the results is to compare how the corner would operate in the after period if pedestrian volumes did not change. The average number of pedestrians for the three peak cycles in the bus bay configuration is 32. The resulting average space per pedestrian is 52 sq ft (4.8 sq m). If the same number of pedestrians present in the bus bay count were applied to the bulb configuration (132 sq ft) [12.3 sq m], the average space per pedestrian would equal 58 sq ft (5.4 sq m), or an increase of 12 percent. This finding in itself shows the impact that the reconfiguration of the bus stop has on the corner level-of-service. By adding square footage to the corner area, the available space per pedestrian is noticeably improved.

The average number of pedestrians in the three peak cycles in the bulb configuration is 35, and the average space per pedestrian is 55 sq ft (5.1 sq m). However, if those 35 people were present in the bus bay configuration (100 sq ft) [9.3 sq m], the average space per pedestrian would be reduced to 39 sq ft (3.6 sq m). This amount, would result in a LOS C which also supports the assertion that the bulb configuration provides an improved level-of-service to pedestrians.

In addition to the peak cycle analysis, all of the available corner LOS data were reduced and evaluated. This provided an overall summary of the conditions that were present over the duration of the data collection effort. The results of the analysis show that all of the corner LOS readings are in either the A or B range. There was a slight improvement in the space per pedestrian as a result of the reconfiguration of the corner area. Table B–15 provides the number of occurrences as a percent of the total observations of a particular LOS.

There was an increase in the percentage of readings that were LOS A as a result of the improvements made at the site. The bus bay configuration with limited storage space had 79 percent of the readings at LOS A. After the bulb was constructed and the additional 6 ft of sidewalk extended at the curb, the percentage of LOS A readings increased to 86 percent. This amounts to an improvement of 9 percent. Although a majority of the LOS readings with the bus bay and bulb were either A or B, there were improvements observed as a result of the reconfiguration. In the site's configuration prior to the installation of a bus bulb, there were noticeable conflicts between pedestrians crossing the street in an inbound direction (towards the study site) and those pedestrians waiting to traverse the cross-street in an outbound direction. This was especially true for pedestrians crossing Mission Street in the inbound direction. The location of street furniture and the pedestrian queues at the corner reduced the area that pedestrians had to enter the pedestrian traffic flow on the bus stop side of the street. However, after the construction, there was a noticeable increase in the area available for pedestrians to queue while waiting to cross the street. This additional space also created fewer conflicts between pedestrians waiting to cross one street and those approaching the corner area on the other street.

BOARDING AND ALIGHTING CHARACTERISTICS

Boarding and alighting information as well as bus arrival and departure times were collected using the palmtop computers running a program specifically designed for this task. Data were collected over a period of five days during peak and off-peak periods at different sites during both data collection trips. Data retrieved from the palmtop data files include bus dwell times and the delay to buses re-entering the traffic stream. Observations on the length of dwell time and the amount of delay to buses are discussed in Appendix C, Roadway Before-and-After Study. The length of bus dwell time is also related to pedestrian activities. If the bus stop area is crowded, patrons may have difficulties in moving to the bus to board or alighting from the bus. The additional space provided by the bus bay may result in more efficient boarding and alighting operations. In addition to the data collected for determining the number of passengers that board or alight during the time that the bus is present at the bus stop, observations were made with regards to pedestrian behavior in the boarding and alighting zone.

Data were collected at two sites: Mission and 30th Street (nearside stop) in the southbound direction and Mission and 30th Street (farside stop) in the northbound direction. One site is adjacent to the study area and the other across the street. Both sites contributed pedestrians to the sidewalk studies being conducted. In the analysis of the bus dwell times, the dwell time of the bus was plotted relative to the number of total passengers boarding and alighting the bus. Dwell times less than 40 sec were used in the analysis. Longer dwell times were associated with drivers meeting with supervisors or other similar reasons rather than being associated with pedestrian activities.

A closer look at the numbers shows that average dwell time (in seconds) per passenger boarding and alighting decreased by nearly one second in the off-peak period at Mission @ 30th Northbound. The remaining analysis groups all showed an increase in the average dwell time per passenger boarding and alighting. Table B–16 provides a summary of the averages.

This finding is misleading in that during the after study of the bus bulbs there were several occasions where a street supervisor stopped the bus and talked with the driver creating an inflated dwell time. These delays ranged from several seconds to almost three minutes. Although there were instances of street supervisors talking to bus operators in the before data collection trip, they seemed to create more delay during the after trip.

Figures B–31 and B–32 provide a before and after overview of the Mission @ 30th southbound site, while Figures B–33 and B–34 provide similar information for the Mission @ 30th northbound site. A review of the dwell time figures reveal an intuitive trend of having longer dwell times associated with higher numbers of patrons boarding and alighting.

Other observations made during the bus arrival departure study were the pedestrian behavior in the bus stop zone when buses were boarding and lighting. Figures B–35 and B–36 provide an overview of common walkway paths made by pedestrians during the boarding and alighting process. The figures show the alighting passengers and their subsequent paths as a solid black line. The boarding passengers are shown as thick gray arrows, and the area where high conflicts occurred are shown as cross-hatched boxes. In the after study, a noticeable improvement was observed at the front door of the bus where patrons alighted and boarded. In both the before and after data collection trips, high levels of congestion were noted in and around the front door of the bus. However, in the before configuration, the congested areas consumed a large portion on the sidewalk space. In the after configuration, the primary congestion occurred on the bus bulb. This allowed for less disruption on traffic on the sidewalk.

CONCLUSIONS

The objective of this study was to evaluate and compare two different bus stop designs – bus bay and bus bulb – on pedestrian operations in and around the bus stop zone. A nearside bus stop located at the intersection of Mission Street and 30th Street was selected as the study site. The bus stop has the highest pedestrian and bus patron volumes among the bus stops located on south Mission Street that was part of the project to reconfigure several bus bays to bus bulbs. The conclusions from this effort are presented in the following sections.

Pedestrian Space

For this study, the number of pedestrians and bus patrons in a defined area in and around the bus shelter were counted for three time intervals: one minute *prior* to the bus arriving, while the bus was *present* with patrons boarding and alighting, and one minute *following* the bus departure. The amount of space available per pedestrian can then be translated into pre-defined levels-of-service. When the bus bay configuration was present, approximately 60 percent of the time the area immediately adjacent to the bus shelter operated at a level-of-service C or greater. After the bulb was constructed, the bus stop operated at a LOS C or greater approximately 72 percent of the time, which is an improvement of 20 percent. The most notable improvement between the bay and bulb designs is the available space per pedestrian during the boarding and alighting activities at the bus stop. The average amount of space for pedestrians and transit patrons improved from 19 sq ft (1.8 sq m) per pedestrian to 44 sq ft (4.1 sq m) per pedestrian after the bulb had been constructed. This is an improvement of 132 percent, which represents a growth factor greater than 2 between the bay and the bulb designs. A similar, though less significant, improvement was observed in the period immediately following the departure of a bus from the bus stop, when the average square footage available per pedestrians increased from 45 to 63 sq ft (4.2 to 5.9 sq m), which is approximately a 40 percent improvement from the bus bay design to the bus bulb design. Therefore, there is significantly more room for pedestrians and transit patrons alike during the boarding and alighting phase when the bus stop is likely to experience the greatest demand for space. This was expected since the bulb essentially extends the curb another 6 ft (1.8 m) from the previous location. There is also significantly more options as far as location for transit patrons to choose to wait, other than on the sidewalk.

Sidewalk Level-of-Service

The pedestrian characteristics studied to evaluate sidewalk operations were pedestrian flow rates during the afternoon peak period. During the four highest 15-minute increments of pedestrian volumes near the bus stop zone, the average flow rate increased by approximately 11 percent from 4.0 ped/min/ft at the bay configuration to 3.6 ped/min/ft in the bulb configuration. This improvement was anticipated to be higher; however, the location of some critical street furniture was not changed. The growth rate does represent a real improvement between the bay design and bus bulb configuration. The bulb design provides more options for pedestrian paths; however, if the location of street furniture is not changed between the two configurations, the same bottleneck points still exist.

When the data are divided into one-minute increments to account for the presence of a bus at or not at the stop, similar results exists. The average flow rate on the sidewalk improved by 17 percent between the bay and bulb designs when the bus was not present at the bus stop boarding and alighting passengers. The average flow rate decreased from 2.8 to 2.4 ped/min/ft (9.2 to 7.9 ped/min/m). Intuitively, the conclusion from this data might suggest that the bulb is providing the necessary space for patrons to wait for their next bus off of the sidewalk, thereby, improving the conditions on the sidewalk. Contrary to this finding, the average flow rate increased with the bulb design when the bus was present boarding and alighting passengers. The rates changed from 4.0 ped/min/ft (13.1 ped/min/m) on the bay to 4.1 ped/min/ft (13.4 ped/min/m) on the bulb, which represents a degradation of only 2 percent. Once again, this finding may indicate that since the location of street furniture did not change between the two configurations (with the exception of the bus shelter), the bus bulb at Mission and 30th Street did not truly achieve enhanced pedestrian movement characteristics during peak conditions, such as what is experienced during the boarding and alighting of buses. Despite the fact that the physical conditions of the data collection point did not change, the bus bulb did appear to be a marked improvement for pedestrians passing through the site and for bus passengers that were boarding and alighting from the buses.

Street Corner Level-of-Service

For this study, the operating characteristics of the corner were evaluated during the afternoon peak period. Pedestrian volumes, signal timings, and area data were collected for the bus bay and bulb configurations. During the three peak signal cycles in the bus bay configuration, there was an average space per pedestrian of 52 square feet. If the same number of pedestrians were present in the bulb configuration, the average space per pedestrian would be 58 sq ft (5.4 sq m), or an increase of 11 percent. When all of the available corner LOS data were analyzed, the results showed that all of the readings fell into the LOS A or B categories. The bus bay had 79 percent of its readings in the LOS A range, while the bus bulb had 86 percent of its reading in LOS A. This represents an improvement of 9 percent. The extension of the curb in the bulb configuration provided a larger queuing area for pedestrians. The larger area reduced the occurrence of conflicts between those pedestrians waiting to cross the street and those approaching the corner. Additionally, the extension of the curb increased the number of people that crossed the street entirely within the crosswalk.

Board and Alighting

Data were collected at two sites in order to determine the boarding and alighting characteristics on the adjacent sidewalk. Using a farside and nearside bus stop in both bus bay and bulb configurations, dwell times were assessed. Dwell times of greater than 40 sec were not evaluated because they were associated with bus drivers talking to supervisors rather than boarding and alighting activities. The average dwell time (in seconds) per passenger decreased by nearly one second in the off peak period at Mission Street and 30th Street in the northbound direction. In the peak period for this site, as well as both the peak and off peak periods for the Mission Street and 30th Street in the southbound direction, there was a slight increase in the average dwell time per passenger. The bulb design provided more space for boarding and alighting activities, as well as moved the area where these activities occurred. In the bus bay configuration, boarding and alighting took place on the sidewalk. This resulted in a disruption of the pedestrian flow on the sidewalk. In the bulb configuration, the boarding and alighting took place on the bulb itself. Therefore, the primary area of congestion was moved out of the pedestrian stream on the sidewalk.

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1. *Highway Capacity Manual*. Special Report 209, Third edition. Transportation Research Board, National Research Council. (1994).
2. Pushkarev, B. and J. Zupan, *Urban Space and Pedestrians.* MIT Press. (1975).
3. Fruin, J.J., *Pedestrian Planning and Design*. Metropolitan Association of Urban Designers and Environmental Planners. (1971).
4. Hall, D. *The Hidden Dimension*. Doubleday and Co., (1966).

Figure B – 1. South Mission Street Neighborhood

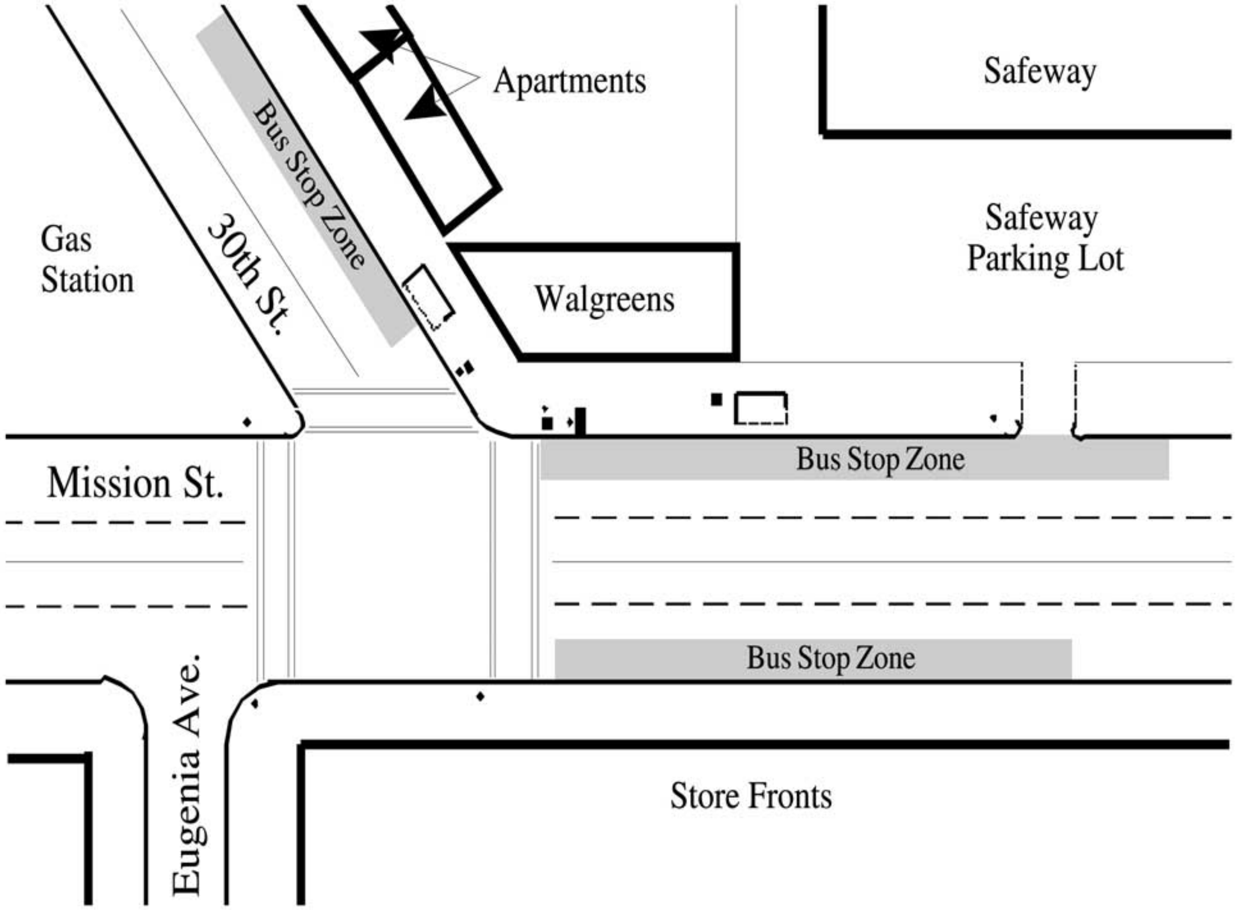


Figure B-2. Mission @ Street Intersection (Bus Bay Configuration).

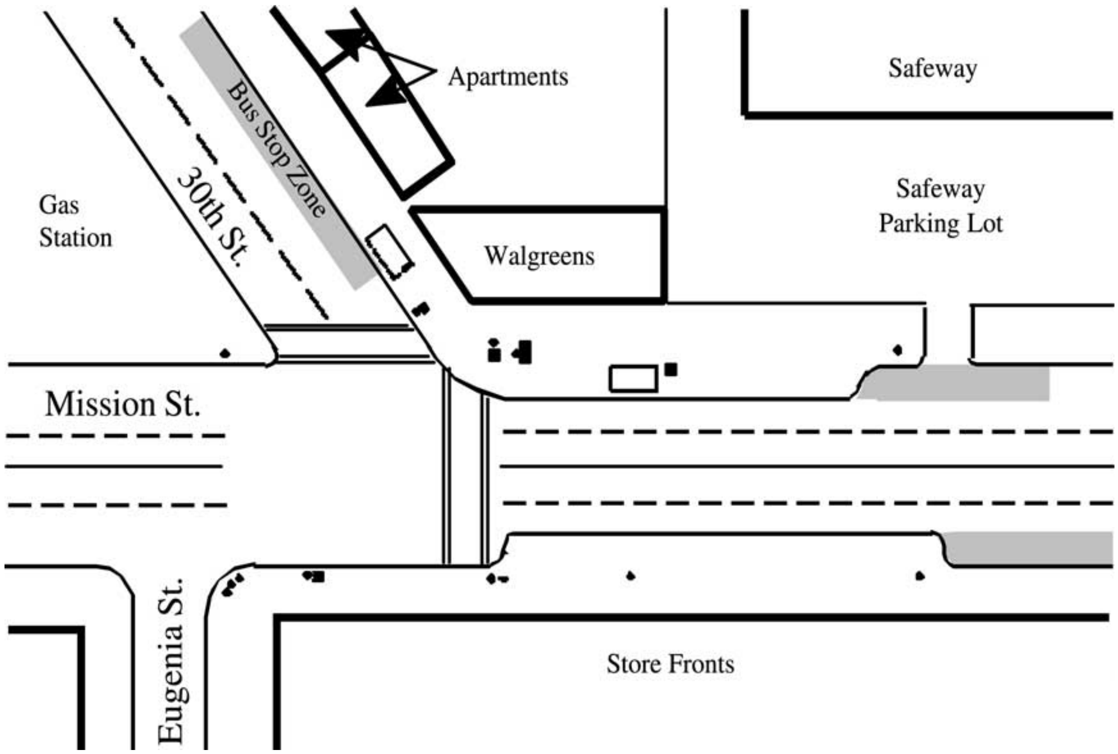


Figure B-3. Mission @ 30the Street Intersection (Bus Bulb Configuration).

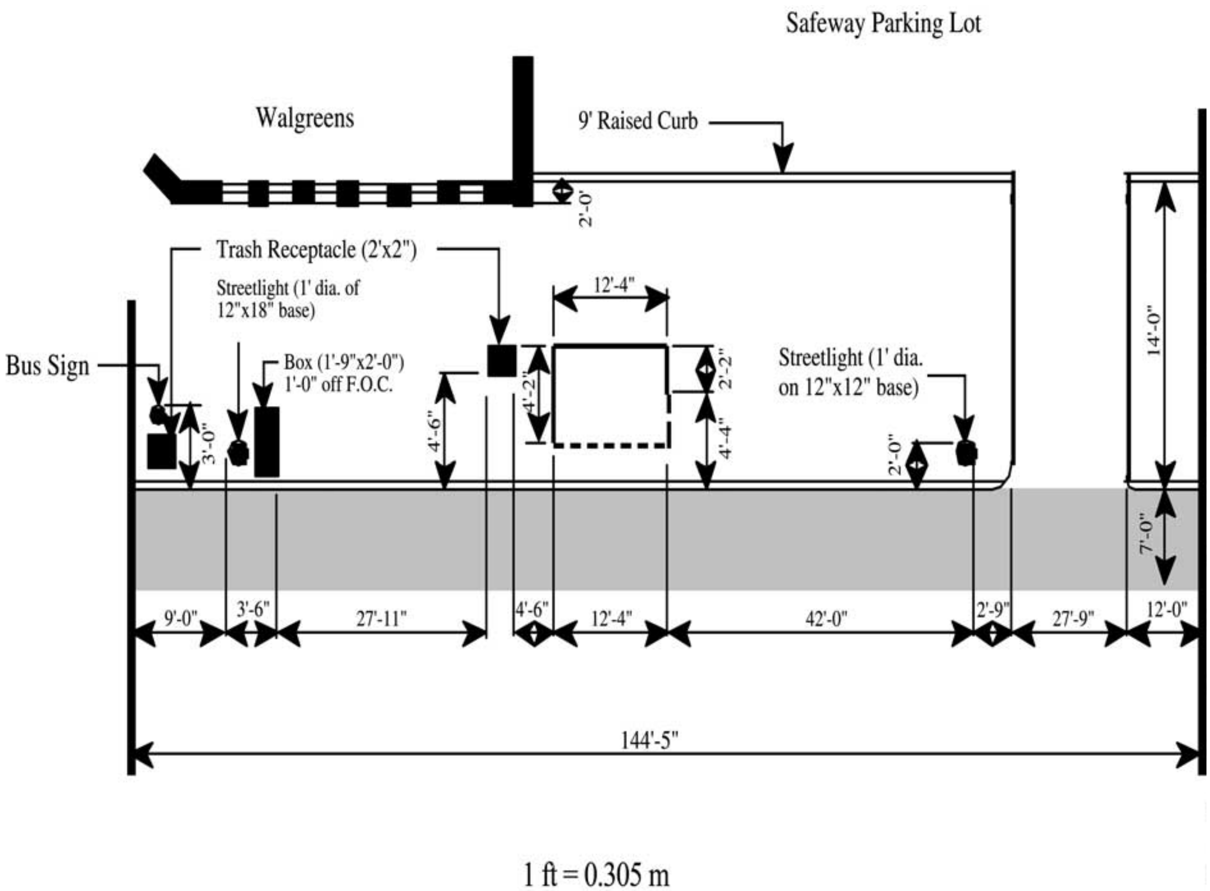


Figure B-4. Mission @ 30th Street Bus Bay Dimensions.

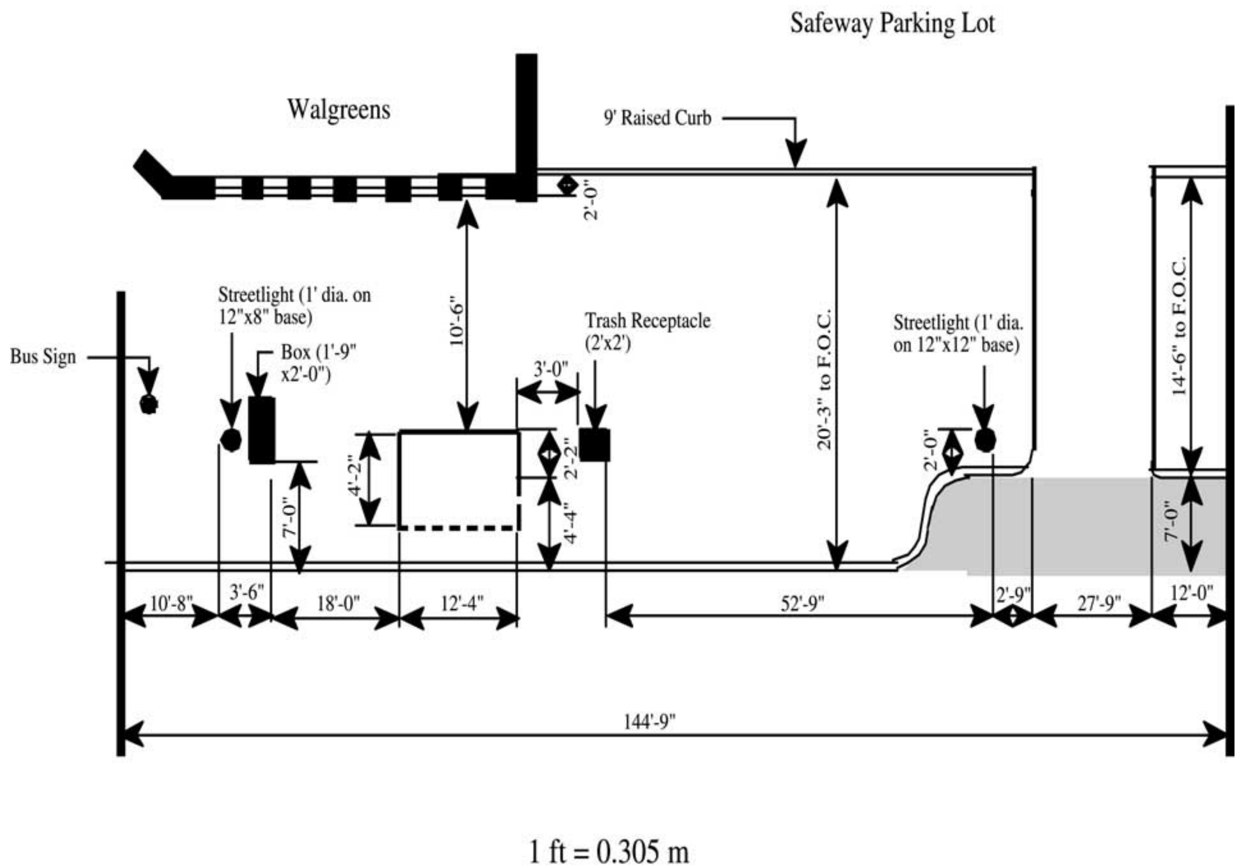


Figure B-5. Mission @ 30th Street Bus Bulb Dimensions.

Figure B-6. Bus Bay Configuration.

Figure B-7. Bus Bulb Configuration.

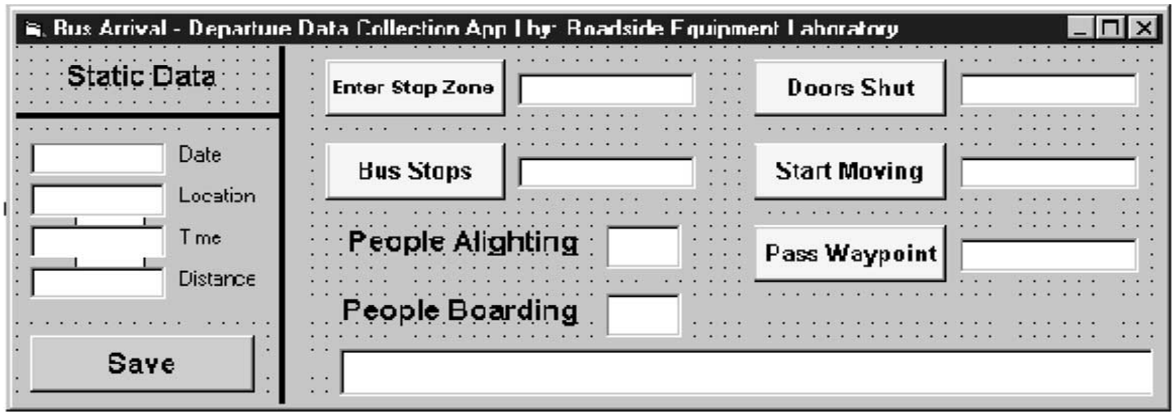
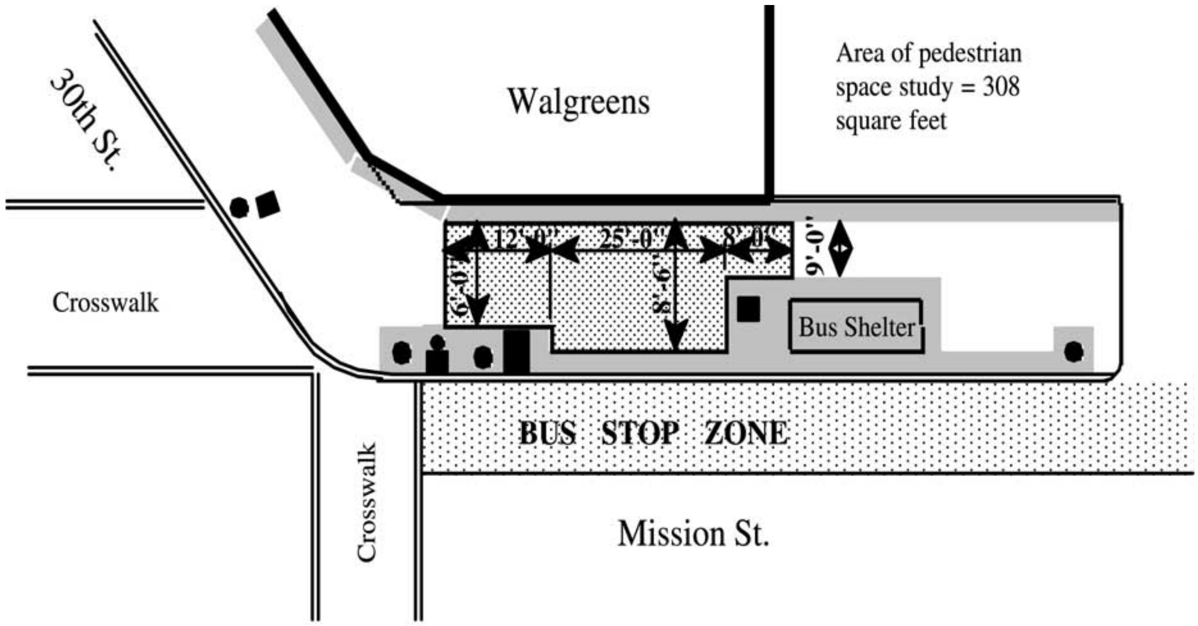
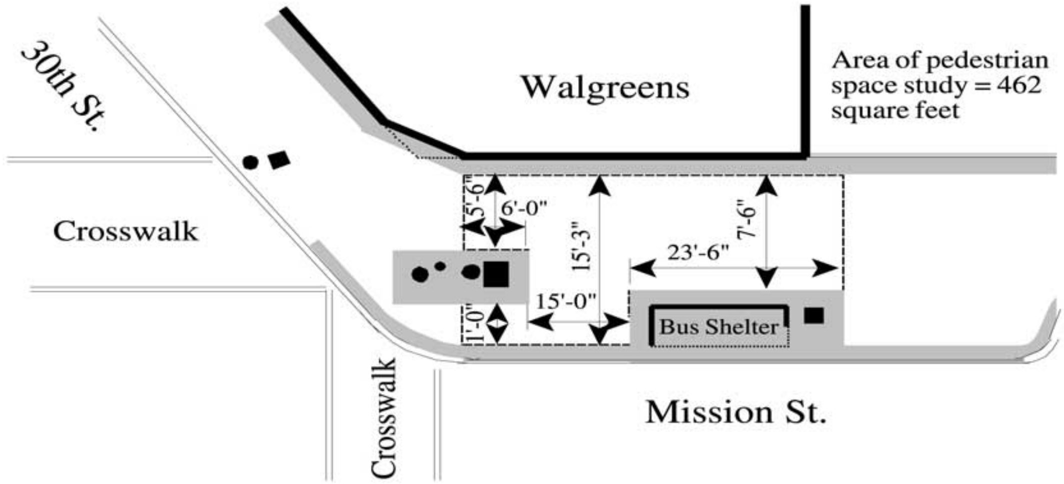


Figure B-8. Palmtop Screen.



1 ft = 0.305 m

Figure B-9. Walkway Space Study (Bus Bay Configuration).



1 ft = 0.305 m

Figure B-10. Walkway Space Study (Bus Bulb Configuration).

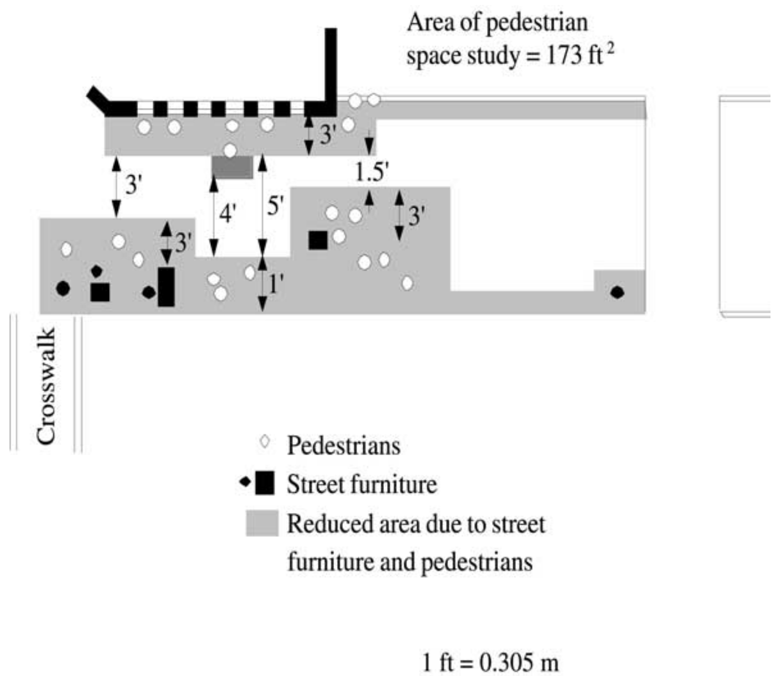


Figure B-11. Common Pedestrian Waiting Areas at Bus Bay.

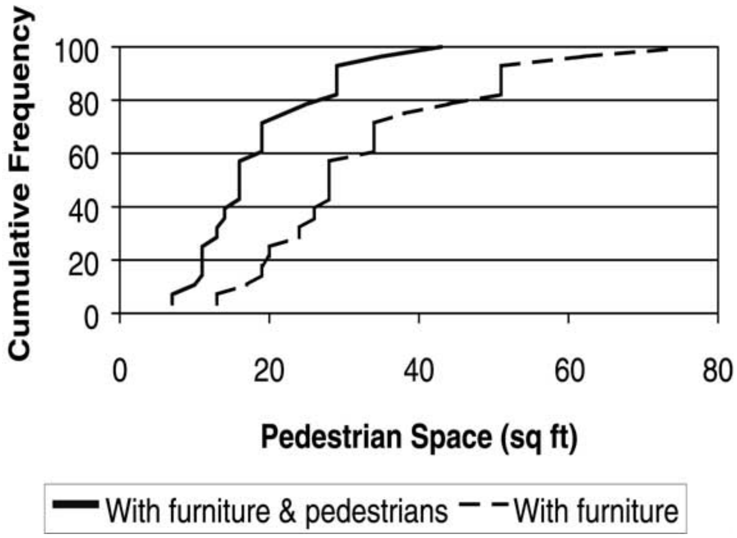


Figure B-12. Comparison of Pedestrian Space When Bus Is Present in the Zone.

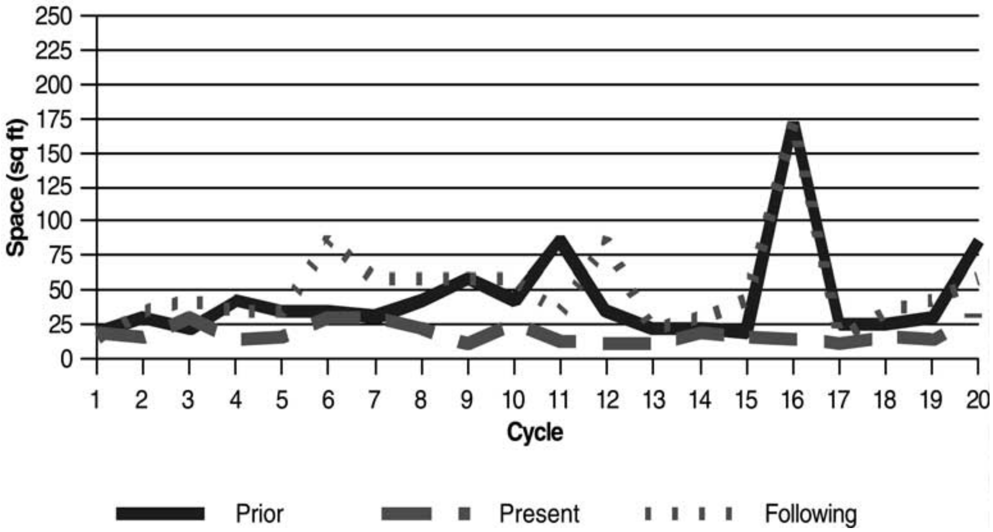


Figure B-13. Pedestrian Space with Reduced Area at Bus Bay.

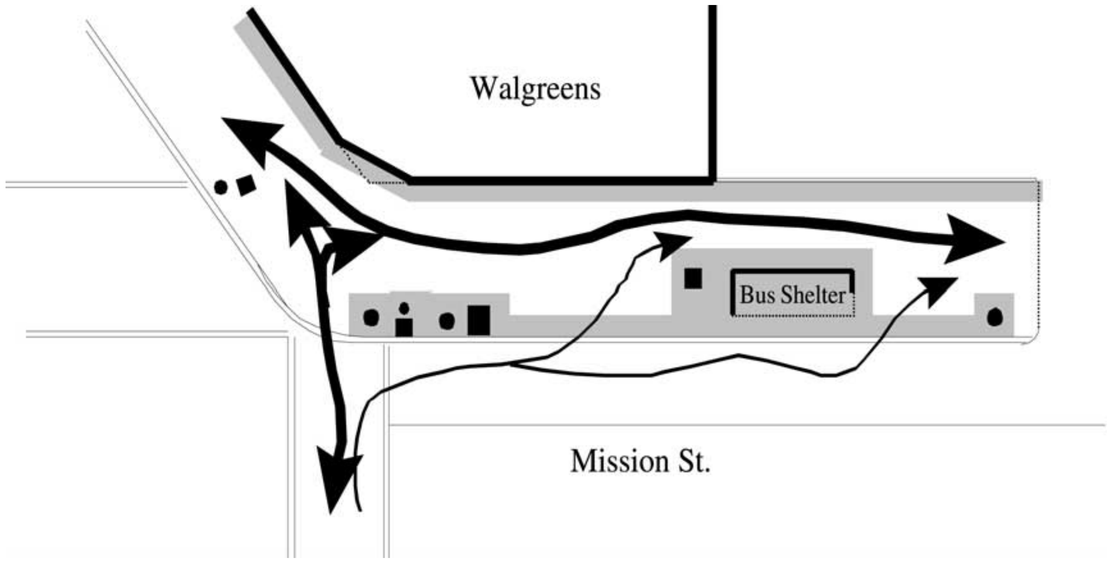
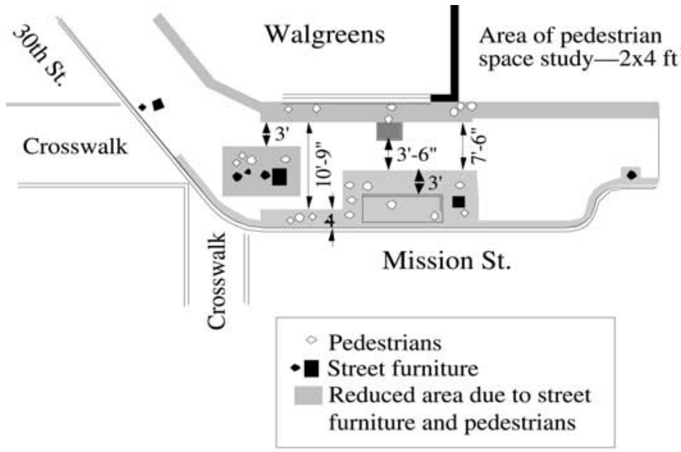


Figure B-14. Common Walkway Paths Through the Bus Bay Zone.



1 ft = 0.305 m

Figure B-15. Common Pedestrian Waiting Areas at Bus Bulb.

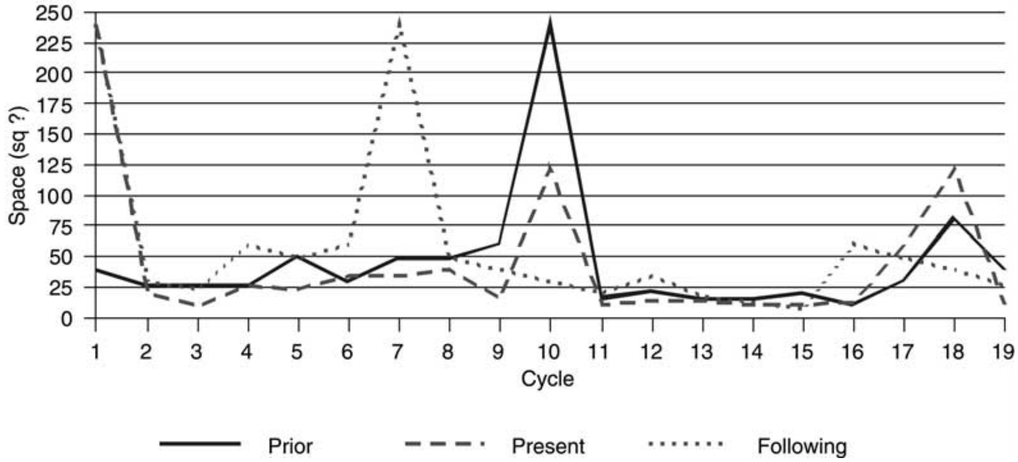


Figure B-16. Pedestrian Space with Reduced Study Area at Bus Bulb.

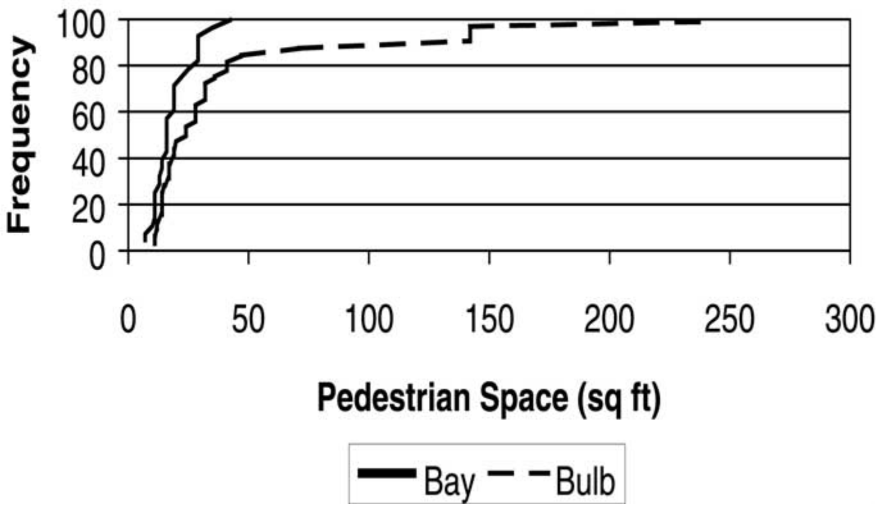


Figure B-17. Comparison of Pedestrian Space Available During Boarding/Alighting Activities (Bus is *Present*).

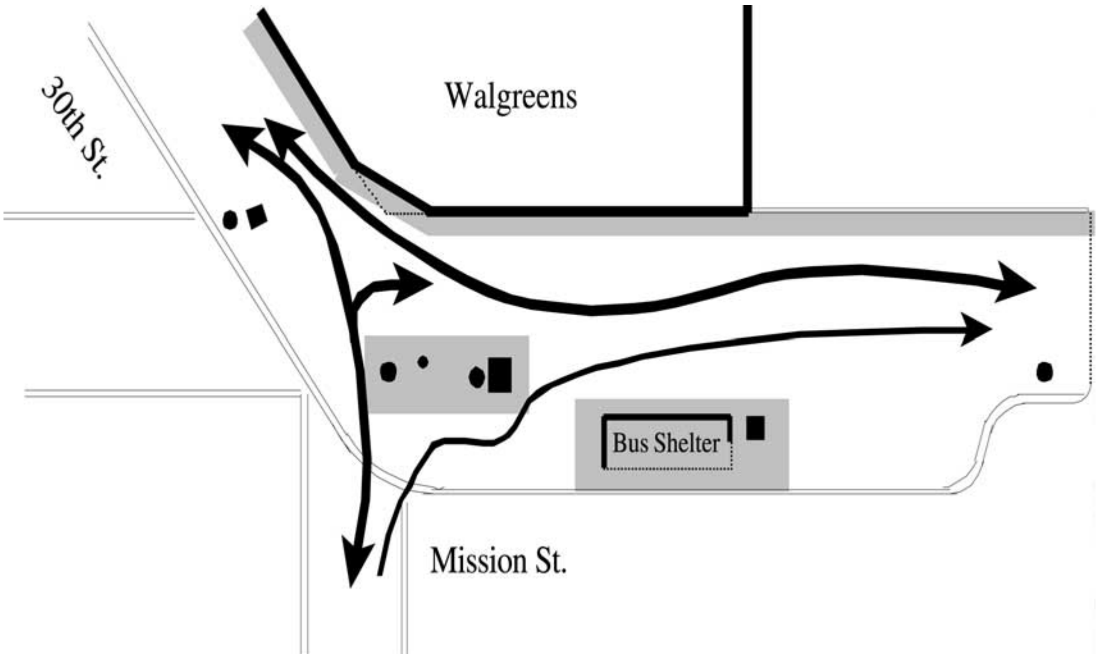


Figure B-18. Common Walkway Paths (Bulb Configuration).

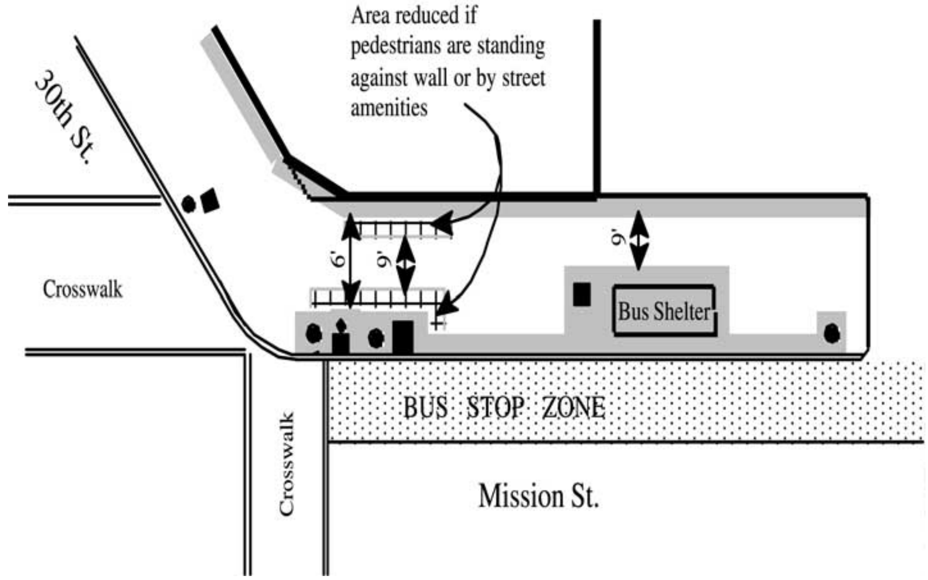


Figure B-19. Sidewalk LOS Study Area of Bus Bay.

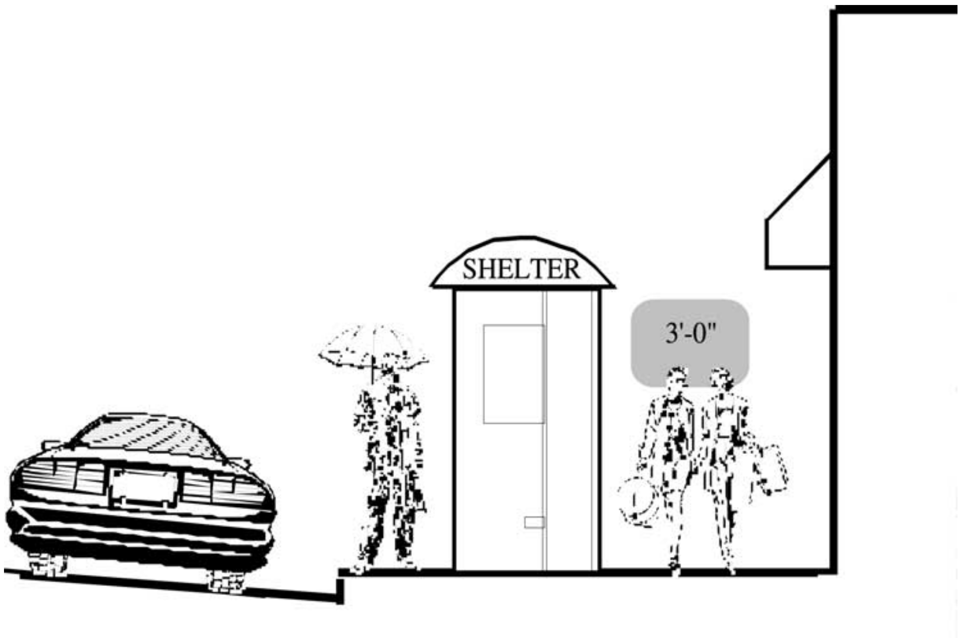


Figure B-20. Cross-Section of Effective Walkway Width Between Bus Shelter and Walgreens (Bay Configuration).

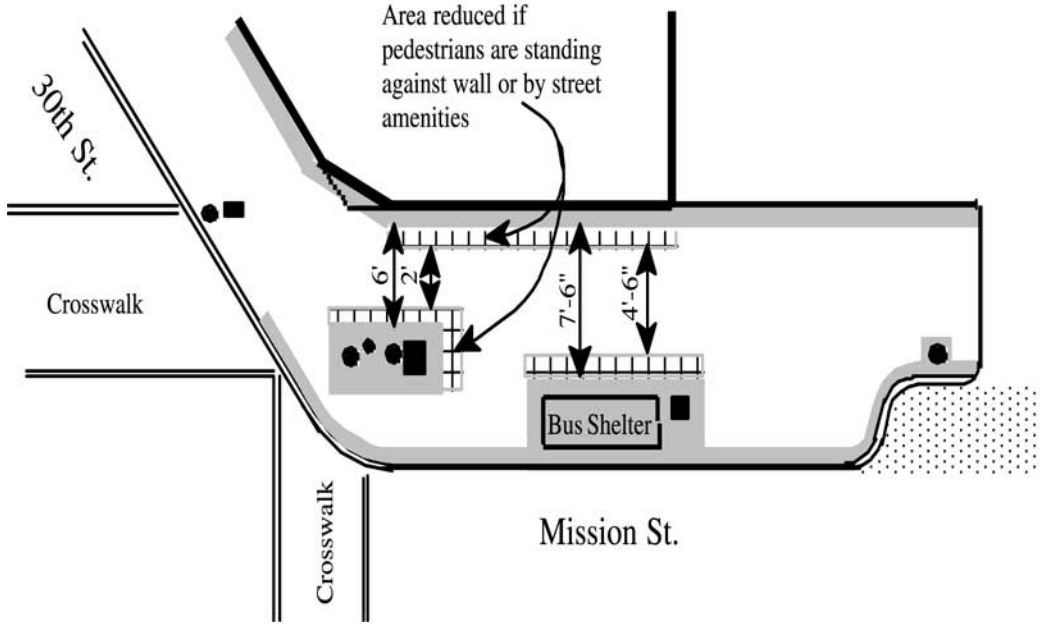


Figure B-21. Sidewalk LOS Study Area of the Bus Bulb Configuration.

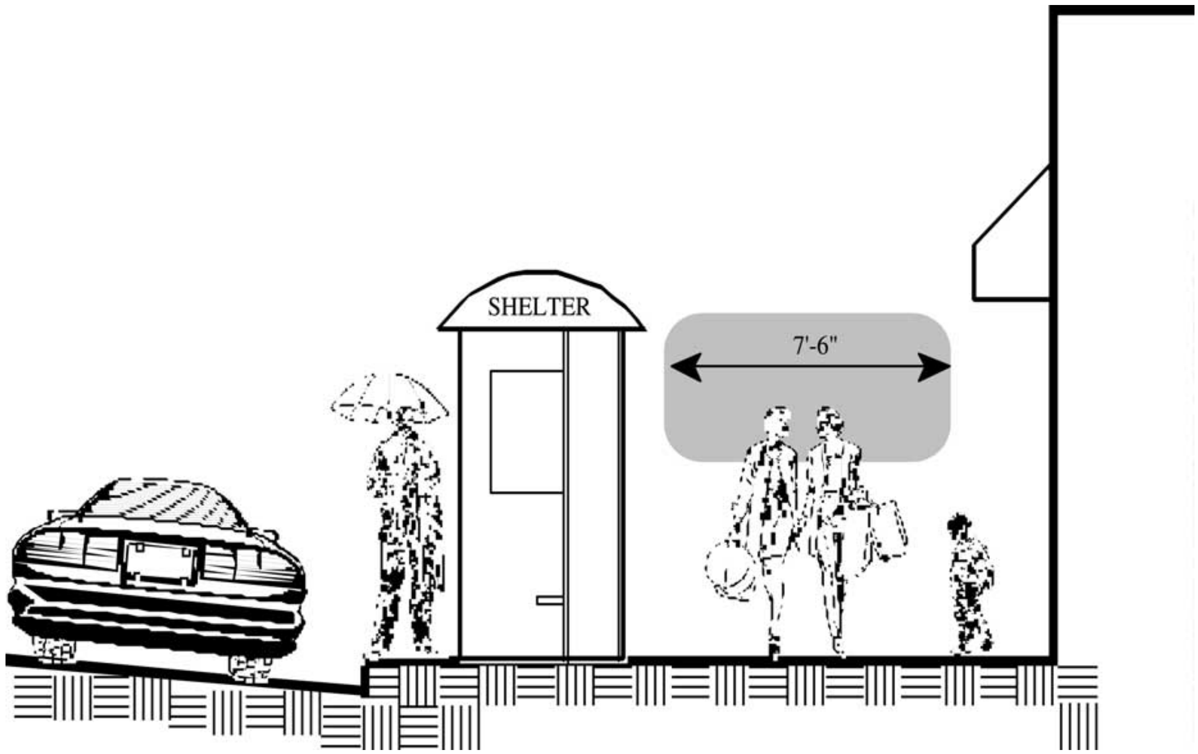


Figure B-22. Cross-Section of Effective Walkway Width Between Bus Shelter and Walgreens (Bulb Configuration).

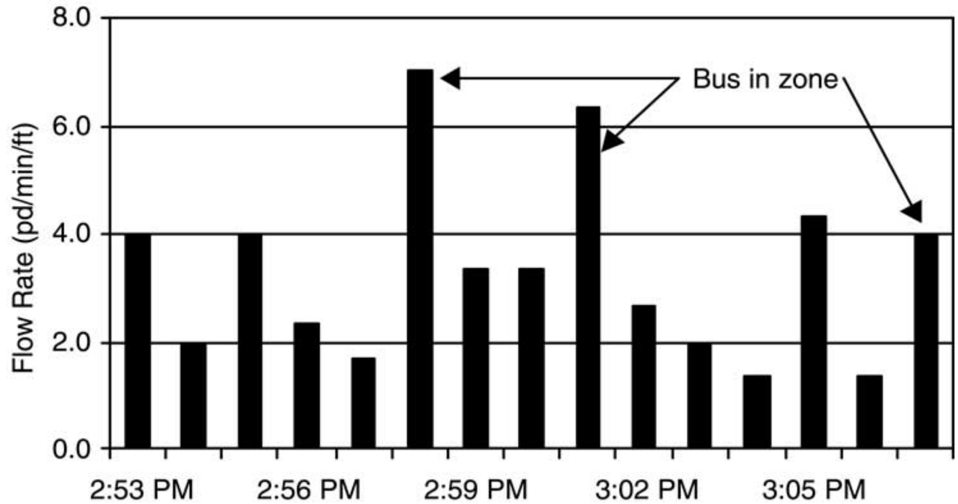


Figure B-23. Summary of Peak 15-Minute Period Divided Into One-Minute Intervals.

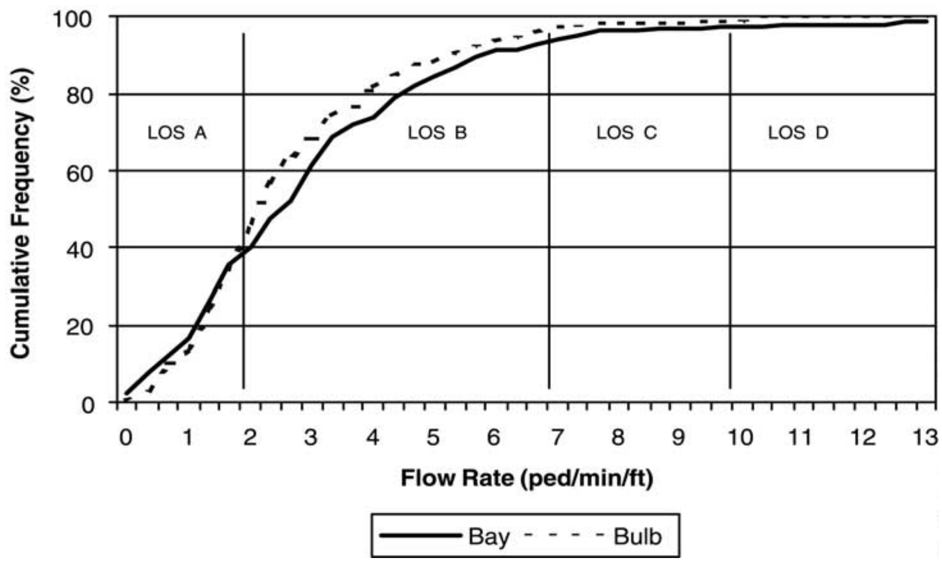


Figure B-24. Pedestrian Flow Rates (Using Data Divided into One-Minute Segments).

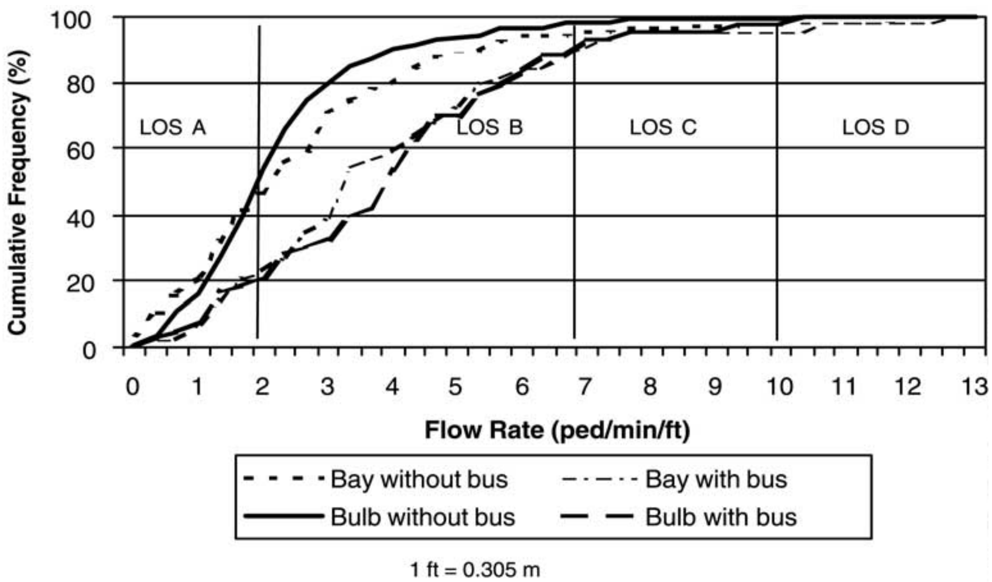


Figure B-25. Pedestrian Flow Rates.

Figure B-26. Corner of Mission @ 30th Street (Bus Bay Configuration).

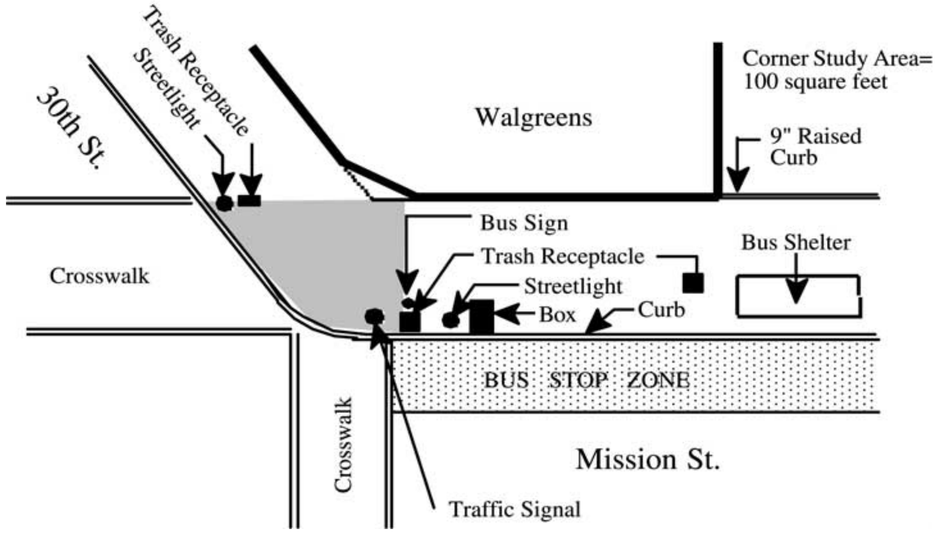


Figure B-27. Corner LOS Study Area for Bus Bay.

Figure B-28. Corner of Mission @ 30th Street (Bus Bulb Configuration).

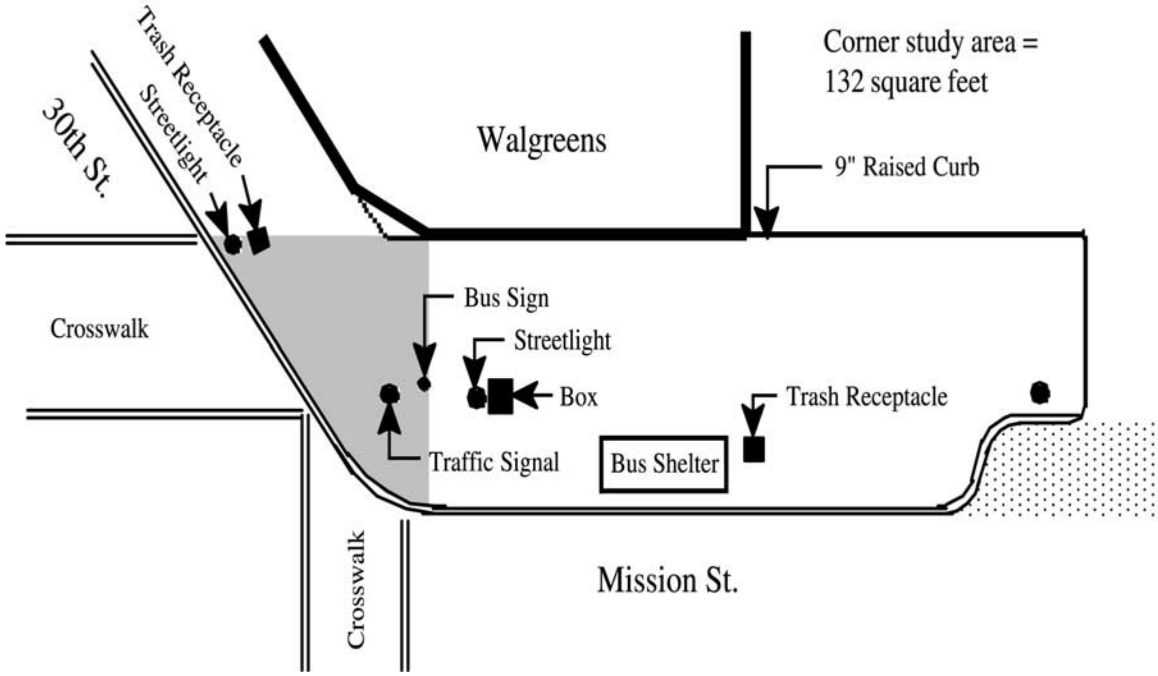
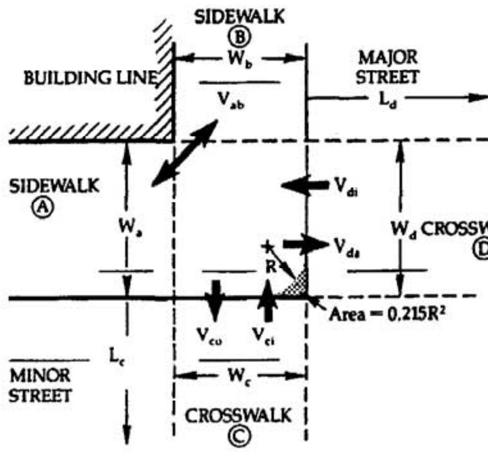


Figure B-29. Corner LOS Study Area for Bus Bulb Configuration.

STREET CORNER ANALYSIS WORKSHEET

Location: ______________________

City, State: ______________________



SIGNAL TIMING (sec)

C = ________

G_{mj} = ________ R_{mj} = ________

G_{mi} = ________ R_{mi} = ________

PEDESTRIAN VOLUMES

Flow	Ped/Min	Ped/Cyc
v_{ci}		
v_{co}		
v_{di}		
v_{do}		
$v_{a,b}$		
v_{tot}		

NET CORNER AREA $A = W_a W_b - 0.215R^2 =$ ________ sq ft

AVAILABLE TIME-SPACE $TS = A \times C/60 =$ ________ sq ft-min

HOLD AREA WAITING TIMES
(use ped/cycle)

$Q_{tco} = [(v_{co})(R_{mj}/C)(R_{mj}/2)]/60 =$ ________ ped-min

$Q_{tdo} = [(v_{do})(R_{mi}/C)(R_{mi}/2)]/60 =$ ________ ped-min

HOLD AREA TIME-SPACE

$TS_h = 5(Q_{tco} + Q_{tdo}) =$ ________ sq ft-min

CIRCULATION TIME-SPACE

$TS_c = TS - TS_h =$ ________ sq ft-min

TOTAL CIRCULATION VOLUME

$v_c = v_{ci} + v_{co} + v_{do} + v_{di} + v_{a,b} =$ ________ ped

TOTAL CIRCULATION TIME

$t_c = v_c \times 4/60 =$ ________ ped-min

PEDESTRIAN SPACE AND LOS

$M = TS_c/t_c =$ ________ sq ft/ped; LOS = ________
(Table 13-3)

Figure B-30. ***Highway Capacity Manual*** **Corner LOS Worksheet.** [1]

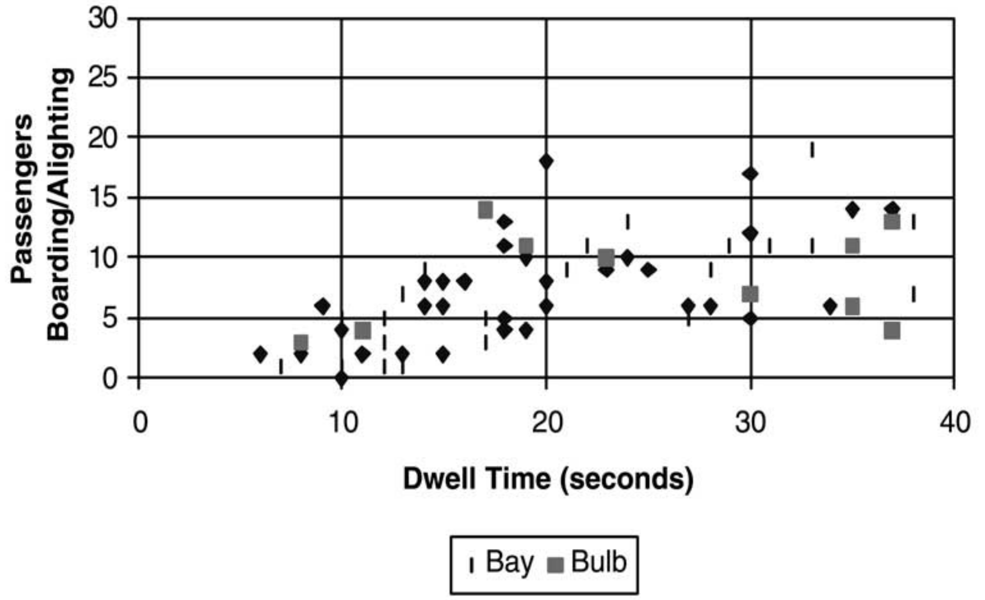


Figure B-31. Mission @ 30th Southbound Off-Peak Dwell Times.

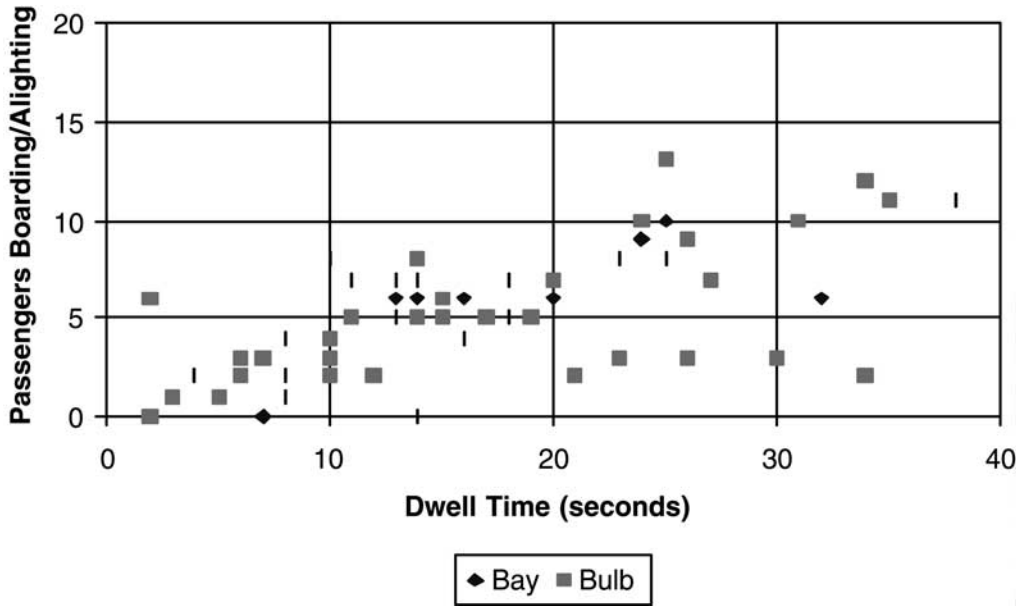


Figure B-32. Mission @ 30th Northbound Peak Bus Dwell Times.

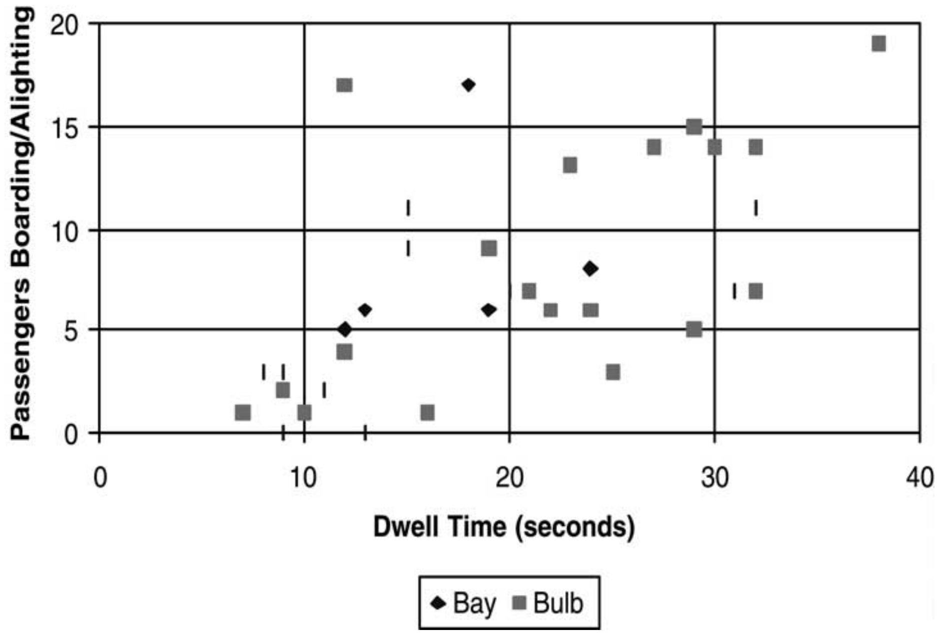


Figure B-33. Mission @ 30th Southbound Peak Bus Dwell Times.

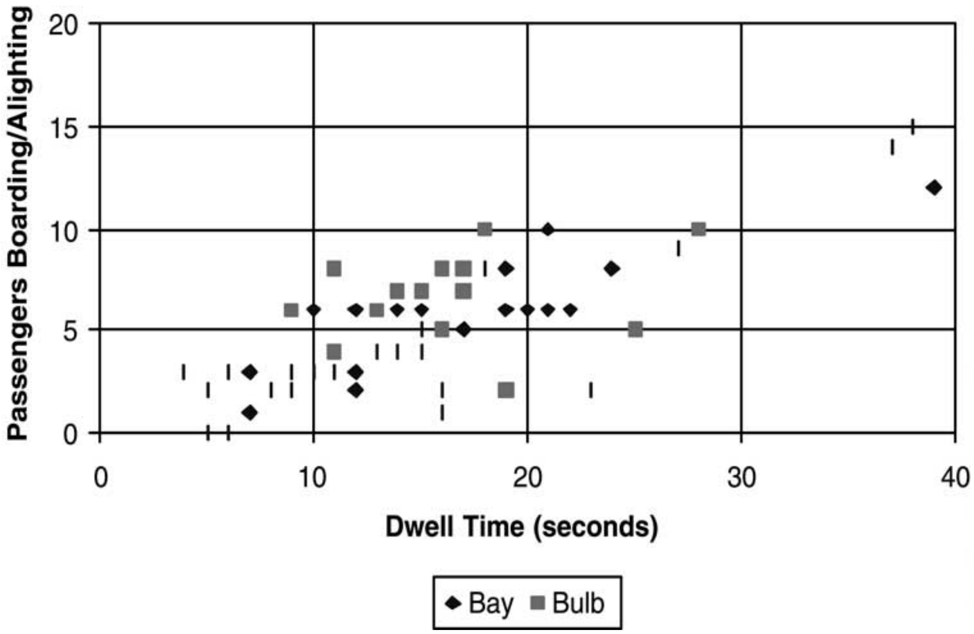


Figure B-34. Mission @ 30th Northbound Off-Peak Bus Dwell Times.

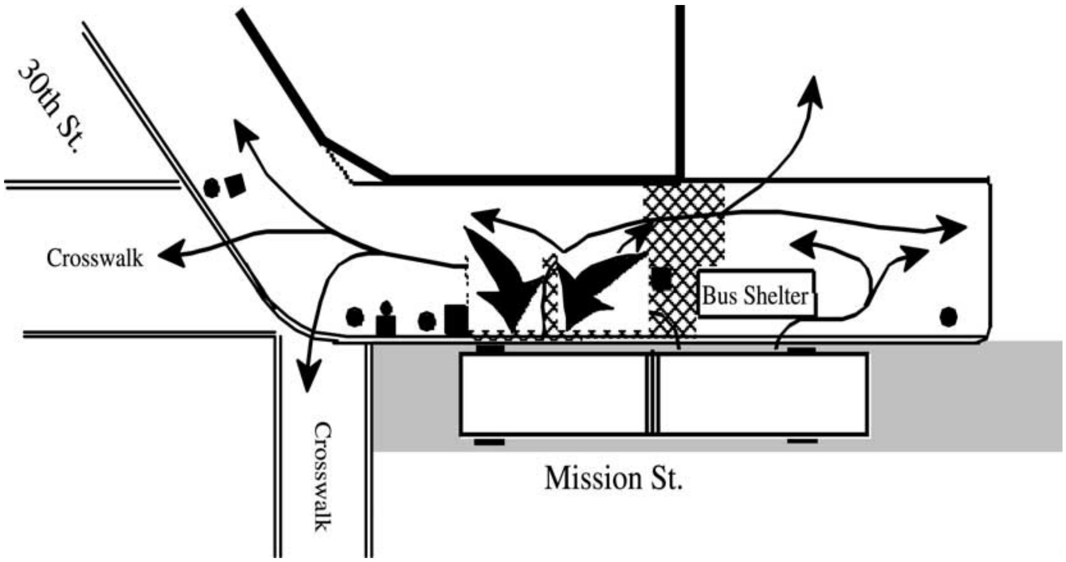


Figure B-35. Pedestrian Walking Paths (Bay Configuration).

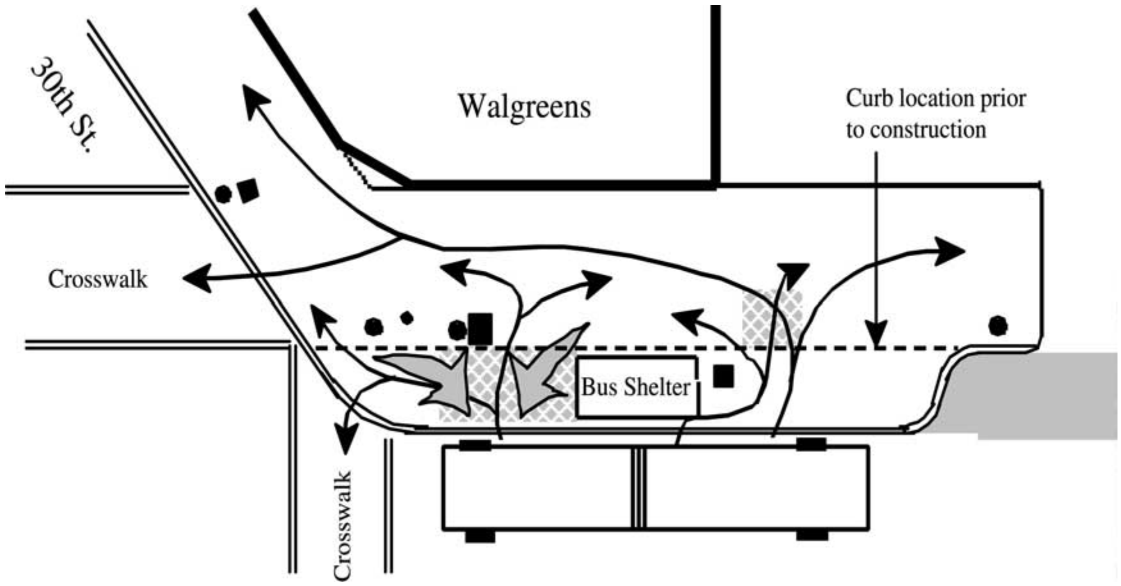


Figure B-36. Pedestrian Walking Paths (Bulb Configuration).

Table B-1. Data Collected for Each Pedestrian Study.

<table>
<tr><th rowspan="2">Study</th><th colspan="3">Data to be Collected</th></tr>
<tr><th>Fixed Data (same for each record)</th><th>For Each Record</th><th>Additional Field(s)</th></tr>
<tr><td>Sidewalk LOS</td><td>• Date
• Location
• Time</td><td>• Clicker (accounts for one person per direction per keystroke)
• Time stamp
• Direction traveling
• Comment field</td><td>• Time stamp for bus arrival
• Time stamp for bus departure</td></tr>
<tr><td>Pedestrian Space</td><td>• Date
• Location
• Time</td><td>• Section number
• Data field (number of people in section)
• Time stamp
• Comment field</td><td>• Time stamp for bus arrival
• Time stamp for bus departure
• Timer (0-60 seconds)
• Beep at one- minute interval</td></tr>
<tr><td>Bus Arrival/ Departure</td><td>• Date
• Location
• Time
• Distance (from end of bus stop zone to fixed point downstream)</td><td>• Time stamp bus enters zone
• Time stamp bus stops
• Time stamp bus doors open
• Time stamp bus starts moving
• Time stamp bus reaches fixed point downstream
• Number of people boarding
• Number of people alighting
• Bus Route
• Bus Number
• Red Light Encountered?
• Comment field</td><td></td></tr>
</table>

Table B-2. Pedestrian Level-of-Service Categories for Walkways.

LOS	Space (sq ft/ped)
A	$ 130
B	$ 40
C	$ 24
D	$ 15
E	$ 6

1 sq ft = 0.093 sq m

Table B–3. Available Space and Resulting LOS for Bus Bay Stop Configuration.

Total Available Area Without Waiting Patrons/Pedestrians (308 sq ft) [28.6 sq m]							
Day/Cycle		Prior[a]		Present[b]		Following[c]	
		Space[d]	LOS[e]	Space	LOS	Space	LOS
1	1	34	C	28	C	28	C
1	2	51	B	28	C	62	B
1	3	38	C	51	B	77	B
1	4	77	B	26	C	62	B
1	5	62	B	28	C	62	B
1	6	62	B	51	B	154	A
1	7	51	B	51	B	103	B
1	8	77	B	38	C	103	B
1	9	103	B	20	D	103	B
1	10	77	B	44	B	103	B
1	11	154	A	24	D	62	B
1	12	62	B	19	D	154	A
1	13	38	C	17	D	38	C
1	14	38	C	34	C	51	B
1	15	34	C	28	C	77	B
1	16	308	A	26	C	308	A
1	17	44	B	19	D	28	C
1	18	44	B	28	C	62	B
1	19	51	B	24	C	77	B
1	20	154	A	62	B	103	B
2	1	24	C	13	E	62	B
2	2	51	B	20	D	38	B
2	3	51	B	34	C	62	B
2	4	77	B	77	B	103	B
2	5	103	B	51	B	51	B
2	6	15	D	13	E	26	C
2	7	51	B	34	C	44	B
2	8	44	B	34	C	31	C

[a] Prior = one minute prior to bus arriving
[b] Present = while patrons are boarding and alighting
[c] Following = one minute following bus departure
[d] Space available for each pedestrian (sq ft/pedestrian)
[e] Based on *Highway Capacity Manual* categories (see Table B–2)
1 sq ft = 0.093 sq m

Table B-4. Summary of Initial Observations at Bus Bay Configuration.

Level of Service	Space (sq ft/ped)	Prior	Present	Following
A	$ 130	3	-	3
B	$ 40	18	7	20
C	$ 24	5	13	5
D	$ 15	1	6	-
E	$ 6	-	2	-

Table B–5. Comparison of Available Space at Bus Bay Configuration.

Day/ Cycle		Without Waiting Patrons/Pedestrians = 308 sq ft (28.6 sq m)						With Waiting Patrons/Pedestrians = 173 sq ft (16.1 sq m)					
		Prior[a]		Present[b]		Following[c]		Prior		Present		Following	
		Space[d]	LOS[e]	Space	LOS	Space	LOS	Space	LOS	Space	LOS	Space	LOS
1	1	34	C	28	C	28	C	19	D	16	D	16	D
1	2	51	B	28	C	62	B	29	C	16	D	35	C
1	3	38	C	51	B	77	B	22	D	29	C	43	B
1	4	77	B	26	C	62	B	43	B	14	E	35	C
1	5	62	B	28	C	62	B	35	C	16	D	35	C
1	6	62	B	51	B	154	A	35	C	29	C	86	B
1	7	51	B	51	B	103	B	29	C	29	C	58	B
1	8	77	B	38	C	103	B	43	B	22	D	58	B
1	9	103	B	20	D	103	B	58	B	11	E	58	B
1	10	77	B	44	B	103	B	43	B	25	C	58	B
1	11	154	A	24	D	62	B	86	B	13	E	35	C
1	12	62	B	19	D	154	A	35	C	11	E	86	B
1	13	38	C	17	D	38	C	22	D	10	E	22	D
1	14	38	C	34	C	51	B	22	D	19	D	29	C
1	15	34	C	28	C	77	B	19	D	16	D	43	B
1	16	308	A	26	C	308	A	173	A	14	E	173	A
1	17	44	B	19	D	28	C	25	C	11	E	16	D
1	18	44	B	28	C	62	B	25	C	16	D	35	C
1	19	51	B	24	C	77	B	29	C	13	E	43	B
1	20	154	A	62	B	103	B	86	B	35	C	58	B
2	1	24	C	13	E	62	B	13	E	7	E	35	C
2	2	51	B	20	D	38	B	29	C	11	E	22	D
2	3	51	B	34	C	62	B	29	C	19	D	35	C
2	4	77	B	77	B	103	B	43	B	43	B	58	B
2	5	103	B	51	B	51	B	58	B	29	C	29	C
2	6	15	D	13	E	26	C	9	E	7	E	14	E
2	7	51	B	34	C	44	B	29	C	19	D	25	C
2	8	44	B	34	C	31	C	25	C	19	D	17	D

[a] Prior = one minute prior to bus arriving
[b] Present = while patrons are boarding and alighting
[c] Following = one minute following bus departure
[d] Space available for each pedestrian (sq ft/pedestrian)
[e] Based on *Highway Capacity Manual* categories (see Table B–2)
1 sq ft = 0.39 sq m

Table B-6. Summary of LOS Readings When Waiting Areas Are Included in LOS Calculations.

Level of Service	Space (sq ft/ped)	Prior	Present	Following
A	$ 130	1	-	1
B	$ 40	8	1	11
C	$ 24	12	6	10
D	$ 15	5	10	5
E	$ 6	2	11	1

Table B-7. Available Space and Resulting LOS for Bus Bulb Configuration.

Day/ Cycle		Total Available Area in Bus Bulb Configuration = 284 sq ft (28.6 sq m)					
		Prior[a]		Present[b]		Following[c]	
		Space[d]	LOS[e]	Space	LOS	Space	LOS
1	1	28	C	20	D	47	B
1	2	28	C	32	C	47	B
1	3	16	D	12	E	36	C
1	4	36	C	28	C	57	B
1	5	32	C	24	C	47	B
1	6	36	C	28	C	28	C
1	7	15	D	15	D	142	A
1	8	24	C	32	C	16	D
1	9	14	E	11	E	28	C
1	10	28	C	36	C	95	B
1	11	71	B	142	A	95	B
1	12	32	C	17	D	41	B
1	13	41	B	19	D	36	C
2	1	47	B	284	A	284	A
2	2	32	C	24	C	36	C
2	3	32	C	11	E	28	C
2	4	32	C	32	C	71	B
2	5	57	B	28	C	57	B
2	6	36	C	41	B	71	B
2	7	57	B	41	B	284	A
2	8	57	B	47	B	57	B
2	9	71	B	19	D	47	B
2	10	284	A	142	A	36	C
2	11	18	D	12	E	24	C
2	12	24	C	17	D	41	B
2	13	18	D	17	D	20	D
2	14	19	D	14	E	15	D
2	15	22	D	14	E	9	E
2	16	12	E	14	E	71	B
2	17	36	C	71	B	57	B
2	18	95	B	142	A	47	B
2	19	47	B	14	E	32	C

[a] Prior = one minute prior to bus arriving
[b] Present = while patrons are boarding and alighting
[c] Following = one minute following bus departure
[d] Space available for each pedestrian (Sq ft/pedestrian)
[e] Based on *Highway Capacity Manual* categories (see Table B-2)
1 sq ft = 0.093 sq m

Table B-8. LOS comparison Between a Curbside Bus Stop and a Bus Bulb Configuration [a].

LOS	Curbside Bus Stop[b]						Bus Bulb Bus Stop[c]					
	Prior		Present		Following		Prior		Present		Following	
	Total[d]	%	Total	%	Total	%	Total	%	Total	%	Total	%
A	1	4	0	0	1	4	1	3	4	13	3	9
B	8	29	1	4	11	39	9	28	4	13	16	50
C	12	43	6	21	10	36	14	44	9	28	9	28
D	5	18	10	36	5	18	6	19	7	22	3	9
E	2	7	11	39	1	4	2	6	8	25	1	3

[a] Waiting patrons and pedestrians factored into space calculations
[b] Total of 28 observations
[c] Total of 32 observations
[d] Total observations in each phase by LOS

Table B-9. Average Space and LOS Between Curbside and Bud Bulb Configurations.

Curbside Bus Stop						Bus Bulb Bus Stop					
Prior		Present		Following		Prior		Present		Following	
Space[a]	LOS	Space	LOS	Space	LOS	Space	LOS	Space	LOS	Space	LOS
Without Waiting Patrons and Pedestrians											
71	B	33	C	80	B	71	B	71	B	102	B
Waiting Patrons and Pedestrians Accounted for In Space Calculations											
40	B	19	D	45	B	44	B	44	B	63	B

[a] Space available for each pedestrian (sq ft/pedestrian)
1 sq ft = 0.093 sq m

Table B-10. Comparison of Pedestrian Crowding Conditions Between a Bay and Bulb.

Type of Pedestrian Crowding Condition	Available Space per Pedestrian (sq ft/ped)	Total		Percent of Total		Total Events Occurring When Bus Present		Percent of Events Occurring When Bus Present	
		Bay[a]	Bulb[b]	Bay	Bulb	Bay[c]	Bulb[d]	Bay	Bulb
Crossing Movement Difficult	$ 15	14	14	17%	16%	11	9	40%	28%
Passing Others is Nearly Impossible	$ 18	23	21	27%	22%	16	12	57%	38%
Passing Others is Difficult	$ 35	63	50	75%	52%	27	23	95%	72%

[a] Total number of bus arrival/departure events observed at bay = 84
[b] Total number of bus arrival/departure events observed at bulb = 96
[c] Total number of bus boarding and alighting events observed at bay = 28
[d] Total number of bus boarding and alighting events observed at bulb = 32
1 sq ft = 0.093 sq m

Table B-11. Sidewalk LOS Summary (Peak Period 15-Minute Increments).

Bay				Bulb			
Date	**Time**	**Ped. Flow Rate (pd/min/ft)**	**LOS**	**Date**	**Time**	**Ped. Flow Rate (pd/min/ft)**	**LOS**
Feb. 25, 1999	3:43-3:58 PM	3.7	B	Nov. 12, 1999	2:17-2:32 PM	2.9	B
Feb. 23, 1999	3:48-4:03 PM	3.9	B	Nov. 12, 1999	2:53-3:08 PM	3.3	B
Feb. 25, 1999	3:26-3:41 PM	4.1	B	Nov. 15, 1999	4:13-4:28 PM	3.6	B
Feb. 23, 1999	4:17-4:32 PM	4.3	B	Nov. 15, 1999	3:40-3:55 PM	4.8	B

Table B-12. Sidewalk LOS Using One-Minute Time Increments.

LOS	Flow Rate (ped/min/ft)	Bay		Bulb	
		Observations	Percent	Observations	Percent
A	# 2	60	40%	63	34%
B	# 7	82	54%	113	62%
C	#10	5	3%	6	3%
D	#15	4	3%	2	1%

Table B-13. Summary of Sidewalk Level-of-Service Data.

LOS	Bay Configuration					Bulb Configuration				
	Total	Bus in Zone		Bus not in Zone		Total	Bus in Zone		Bus not in Zone	
		Obs[a]	%[b]	Obs[a]	%[c]		Obs[a]	%[b]	Obs[a]	%[c]
A	60	13	21	47	52	63	8	19	55	39
B	82	41	67	41	46	113	30	70	83	59
C	5	4	8	1	1	6	4	9	2	1
D	4	3	4	1	1	2	1	2	1	1

[a] Number of observations for corresponding LOS
[b] Percent of observations for corresponding LOS when bus is in zone
[c] Percent of observations for corresponding LOS when bus is not in zone

Table B-14. Corner LOS Summary for Peak Cycles.

Configuration	Period	Total Peds	Signal Cycle Length	Area (sq ft)	Ped Space (sq ft/ped)	LOS
Bay	1	34	60	100	41	B
	2	38	60	100	50	B
	3	23	60	100	64	B
Bulb	1	42	60	132	45	B
	2	33	60	132	57	B
	3	30	60	132	61	B

1 sq ft = 0.093 sq m

Table B-15. Resulting LOS at corner of Mission Street and 30th Street.

Site Configuration	Total Signal Cycles	LOS A Cycles	% LOS A	LOS B Cycles	% LOS B
Bay	156	123	79%	33	21%
Bulb	273	234	86%	39	14%

Table B-16. Average Dwell Time [a] Per Passenger Boarding and Alighting (in seconds).

Mission @ 30th Southbound			
Off-Peak		**Peak**	
Bay	Bulb	Bay	Bulb
2.9	3.1	2.4	2.6
Mission @ 30th Southbound			
Off-Peak		**Peak**	
Bay	Bulb	Bay	Bulb
3.2	2.3	2.7	3.4

[a] Dwell times less than 40 sec used in calculations. Longer dwell times were associated with meetings with supervisors rather than boarding and alighting activities.

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.

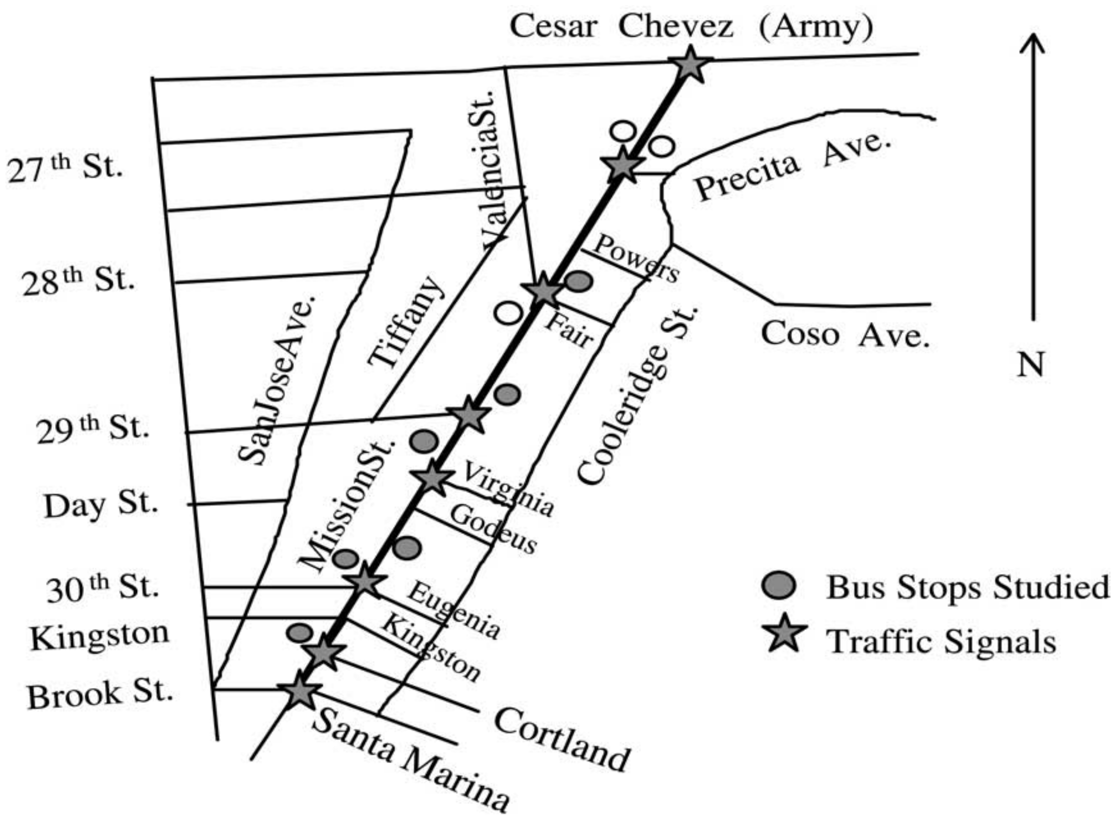
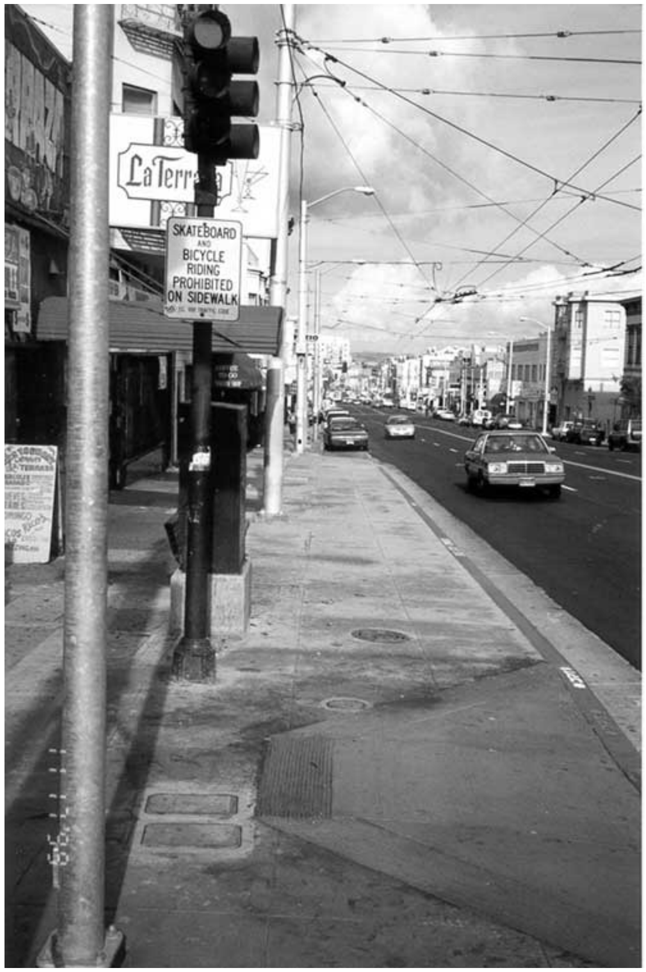


Figure C-1. Study Location.

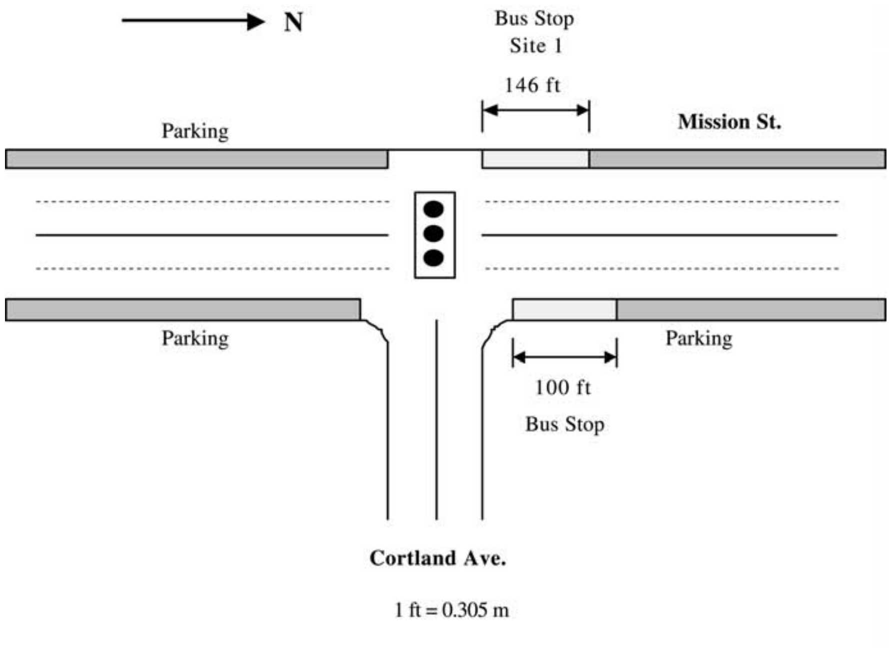
(a) Bus Bay

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



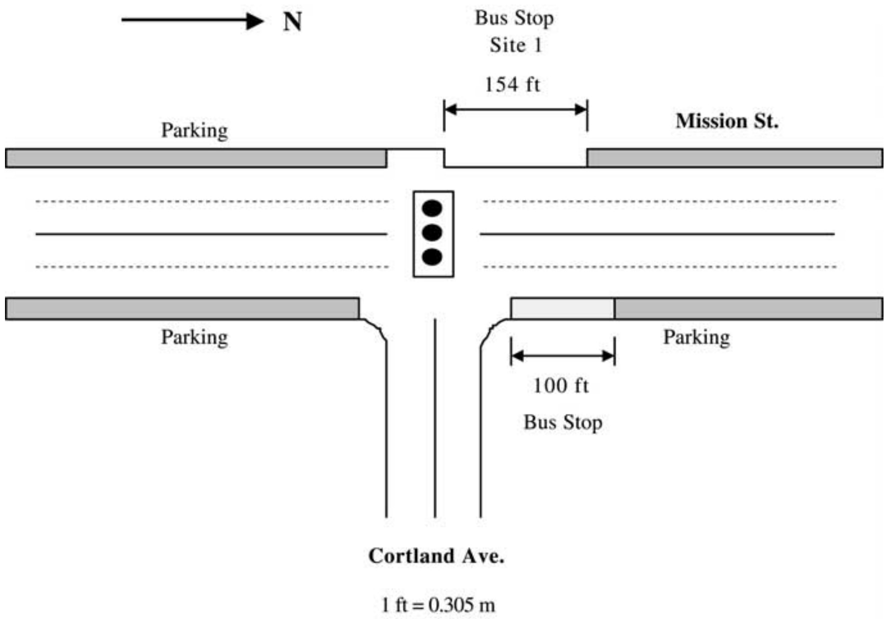
(b) Bus Bulb

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).

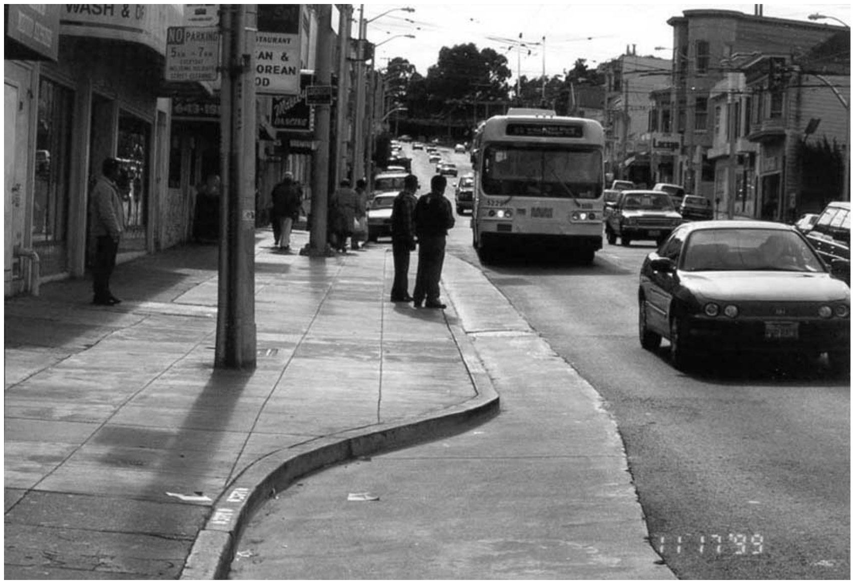
Figure C-4. Bus Stop 2: Southbound on Mission Street at 30th Street.

(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).

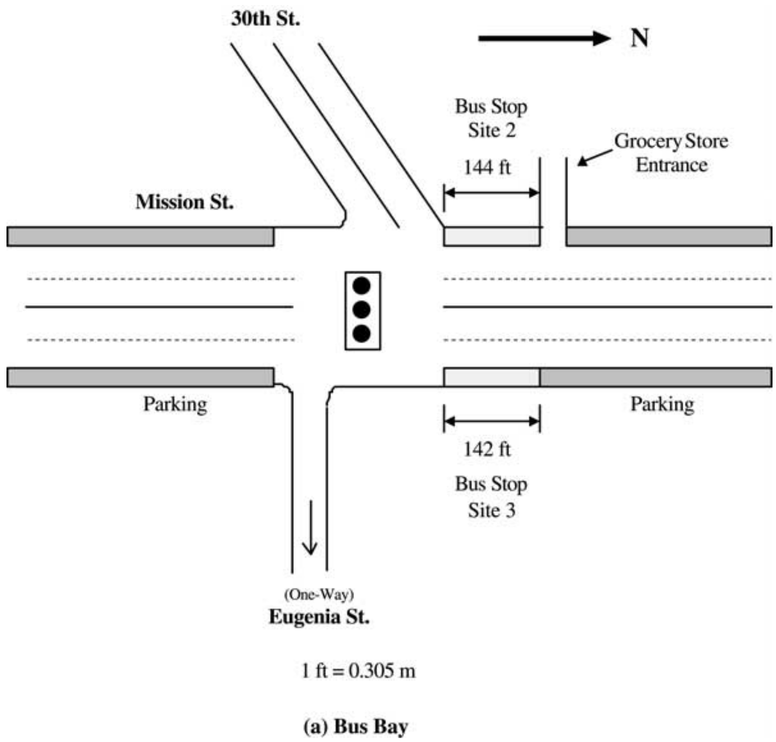


Figure C-6. Site 2 and Site 3: Mission Street at 30th Street.

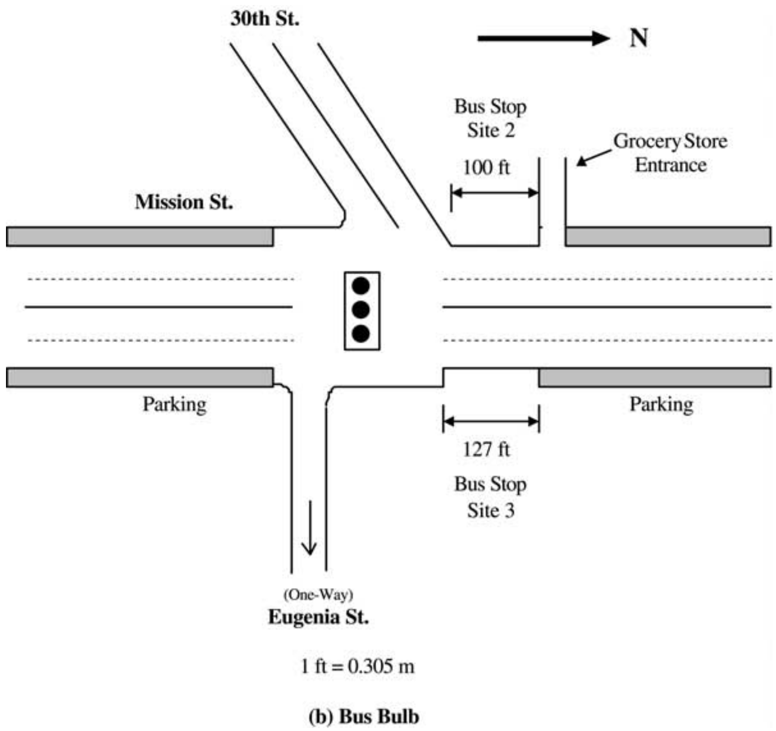


Figure C-6. Site 2 and Site 3: Mission Street At 30th Street (continued).

(a) Bus Bay

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

(b) Bus Bulb

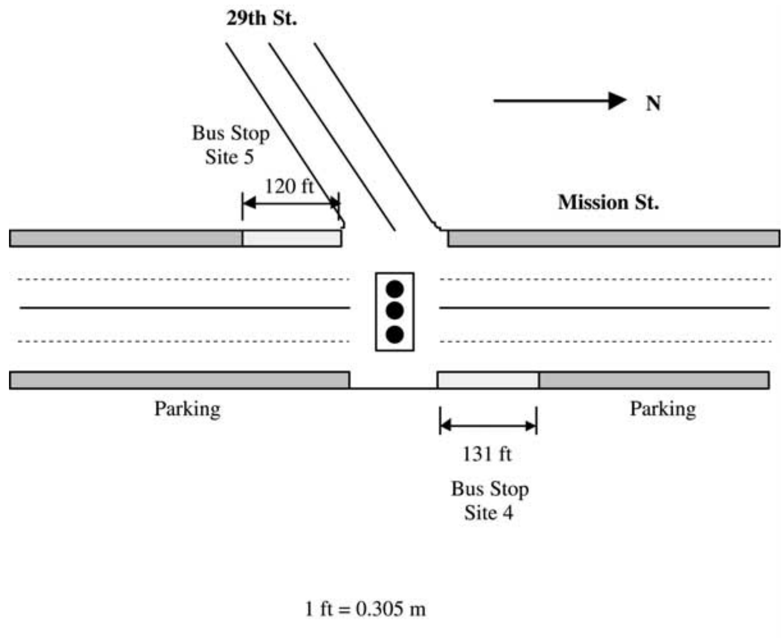
Figure C-7. Bus Stop 4: Northbound on Mission Street at 29th Street (continued).

(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.

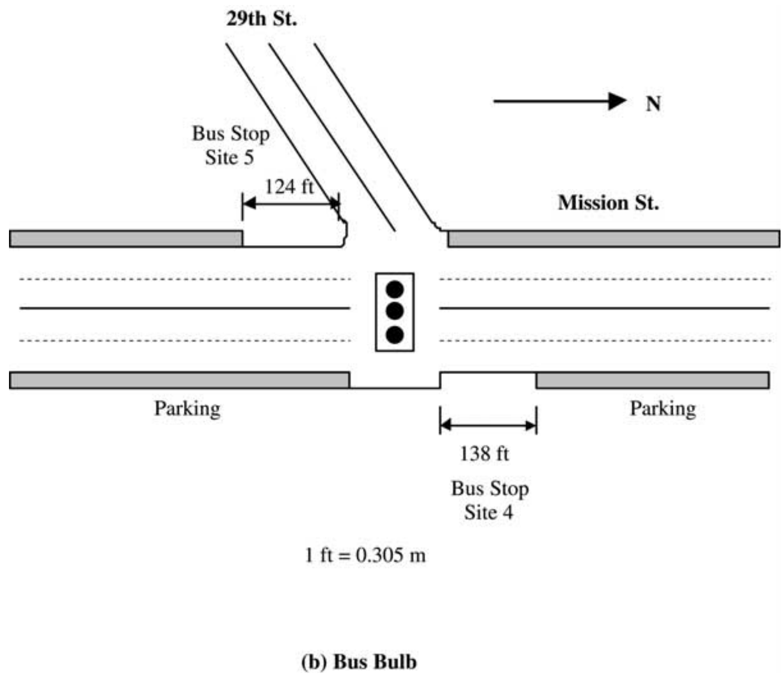


Figure C-9. Site 4 and Site 5: Mission Street At 29^{th} Street (continued).

(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).

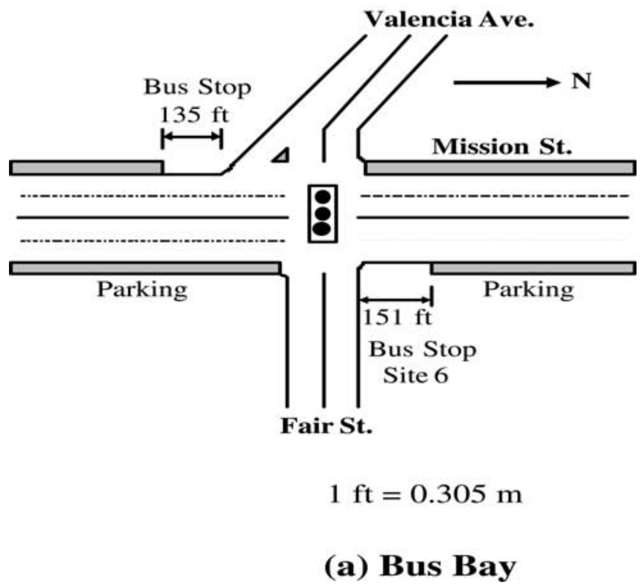
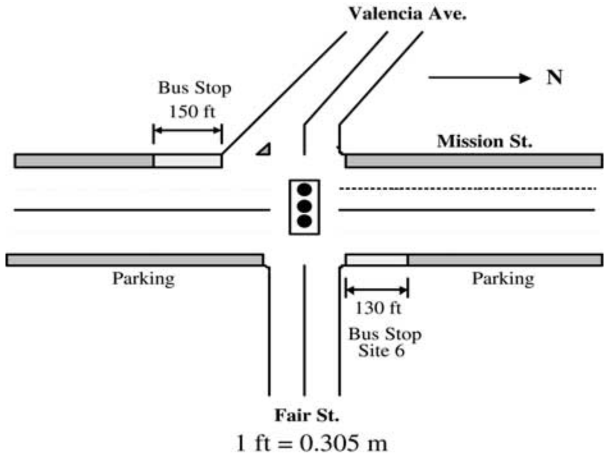


Figure C-11. Site 6: Mission Street at Valencia Street.



(b) Bus Bulb

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

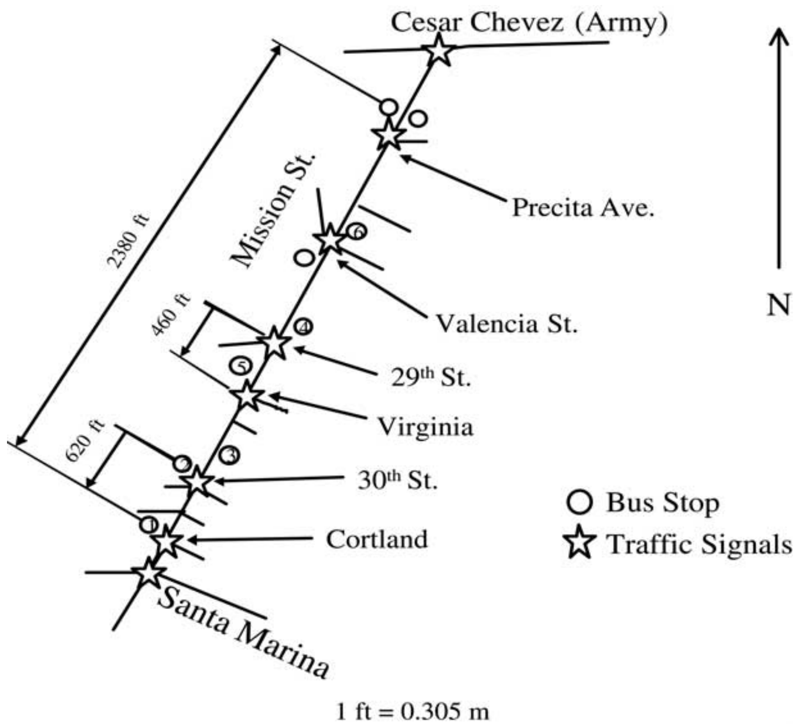


Figure C-12. Travel Time Collection Locations.

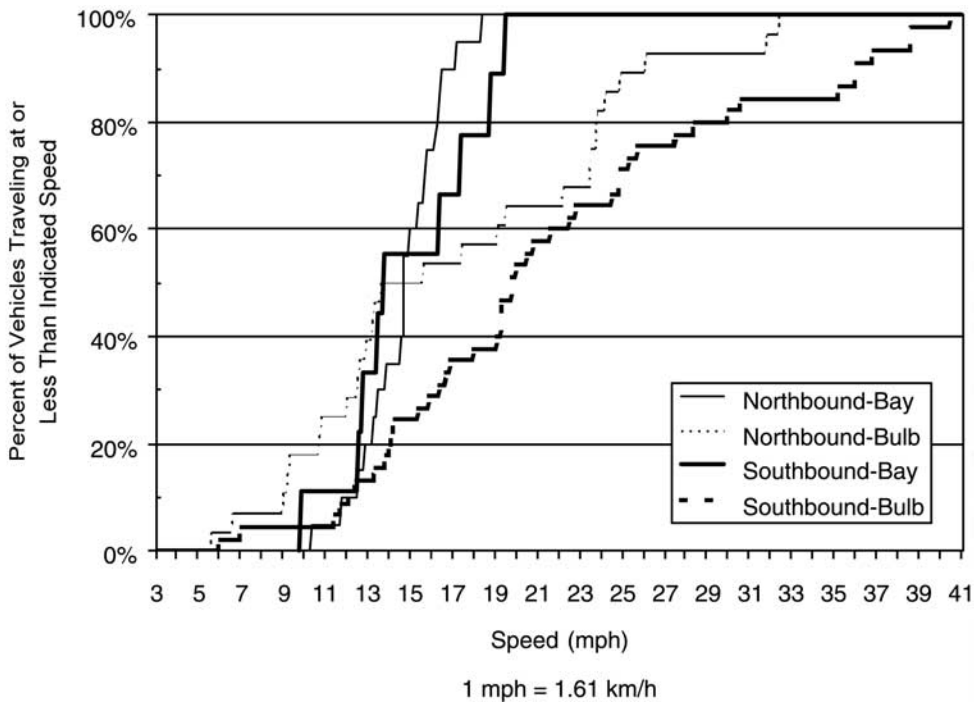


Figure C-13. Vehicle Travel Speeds in Corridor.

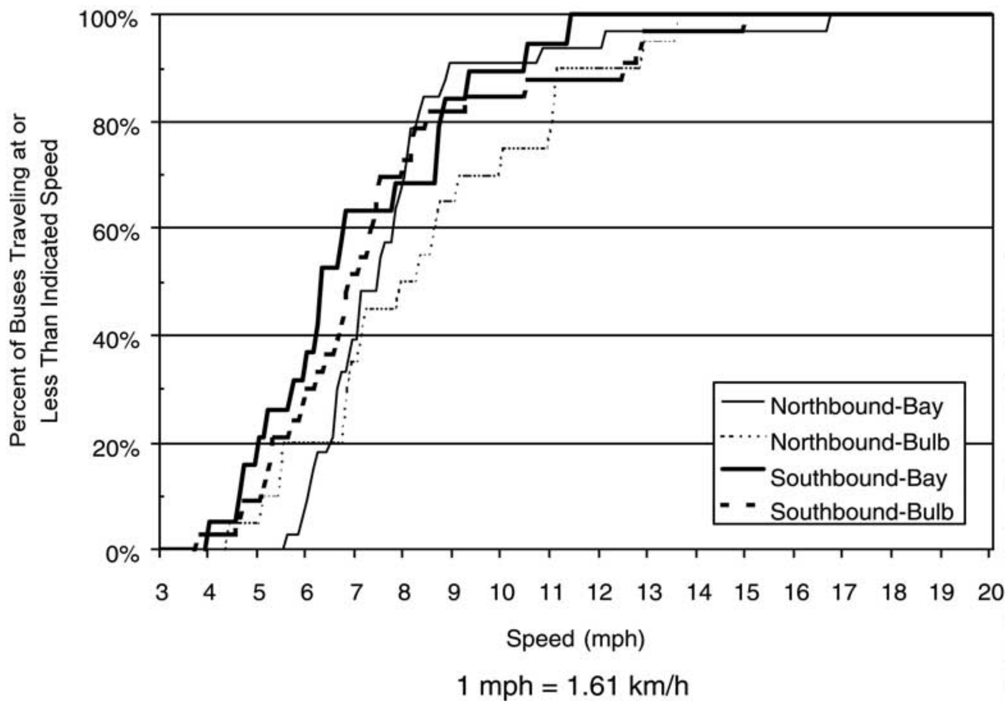


Figure C-14. Bus Speeds in Corridor.

(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.

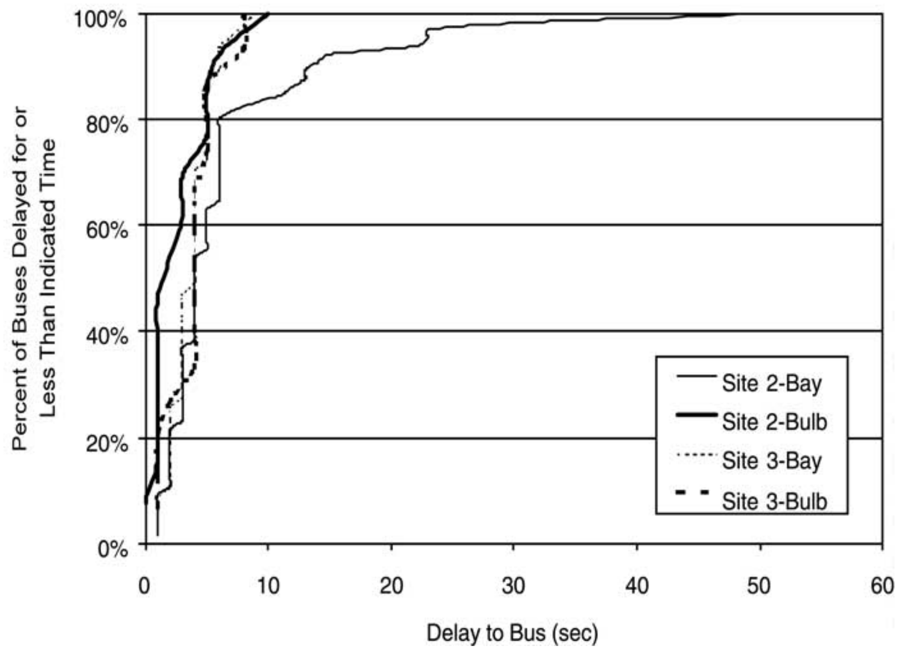


Figure C-18. Non-Peak Bus Delay.

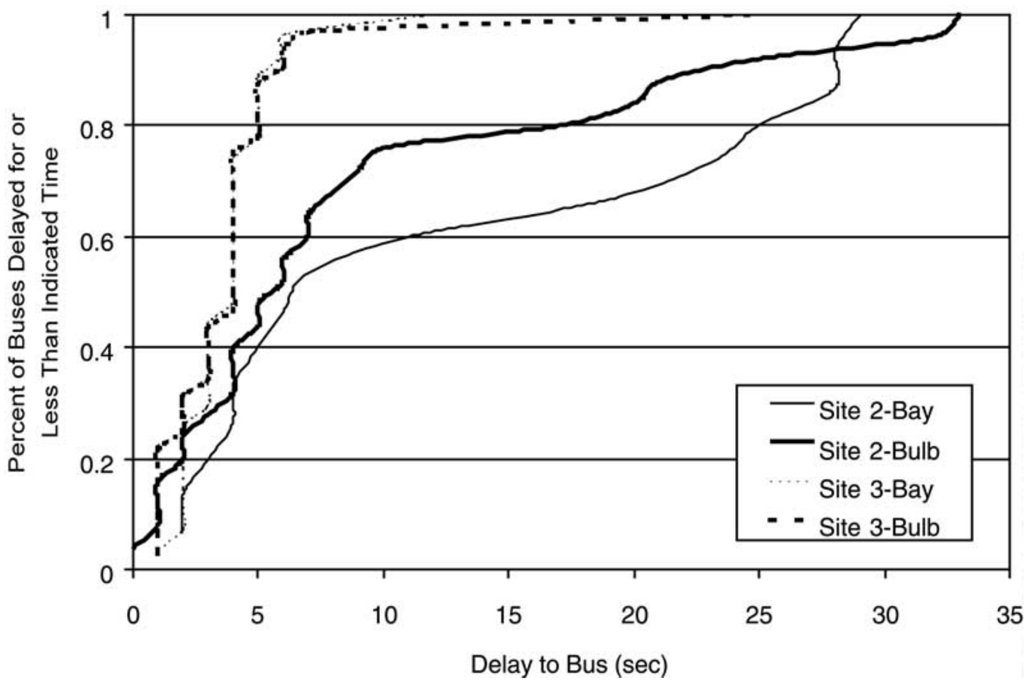


Figure C-19. Peak Bus Delay.

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
Cortland	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 %
	After	Cortland	271 (1 % +)	52 %	--	48 %
30th/Eugenia [b]	Before	Mission-Northbound	617	10 %	89 %	1 %
	After	Mission-Northbound	768 (+ 20 %)	8 %	90 %	2 %
	Before	Mission-Southbound	859	1 %	90 %	9 %
	After	Mission-Southbound	863 (0 %)	1 %	91 %	8 %
29th	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 %
	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 [$\leq$ 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 ($\leq$ 1mph [$\leq$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 ($\leq$ 1mph [$\leq$ 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.

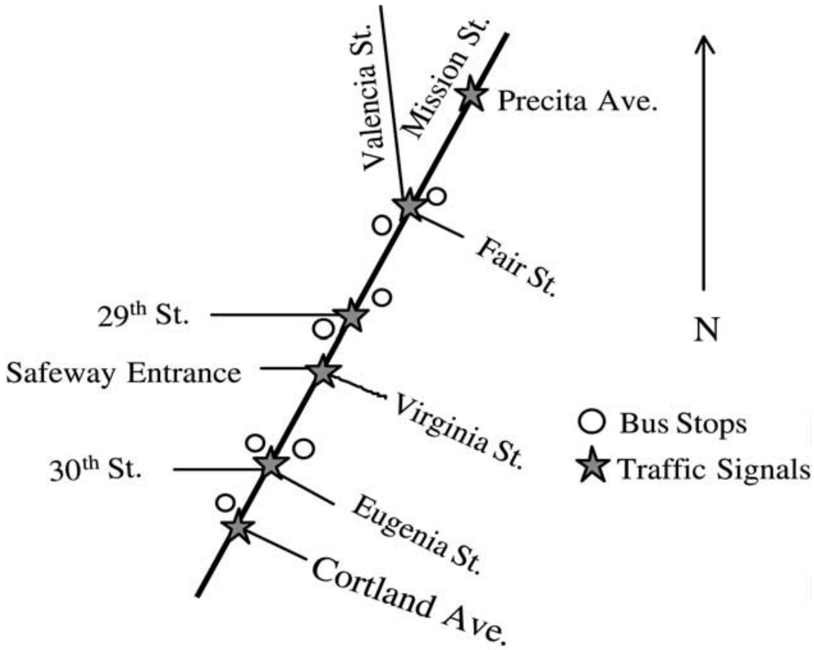


Figure D-1. Corridor and bus Stops Included In the Computer Simulation.

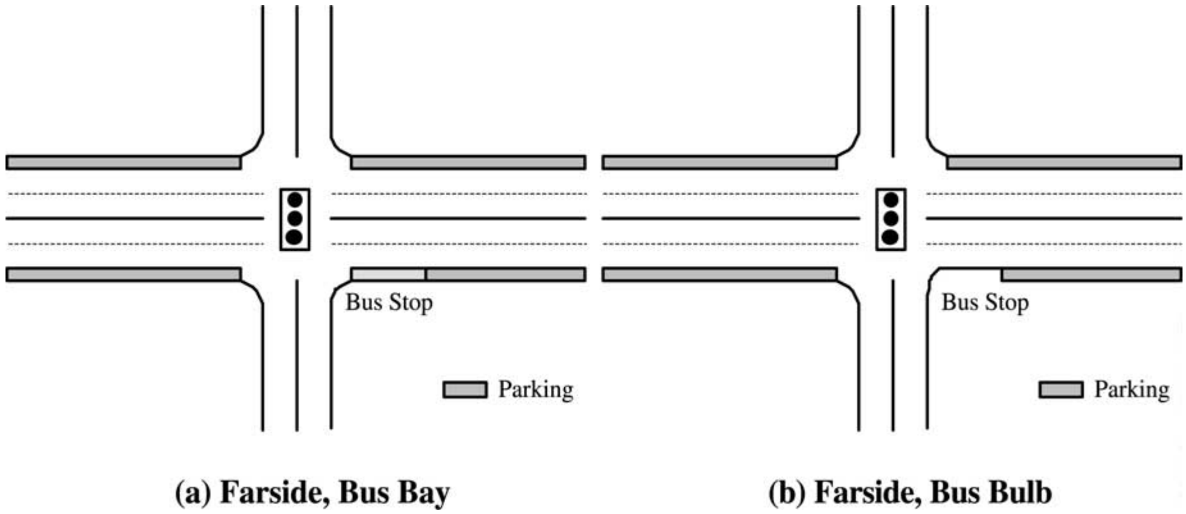


Figure D-2. Farside Bus Stop

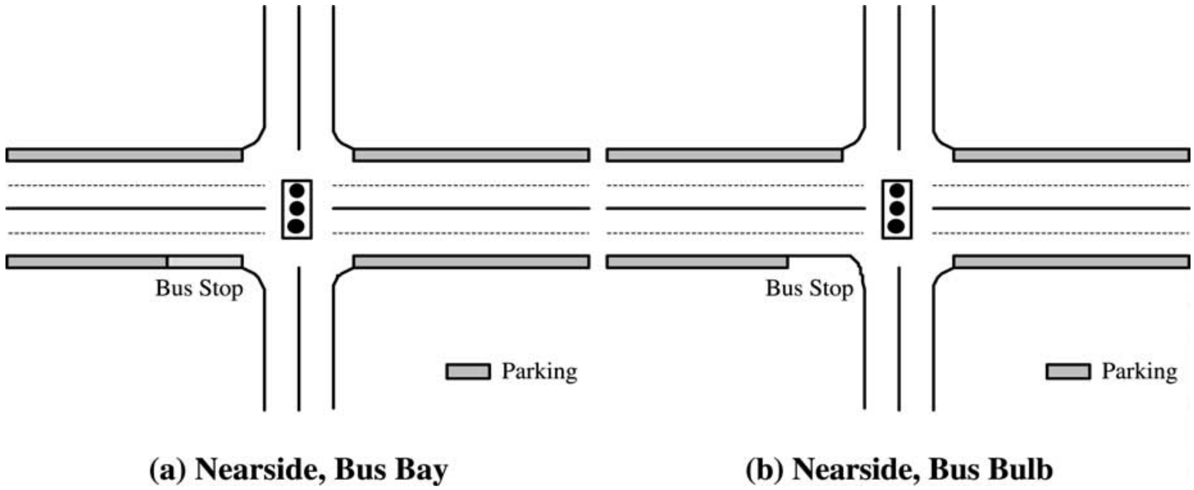


Figure D-3. Nearside bus Stop Designs.

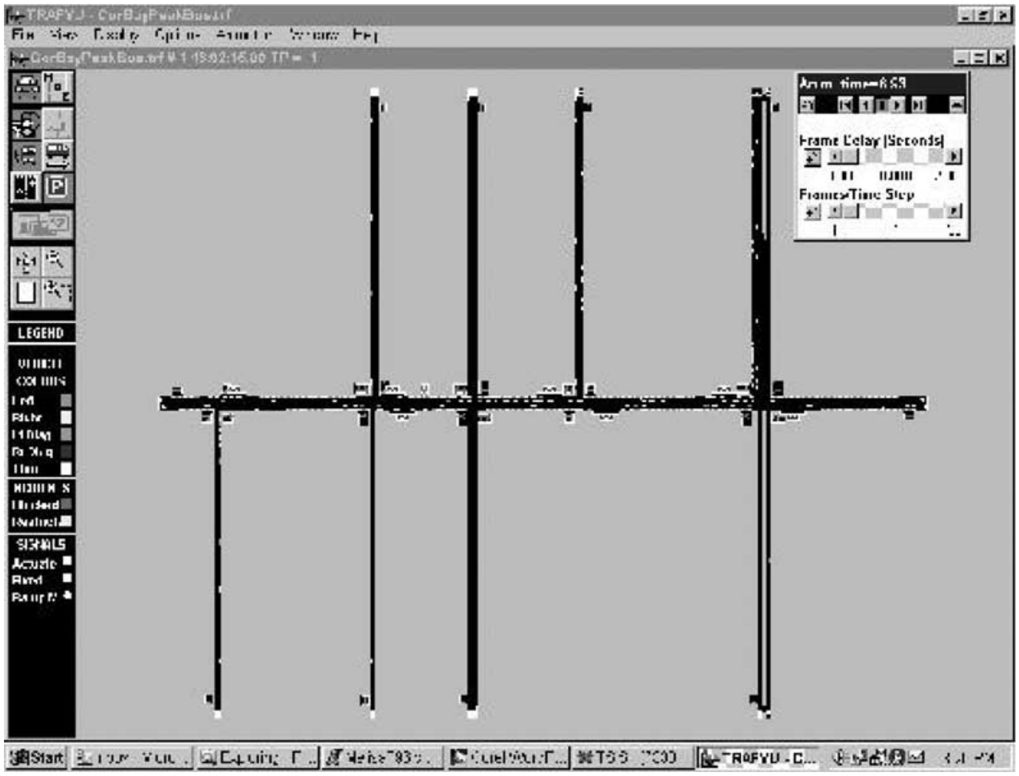


Figure D-4. Corridor Graphical Interface.

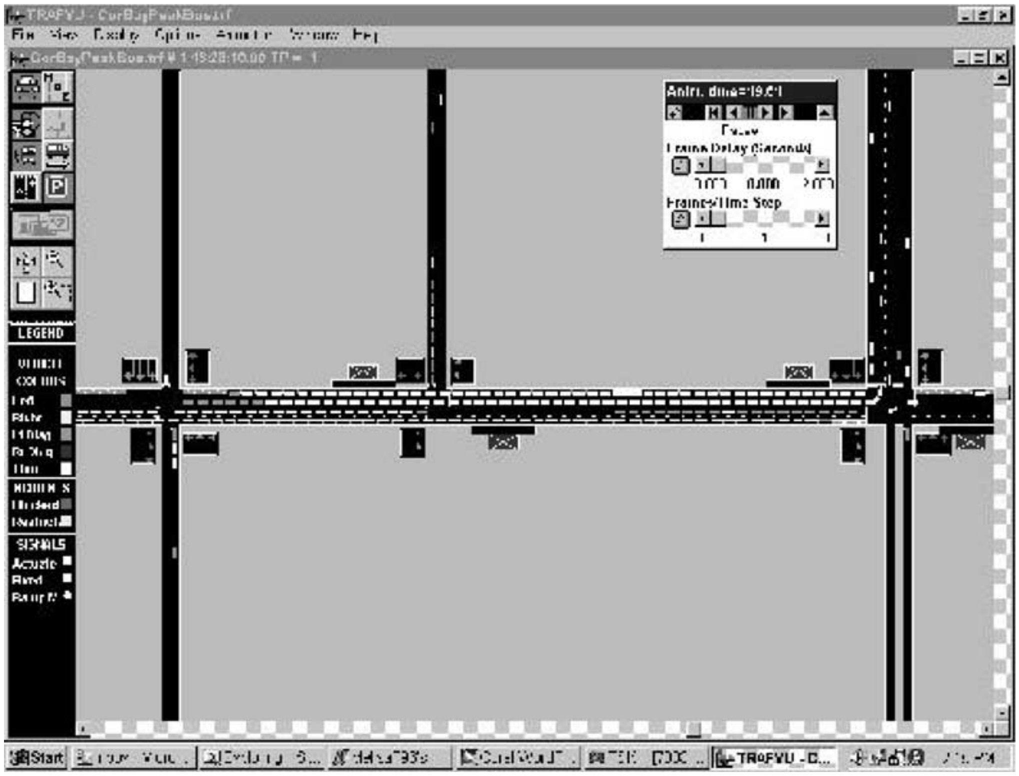


Figure D-5. NETSIM Graphical Interface at 1100 vph.

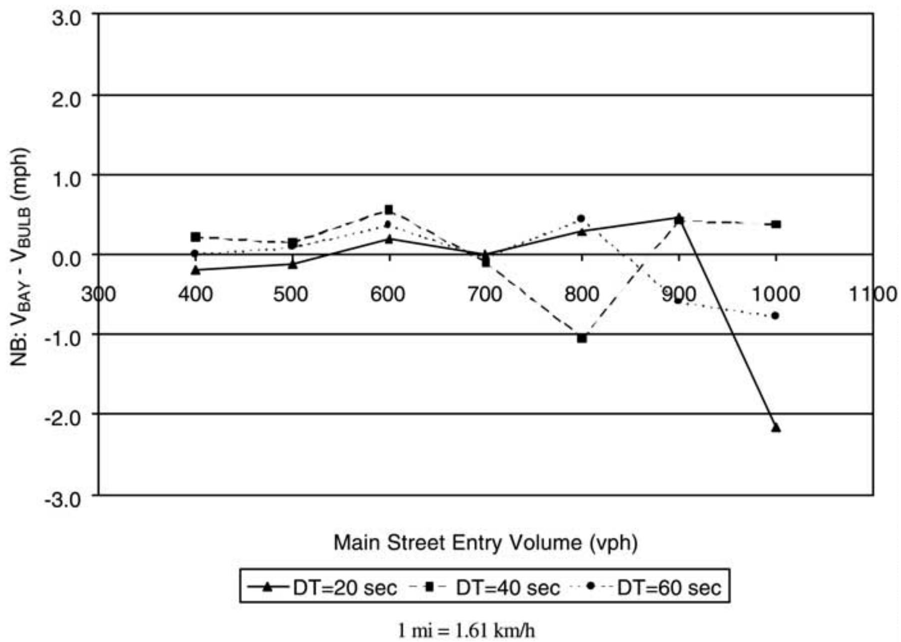


Figure D-6. Northbound Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design.

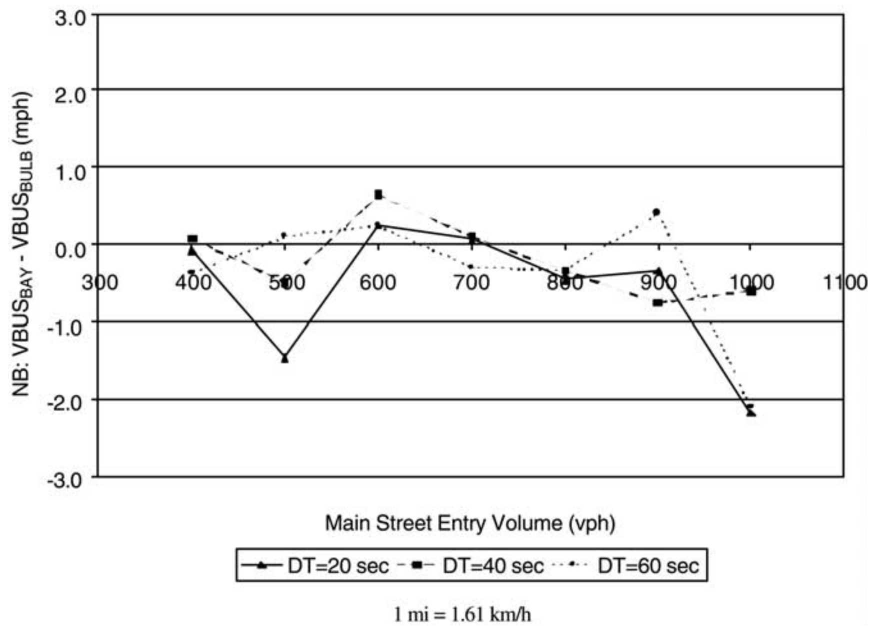
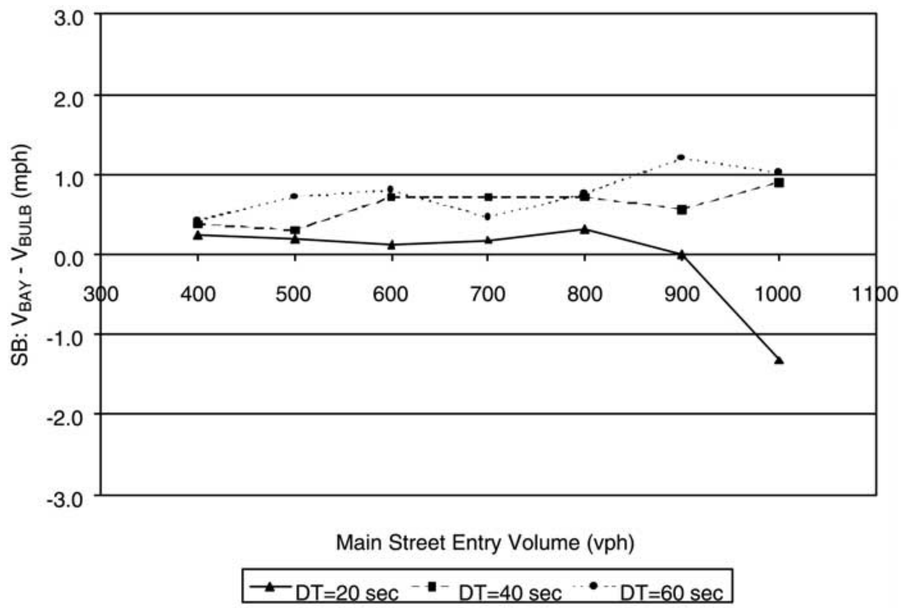
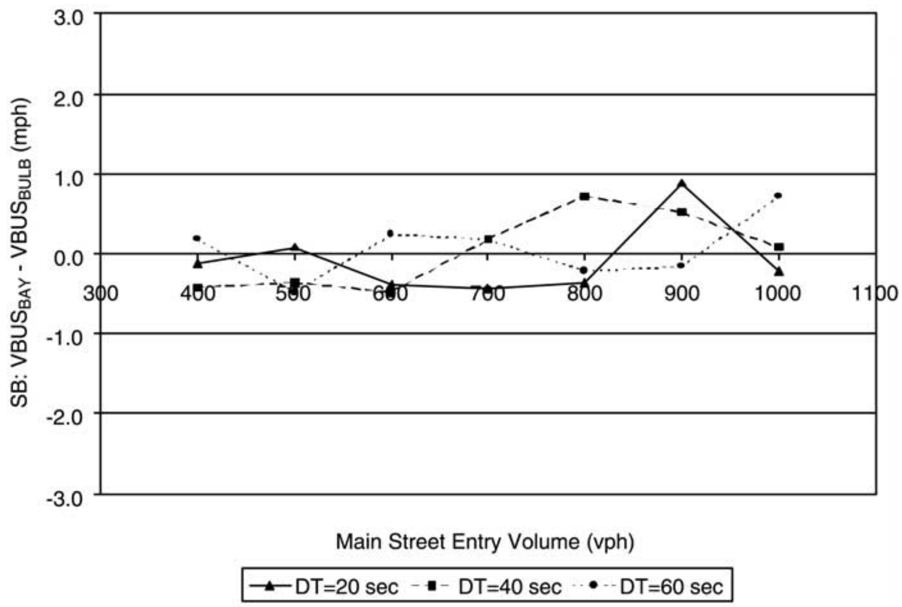


Figure D-7. Northbound Average Bus Speed Difference Design Between Bus Bay and Bus Bulb.



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.

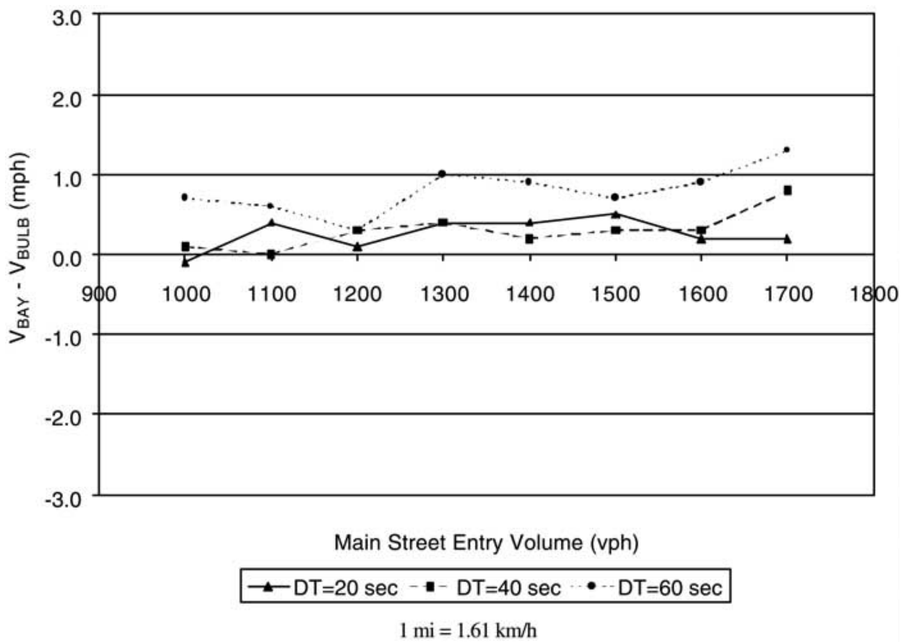


Figure D-10. Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design for a Farside Location.

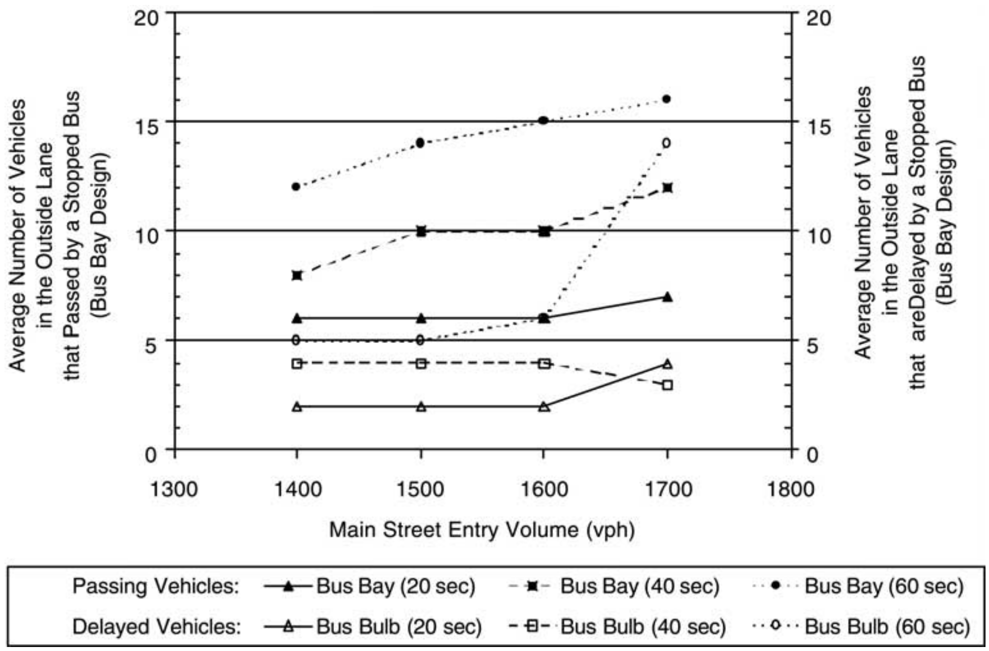
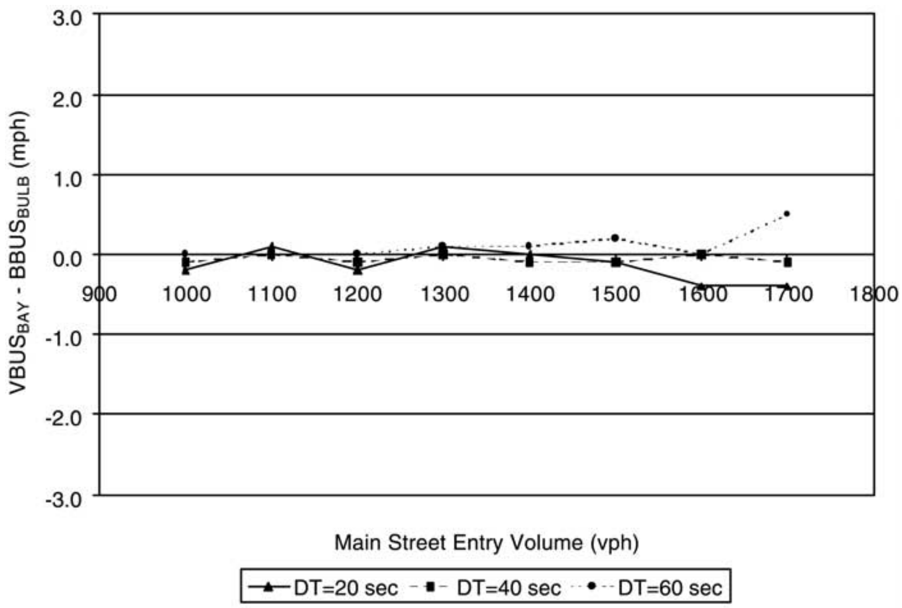


Figure D-11. Relationship Between the Average Number of Vehicles that Passed by a Stopped Bus and the Average Number of Vehicles that Are Delayed by a Stopped Bus for a Farside Location.



1 mi = 1.61 km/h

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

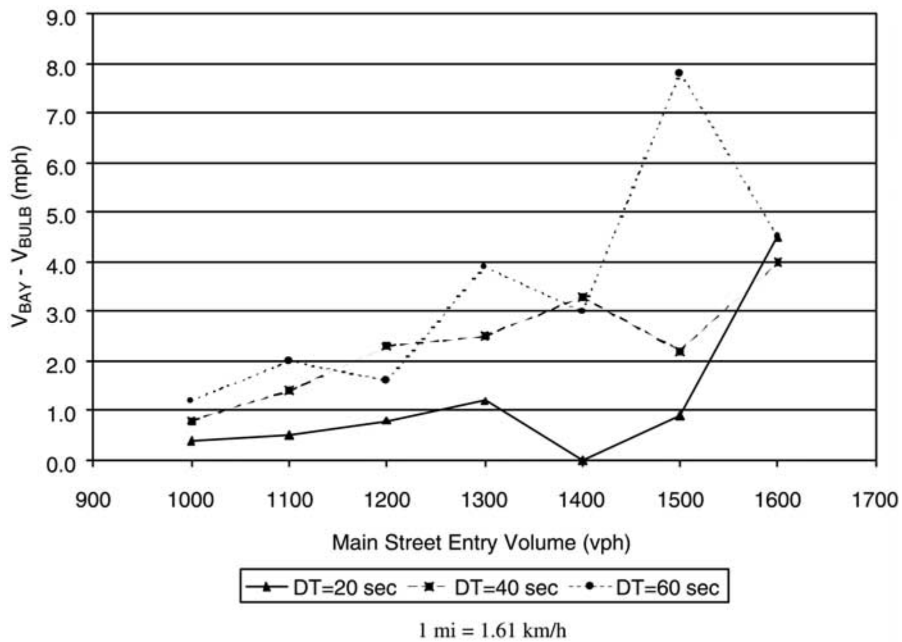


Figure D-13. Average Vehicle Speed Difference Between Bus Bay and Bus Bulb Design for a Nearside Location.

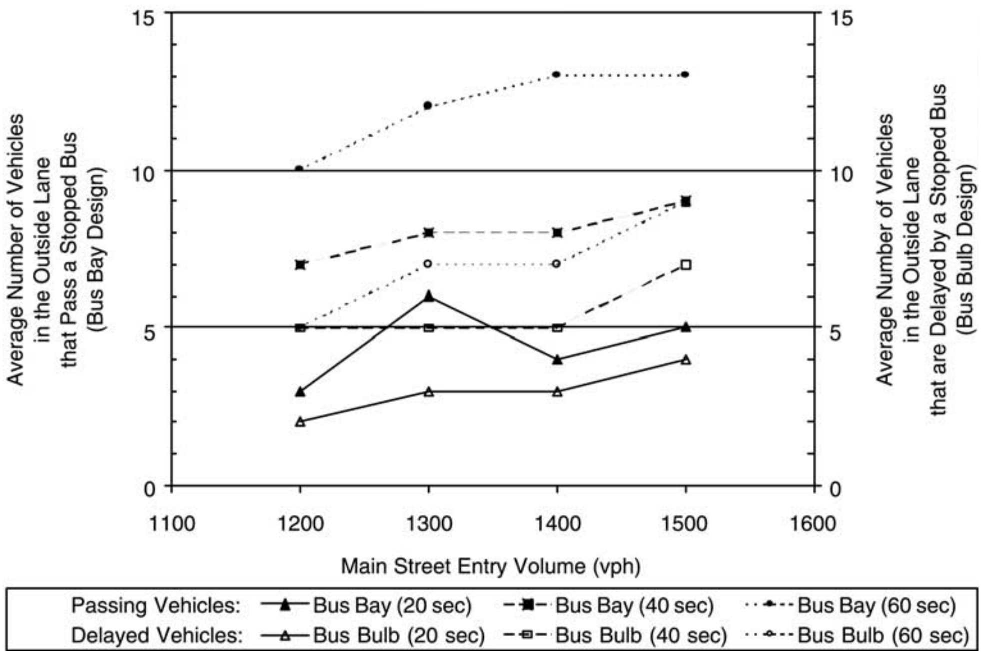


Figure D-14. Relationship Between the Average Number of Vehicles that Pass a Stopped Bus and the Average Number of Vehicles that Are Delayed by a Stopped Bus for a Nearside Location.

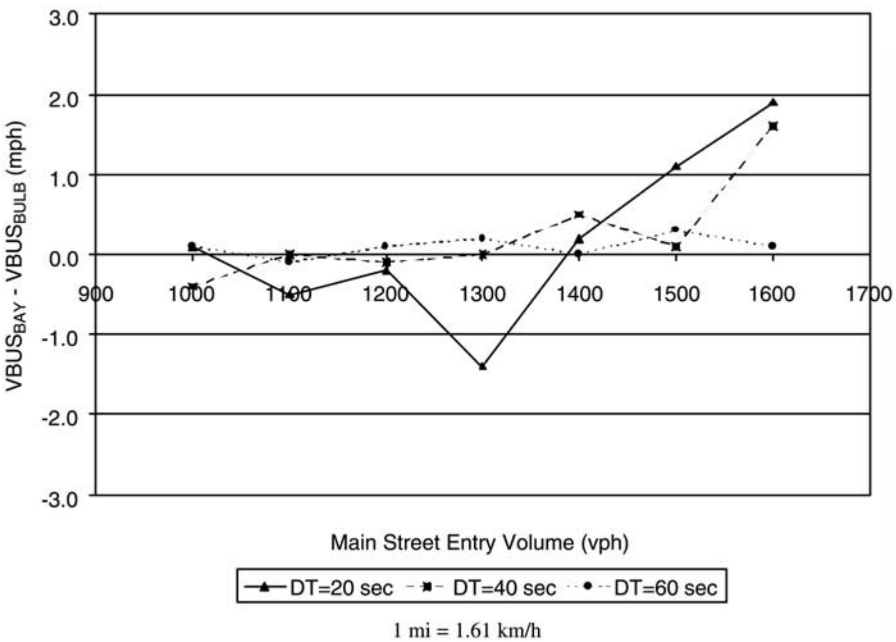


Figure D-15. Average Bus Speed Difference Between Bus Bay and Bus Bulb Design for a Nearside Location.

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 40 60	26.1 25.8 25.6	26.2 25.7 24.9	9.3 6.4 4.9	9.5 6.5 4.9
1100	20 40 60	26.2 25.8 25.6	25.8 25.8 25.0	9.3 6.4 4.8	9.2 6.4 4.8
1200	20 40 60	26.3 26.0 25.4	26.2 25.7 25.1	9.4 6.4 4.9	9.6 6.5 4.9
1300	20 40 60	26.3 25.8 25.4	25.9 25.4 24.4	9.3 6.4 4.8	9.2 6.4 4.7
1400	20 40 60	26.1 25.7 25.5	25.7 25.5 24.6	9.4 6.4 4.9	9.4 6.5 4.8
1500	20 40 60	26.1 25.7 25.2	25.6 25.4 24.5	9.2 6.4 4.9	9.3 6.5 4.7
1600	20 40 60	25.9 25.5 25.3	25.7 25.2 24.4	9.1 6.4 4.9	9.5 6.4 4.9
1700	20 40 60	25.8 25.8 25.4	25.6 25.0 24.1	8.8 6.4 4.9	9.2 6.5 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	21.1	20.7	10.2	10.1
	40	20.9	20.1	6.6	7.0
	60	20.5	19.3	5.0	4.9
1100	20	20.3	19.8	9.4	9.9
	40	20.4	19.0	6.7	6.7
	60	19.9	17.9	5.0	5.1
1200	20	19.7	18.9	9.4	9.6
	40	19.7	17.4	6.4	6.5
	60	19.5	17.9	5.0	4.9
1300	20	18.6	17.4	7.7	9.1
	40	19.2	16.7	6.1	6.1
	60	18.8	14.9	5.0	4.8
1400	20	17.2	17.2	9.2	9.0
	40	19.0	15.7	6.8	6.3
	60	17.2	14.2	5.0	5.0
1500	20	19.3	17.4	9.3	8.2
	40	17.3	15.1	6.2	6.1
	60	18.0	10.2	4.9	4.6
1600	20	14.1	9.6	8.4	6.5
	40	14.4	10.4	6.5	4.9
	60	15.0	10.5	4.7	4.6
1 mi = 1.61 km/h					