ESTIMATING TIME-BASED BUS SERVICE AREA USING THE TIME-BASED BUS SERVICE AREA TOOL (TBSAT)

A Planning Report

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ABSTRACT

This research proposes a new type of bus service area measurement: the **time-based bus service area (TBSA)**. TBSA visually indicates the area that a person can reach by bus from a designated location within his/her given travel time budget. This research describes the **Time-Based Bus Service Range Tool (TBSAT)**, developed by the author, to measure TBSA. This computer application incorporates the ESRI ArcGIS application (for geographical computations) and Microsoft Access (as its bus information database). To apply TBSAT to a designated location, a user sets values for pertinent conditional factors, such as the total travel-time budget, the acceptable length of time to access bus service, and the traffic conditions. TBSAT then calculates and maps the TBSA for that location.

This report first explains the theory behind TBSAT, and describes its operation. Then, it demonstrates the tool with real-world data from the Santa Clara Transit Center, in Santa Clara, CA. The resulting sample TBSA maps demonstrate a method for planners to analyze visually bus service quality under various transportation scenarios.

TBSAT's mapping and analysis capabilities present the possibilities of numerous potential applications for planners, developers, or private individuals working to create transit-accessible communities. As such, TBSAT can support applications in many of the most important aspects of contemporary urban planning, including support of smart-growth planning efforts and the assessment of equity issues, such as the ability of the transit-dependent to commute within their urban area to reach jobs and social services.

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Chapter 1 : INTRODUCTION

The result of this research was the development of a new tool that allows planners and public transportation system designers to identify the bus service area of a given location, given a travel-time limit and other constraints. This new tool is the **Time-Based Bus Service Area Tool** (**TBSAT**).

TBSAT is a two-part computer application that utilizes the ESRI ArcGIS (for spatial computation and display) and Microsoft Access (for its bus information database). It generates bus service area maps that visually portray realistic travel-time specific and location specific bus service quality. This is a significant advancement beyond predecessor planning tools that simply draw fixed service area maps and neglect the travel-time factor. TBSAT calculates the bus service area from a specific location by estimating the time needed for each segment of a bus trip: traveling from the trip origin to the boarding bus stop, waiting for the bus, in-vehicle travel time on the bus, and finally the time spent traveling to the final destination after disembarking. By contrast, existing methods are unable to produce the bus service area map of a starting location that realistically reflects the presence of a bus rider's inherent travel-time budget.

1.1. Research Goal

The goal of this research was actually two-fold. The primary goal was to develop an easy-to-use tool that planners and public transportation users, alike, could use to create time-based bus service area maps—that is, to create maps that reveal the bus service area of a designated location within a given travel-time budget. Once TBSAT was developed, the secondary goal was to demonstrate the tool's applicability using real-world scenarios.

TBSAT may be used by a planner to answer questions such as: *What areas may be reached by bus from a transportation hub, during peak service time, within a 30-minute travel-time?* To answer this question, the planner provides TBSAT two inputs: the location of the trip origin and the time constraints. In this case, the planner would enter the location of this transportation hub and the travel-time limit of 30 minutes. TBSAT produces two time-based bus service area maps that indicate the area that is serviced from that hub within a 30 minute limit, one during the peak service time and another during the off-peak service time. Figure 1 depicts the peak-hours service area map of this scenario. In this case, the hub is the Santa Clara Transit Center (SCTC) in Santa Clara, California. The green area indicates the area that can be reached by bus from the SCTC. This is the Peak Bus Service Area map.

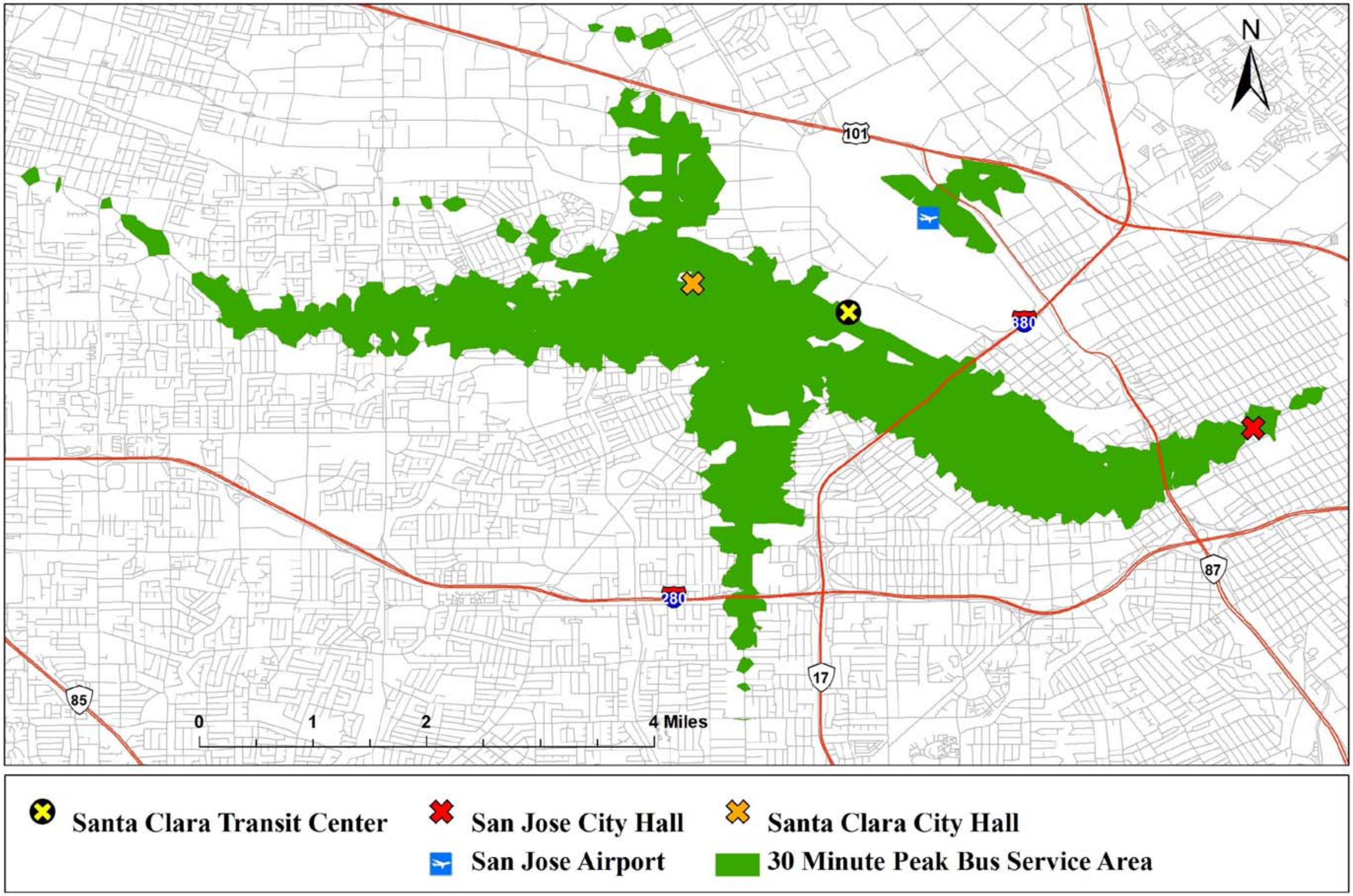

Figure 1: 30-Minute Peak Bus Service Area for Santa Clara Transit Center

TBSAT allows the public transportation user to visually identify the bus-accessible area from a location given various criteria, such as total travel-time limit, acceptable walking time, and walking speed. TBSAT assigns default values to various input factors, including access speed, maximum acceptable access distance, and the ratio between passenger waiting time (the amount of time the traveler spends waiting for the bus) and bus headway (service frequency). These are all factors that affect the time-based bus service area of a location. Advanced TBSAT users may manipulate any of these factors for a single origin to see the change in reachable area from that location under different conditions. TBSAT system administrators may modify underlying database information regarding the current bus system that affects the time-based bus service area of an origin. Such information includes the bus stop locations, the bus route timetables, the bus route peak/off-peak headway values, and the street network pattern. With its programmable flexibility, TBSAT is also useful as a modeling tool, not simply a descriptive tool.

Once this tool was developed, the second goal was addressed: examination of its applicability in the real world. TBSAT was applied to data using the Santa Clara Transit Center (SCTC) as the location of origin. Five hypothesized scenarios were generated to demonstrate the analytical applications of TBSAT.

1.2. Research Value

The unique value of TBSAT is its ability to identify and portray visually the time-based bus service area of a selected origin under a variety of user-defined conditions. The results support planners and residents, alike. The tool answers questions that cannot be answered by any traditional bus service area measurements, such as *What is the one-hour bus service area of this shopping center?* or *Is it possible to travel from my home to other locations of interest by bus within my limited time budget?*

The ability of TBSAT to address questions such as these makes it a powerful tool that can be used by a range of professionals, organizations, and individuals. The following descriptions provide a few examples.

1. Transportation Planner

Given specific input, TBSAT allows the transportation planner to quickly examine the bus service areas of the origin of his/her choice under various designated travel-time limits. The results of these applications may support planners when developing urban transportation planning strategies or making decisions between various scenarios.

TBSAT can be used as a descriptive tool to verify whether the current bus system accomplishes its mission of transporting people between two locations effectively. For example, TBSAT can support planners to determine whether the 30-minute bus service area from a rapid-transit station actually allows riders to reach the downtown core within that 30 minutes. Or, used as a modeling tool, planners could assess a proposed low-income housing project to see whether its residents would be able to access typical job locations and needed public services by bus within a reasonable time period.

Furthermore, the time-based bus service area map is a powerful tool when performing transit cost-benefit analysis. For example, TBSAT could be used to simulate the change in the one-hour bus service area of a specific location before and after a proposed bus service extension is constructed. This information could then help estimate the change in ridership or in fare-box revenue due to this service extension. The benefit derived from the extension could be compared with the cost of the proposed extension, giving planners additional information to use in evaluating the worthiness of the extension proposal.

Moreover, combining the time-based bus service area information with other types of statistics, TBSAT can produce social statistics that cannot be generated through other means. For example, by incorporating population census block data in the TBSAT results, it is possible to calculate how many residents, living below the poverty level, are covered by the one-hour bus service area of the downtown core. As another example, a city could map all of its hospitals. This mapping data could then be used in TBSAT to visualize what portion of the city's territory is within a one-hour bus ride of at least one hospital. It could also be used to visualize what percentage of the population could reach at least one hospital within a one-hour bus ride.

2. Public Transportation Operator

TBSAT allows public transportation operators to visualize the bus-accessible area from/to specific locations based on the service that operators can provide. Such information is especially valuable in the service optimization process since TBSAT can generate different sets of bus-accessible area maps from/to specific locations that indicate the bus-accessible area change before and after certain change in route design.

For example, as previously described in the example for Figure 1, in this report TBSAT was applied to the SCTC as an demonstrative application of TBSAT. Six VTA bus routes pass through this hub. The TBSAT results visualize for VTA the estimated time-based bus service area from the SCTC. The time-based bus service area map verifies for VTA whether its current bus service allows its customers to travel to important locations, such as South Bay Area downtowns, from the SCTC in a given time limit. Also, modeling of future route adjustments and schedule adjustments (to improve service efficiency), can be developed with the support of TBSAT. Moreover, since TBSAT produces visual bus service area maps that directly reflect changes in bus routes or schedules, the service area maps before and after such adjustments are useful for illustrating VTA's efforts in route design. These maps can provide persuasive information to the public and to decision makers.

3. Local Developer

Local developers can benefit from TBSAT in two ways. TBSAT allows land developers to:

(1) Examine the bus accessibility of current properties

By applying TBSAT to their properties, developers can visually determine how well their proposed developments are connected to other important locations in the bus network, such as transit centers and major retailers. In highly urbanized areas, such as San Francisco, New York, or Los Angeles, bus service accessibility always provides advantages that increase the value of a property.

(2) Locate potential housing project sites with bus accessibility

Alternatively, land developers interested in developing Transit-Oriented Development (TOD) projects may use TBSAT to locate potential properties with the best public bus access and routes to important locations, such as major retailers and transit stations. The visual bus service area map and its related travel-time data produced by TBSAT could be persuasive instruments in promoting TOD projects to funding sources as well as potential clients (such as potential home-buyers and renters).

4. Realtor, Renter, or Home-Buyer

Finally, the time based service area map to offers realtors, renters, and home-buyers information about the transit availability of specific locations . For example, today, a real estate advertisement might include information such as: “15-minute drive to major retailers.” However, rarely do we see advertisements such as: “15-minute bus travel to major retailers.” This is because the traditional bus service area measurements are unable to identify whether a property is bus accessible to major retailers within a specific amount of time.

The time-based bus service area information provided by TBSAT allows realtors to promote their properties with good bus accessibility in clear statements such as “less than 30-minute to the university by bus,” or by presenting a time-based service area map with major destinations highlighted. Publicizing such information allows renters or home-buyers who seek a less automobile-dependent life-style to quickly locate properties that suit their transportation requirements (locale and time limit).

As all the examples above demonstrate, TBSAT is a powerful tool that assists its users in their understanding of the true service potential of a bus service. Such information is critical to addressing many of the most pressing issues currently facing urban areas today. Good transit service is needed in many areas to provide transportation for those who cannot drive. Transit service is also a critical component of *smart growth* planning.

Smart growth is a broad concept rather than a definitive term. This concept encompasses all strategies that emphasize environment protection and land reuse. Reusing developed lands results in more efficient management of resources within the current urban development boundary.

For example, adjusting bus service based on the information provided by TBSAT can provide higher bus accessibility to specific areas, with the intention of decreasing automobile-dependence, thereby decreasing the demand for parking spaces. With the decrease in the demand for parking spaces, the land currently used as parking facilities may be redeveloped according to the land use demand. As another example, the goal of transit-oriented development (TOD) is to develop or redevelop lands within easy access of public transit. The term "easy access" actually implies access within an acceptable amount of travel time. As discussed above, while other planning tools are unable to reflect the bus service area due to a limited amount of travel-time limit, TBSAT is specifically designed for planners to actually visualize the bus accessibility of a specific location under a specified travel-time limit. This capability makes TBSAT uniquely useful to planners who need to model the bus service resource within specific areas in order to develop transit-oriented land-use strategies. TBSAT is simply one more method to promote smart growth.

1.3. Content of this Report

The remainder of this report is split into three parts: a research that reveals the unique value of TBSAT, the technical discussion of the design of TBSAT, and the presentation of the tool's use. A concluding chapter, discussing the applicability of TBSAT and its future development, closes the report.

Part I has a single chapter, Chapter 2, that explains the history and current state of tools for modeling bus service area. This chapter establishes the unique value of the information that TBSAT provides. It reveals the information insufficiency produced by traditional service area measurements and proposes a new service area measurement that allows planners to examine the accessibility of a bus service system using a new perspective: the time-based bus service area (TBSA). TBSAT is the tool to support planners in calculating and visualizing the TBSA.

Part II, composed of Chapters 3 and 4, presents technical details regarding the development of TBSAT. This section explains how TBSAT calculates the time-based bus service area. (Readers who are more interested in the application of TBSAT to real-world situations may wish to skip to Part III.)

Chapter 3 explores the underlying concepts on which TBSAT is based. It defines the concept of time-based service area of a bus system. It describes how TBSAT measures the time-based service area of a bus system through its series of processes. Finally, the underlying algorithms of TBSAT are described.

Chapter 4 discusses the TBSAT programmability. It defines and describes for the reader the factors and variables that are involved in the TBSAT calculations. TBSAT users set factors, such as trip origin and the predetermined travel-time budget. These are predetermined conditions of users' scenario and are fixed throughout the computation. On the other hand, variables represent the outputs of the TBSAT processes. For example, the walking time from the designated trip origin to a bus stop is calculated by TBSAT and stored as the access time variable so that this value can be referred to by following TBSAT processes.

Part III is composed of Chapter 5. This part of the report returns to a discussion of the information that TBSAT can generate for the user. By applying TBSAT to the SCTC in five hypothesized scenarios, Chapter 5 presents TBSAT's capability to correctly reflect the change in the time-based bus service area of the SCTC under different conditions. One of these scenarios demonstrates the power of performing planning analyses that combine TBSAT's TBSA maps with other types of planning data, such as census data.

The report concludes with Chapter 6. This chapter first discusses the improvements that could be undertaken to make TBSAT more user-friendly, versatile, and precise. In closing, the chapter discusses the applicability of TBSAT as an analytical planning tool by examining how well TBSAT achieves its goals.

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PART I: TRANSPORTATION SERVICE AREA ANALYSIS: THE TRADITIONAL APPROACH

Chapter 2 : THE UNIQUE VALUE OF TIME-BASED BUS SERVICE AREA MEASUREMENT

Optimizing bus routes to serve as many potential riders as possible within a particular bus service area is the goal of many local transportation studies and modeling tools. This is the goal of TBSAT use as well. This chapter examines the importance of accuracy in the optimizing bus service area calculation. For comparison purposes, an analysis of previous efforts to measure the service area is presented. The final portion of this chapter discusses the shortcomings of evaluating the bus accessibility of a bus service system through only traditional service area measurement methods. It describes how TBSAT is suited to providing information regarding the bus accessibility of specific locations, which cannot be provided by previous methods. Finally, this chapter describes how TBSAT enables planners and other designers to evaluate the bus accessibility from a location specific perspective, unlike predecessor methods. Through these analyses, the unique value of TBSAT is established.

2.1 The Importance of Measuring Bus Service Area in Order to Maximize Service

One objective of public transportation is to provide an alternative to the use of the private automobile in order to alleviate negative externalities created by automobile dependency. These negative effects include environmental degradation,[1] equity issues (for example, the difficulty experienced by people who are unable to drive due to some physical disability), and economic impacts (such as time lost due to driving congestion and lack of parking space) . As one of many available alternative transportation modes, bus service must attract ridership to be competitive.

One of the most effective ways to increase attractiveness is to increase system performance[2] by maximizing the service area of the system. Increasing the service area

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[1] Somporn Tanatvanit, Bundit Limmeechokchai, and Supachart Chungpaibulpatana, "Sustainable energy development strategies: Implications of energy demand management and renewable energy in Thailand," *Renewable and Sustainable Energy Reviews* 7, no. 5 (October 2003): 367-395.

[2] Maurizio Bielli, Azedine Boulmakoul, and Hicham Mouncif, "Object modeling and path computation for multimodal travel systems," *European Journal of Operational Research* 175, no. 3 (2006): 1705-1730.

Debashish Chowdhury, "Statistical Physics of Vehicular Traffic and Some Related Systems," *Physics Reports* 329, no. 4-6 (May 2000): 199-329.

increases the number of potential riders that have access to the bus system. Higher ridership is assumed to follow. In the past, to evaluate the results of various service area maximizing strategies, bus service area measurements methods were developed. These methods helped identify the overall bus service coverage within a geographical area. However, these methods did not necessarily identify how well or how efficiently the bus service serves an area when a travel-time budget limit is considered.

2.2 Previous Bus Service Area Measurements

Before service area-maximizing proposals can be produced, it is essential to possess tools that allow analysts to measure the bus service area of the current system or the theoretical service area of the proposed plan. Several different bus service area measurement methods are currently used in planning. Each method has its benefits. However, each method also has its shortcomings. No single method can provide a comprehensive measurement.

The **service area** of a bus system is usually defined as a static area over a geographical territory within a certain distance of the actual bus service system (bus stop). Since bus routes can never be designed to provide everyone door-to-door service, riders usually spend time traveling to and from bus stops. It is reasonable to assume that people beyond some distance of a bus stop will not use the bus; their overall trip time would be too long, considering the time on the bus and the time spent traveling to and from bus stops.

Early efforts to measure bus system coverage looked at the system in terms of "corridors," or the immediate area along the two sides of the streets along each bus route.[3] The corridor measurement method is demonstrated in Figure 2.

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[3] S. C. Wirasinghe and U. Vandebona, "Some Aspects of the Location of Subway Stations and Routes," in *Fourth International Symposium on Locational Decisions (ISOLDE IV) Congress Held in Namur, Belgium June 1987*.

R. Chapleau, P. Lavigueur, and K. G. Baass, "A Posteriori Impact Analysis of a Subway Extension in Montreal," *Transportation Research Record*, no. 1152 (1987): 25-30.

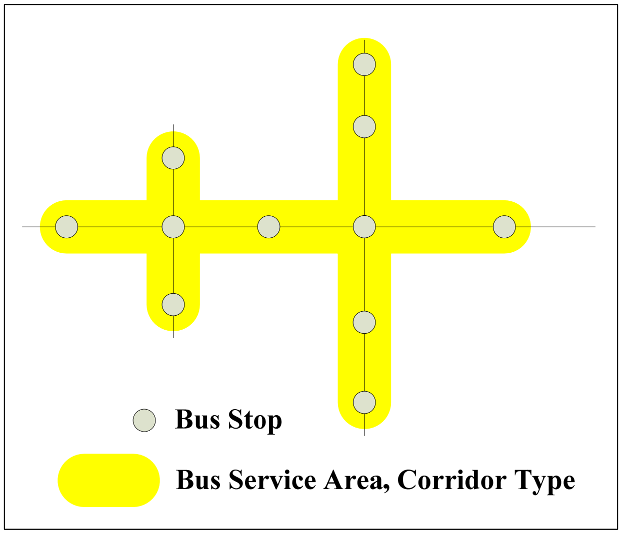

Figure 2: Bus Service Area, Corridor Type

The flaw in this concept is that it *overestimates* the bus service area. Note that areas between bus stops are included in the service area, even though many stops may be too far apart to be considered as part of the actual service area.

After realizing the flaw of measuring bus service area as corridors, modern transportation planners began to measure the bus service area as multiple **concentric polygons** around each bus stop. This system was an improvement, since bus service is truly only accessible around bus stops.[4] The polygons can be drawn using two basic methods: the **Euclidian metric** and **Manhattan metric**. These methods are compared in Figure 3.

The Euclidian metric encloses each stop in a circle. It assumes people can walk freely from the bus stops—as the crow flies—without being blocked by buildings or other physical barriers. Consequently, each node in the system is depicted as a circle radiating out from the bus stop. The first image in Figure 3 depicts a typical Euclidian metric.

Alternatively, the Manhattan metric attempts to simulate people's walking behavior. It assumes that people access bus stops by walking along a perfect street grid (of strictly eastern-western and northern-southern streets), and that the travelers may make only one right-angle turn. Consequently, the service area around a bus stop drawn using Manhattan metric is typically a diamond shape, as shown in the second image of Figure 3.

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[4] Hélène Dufourd, Michel Gendreau, and Gilbert Laporte, "Locating a Transit Line Using Tabu Search, " *Location Science* 4, no. 1-2 (May-August 1996): 1-19.

Giuseppe Bruno, Gianpaolo Ghiani, and Gennaro Improta, "A Multi-Modal Approach to the Location of a Rapid Transit line," *European Journal of Operational Research* 104, no. 2 (January 1998): 321-332.

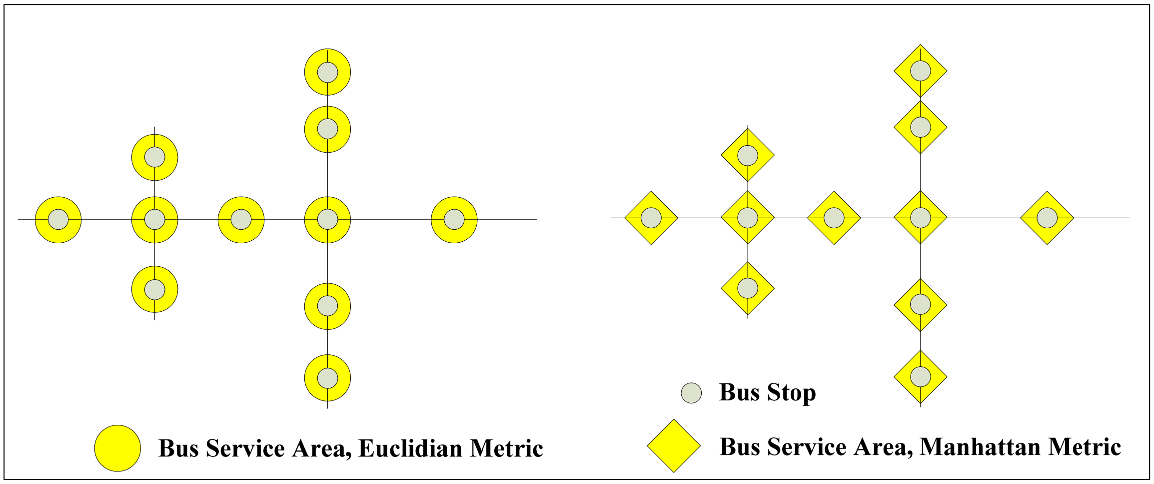

Figure 3: Bus Service Area, Concentric Type

In these concentric polygon type bus service area measurements, destinations beyond the polygons are considered too far away from the bus stops to be easily accessible to riders, so it is assumed that only the traveler whose trip origin *and* trip destination are both covered by these polygons, are considered as the potential riders of the bus service. The area inside each polygon then becomes the *served* area and a part of the service area of the entire bus system.

Numerous studies, including transit accessibility studies[5] and urban design studies,[6] have used concentric shapes to indicate bus service area. However, the shortcoming of drawing concentric shapes as service areas is that people cannot fly over physical barriers, as the Euclidian metric assumes, nor are they restricted to walking only horizontally and vertically, as Manhattan metric assumes. As a result, concentric shape measurements still *overestimate* the bus service area in the real world.

With the development of modern computer software, we can now draw bus service areas more precisely using network analysis. As, shown in Figure 4, bus service areas around bus stops no longer have to be depicted as perfect circles or diamonds. They can be drawn precisely according to actual street patterns along passable routes that surround each bus stop. Thus, the geometry of the service areas around different bus stops can be

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[5] Amr Mohammed, Amer Shalaby, and Eric J Miller, "An empirical analysis of transit network evolution: case study of the Mississauga, Ontario bus network," in *85th Transportation Research Board Annual Meeting Congress Held in Washington, D.C. Jan 22-26 2006*.

[6] André Sorensen, "Land readjustment and metropolitan growth: An examination of suburban land development and urban sprawl in the Tokyo metropolitan area," *Progress in Planning* 53, no. 4 (May 2000): 217-330.

individually calculated in order to more accurately portray the service area, as shown in Figure 5.[7]

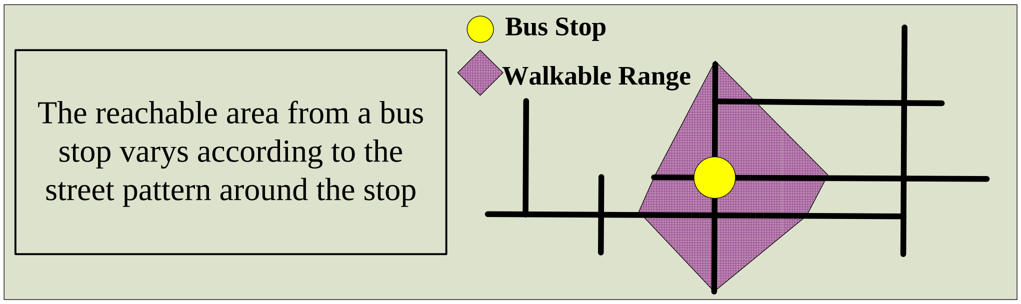

Figure 4: Service Area Generated by Network Analysis

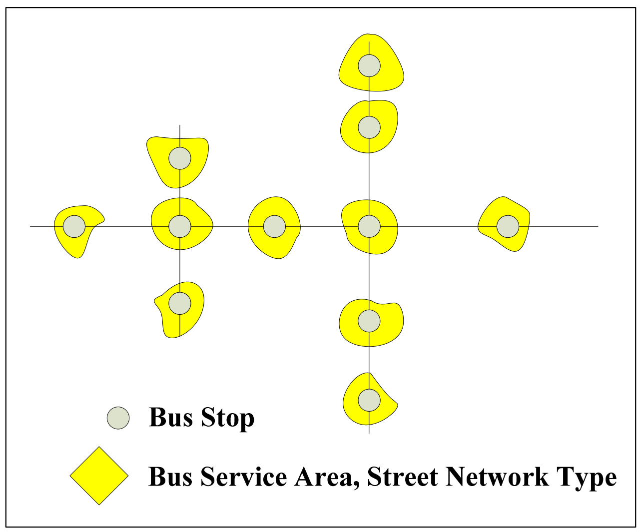

Figure 5: Bus Service Area, Network Analysis Type

Although the precision level of deriving service area from bus stops increased significantly with the improvement of area-calculating techniques, the information provided by these service area measurements remained unchanged. Missing was the overall travel-time factor. That is, these older methods calculated only the *area* that could be reached by bus, regardless of the *time cost* traveling between two locations within the bus service area.

This travel-time factor is a very important factor when the traveler decides whether to take the bus. Maps generated from previous service area measurements tell people

[7] Thomas Kimpel, Kenneth J. Dueker, and Ahmed M. El-Geneidy, *Using GIS to measure the effects of service areas and frequency on passenger boardings*, Nevada: Urban and Regional Information Systems Association (URISA) (16 August 2006), 5. < http://www.urisa.org/kimpel > [29 April 2008].

where they can go by bus, without indicating whether this service area can be reached when people have a predetermined travel-time limit. These maps answer none of the questions that planners or the public usually ask, such as:

- What part of the city can people access from this regional transit center, by bus, within one hour?
- Can that shopping center be accessed from the downtown core within a one-hour bus trip?
- Where can I go shopping, without spending more than one hour taking the bus from my home?

2.3 Propose a Trip Origin and Travel-Time Specific Bus Service Area Measurement

The most important feature of TBSAT is that it identifies the bus service area of a given location with a given travel-time limit. This represents the area a traveler can reach by bus under a given time constraint. Such an area is defined as the **time-based bus service area (TBSA)** of the given trip origin. Unlike a traditional bus service area map, which shows only the absolute service area of the entire system without considering the travel-time cost, a TBSA map emphasizes the bus accessibility of a specified trip origin within a specified travel-time limit.

In short, given a travel-time limit and a location of interest, TBSAT calculates the estimated duration of each of the major actions that comprise a trip from the location of origin to the destination. These actions include accessing the origin's bus stop (usually by walking), waiting for the bus, traveling on the bus, disembarking the bus, and accessing final destination. Then, TBSAT generates a TBSA map that indicates the area that a traveler can actually reach by bus within the desired travel-time limit.

Anthony A. Saka raised an important observation regarding bus route design: "Often, transit service providers are required to make transit highly accessible to their patrons, because they operate under stringent budgets."[8] Traditional bus route design aims to optimizing route design so as to use a minimal number of bus stops to cover the largest area possible. Numerous studies have focused on developing optimal design solutions under this assumption.[9]

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[8] Anthony A. Saka, "Model for determining optimum bus-stop spacing in urban areas," *Journal of Transportation Engineering* 127, no. 3 (2001): 195-199.

[9] Gilbert Laporte, Juan A. Mesa, and Francisco A. Ortega, "Optimization methods for the planning of rapid transit systems," *European Journal of Operational Research* 122, no. 1 (April 2000): 1-10.

Giuseppe Bruno, Gianpaolo Ghiani, and Gennaro Improta, "A multi-modal approach to the location of a rapid transit line," *European Journal of Operational Research* 104, no. 2 (January 1998): 321-332.

However, when travel times become too lengthy, the term “accessible” becomes less applicable. The traditional measurements of bus service area, in fact, only identifies the *spatial* coverage of a bus system, instead of verifying whether a specific destination is truly bus-accessible, given a pre-established time limit. TBSAT overcomes this hurdle, allowing planners to calculate the origin-specific bus accessibility of a particular place. The following scenario demonstrates how TBSAT reveals the origin -specific bus service area that cannot be revealed by traditional service area measurements.

Scenario: Service Area of a Trip Origin with Travel-Time Limit

The following two figures illustrate the difference between the bus service area generated by traditional measurements and the time-based bus service area generated by TBSAT.

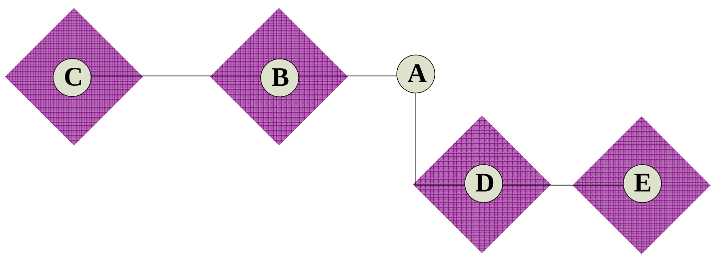
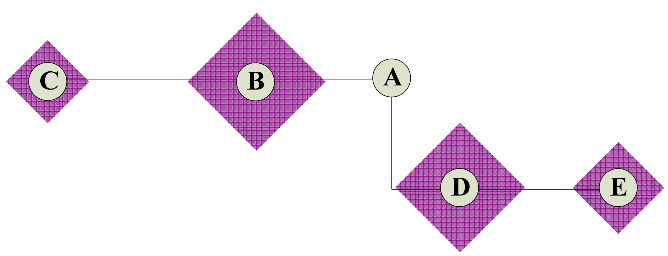


Figure 6: Traditional Service Area Calculation from Example Origin “A”

As can be seen in Figure 6 (which represents traditional measures), if a traveler boards the bus at point A, the size of the service area around bus stops B, C, D, and E are the same, assuming the street layout is perfect grid. This is consistent with the approach taken by the traditional service area measurements introduced in section 2.2.



Hélène Dufourd, Michel Gendreau, and Gilbert Laporte, “Locating a transit line using tabu search ,“ *Location Science* 4, no. 1-2 (May-August 1996): 1-19.

Göran Tegnér, “The use of emme/2 for an improved bus network in the city of örebro, sweden,” in *9th European EMME/2 Users' Conference Congress held in Stiges, Spain, June 6 2000*.

Alon Elgar, Gadi Kfir, and Tel Aviv, “Computer aided bus route planning.” in *1st European EMME/2 Users' Conference Congress held in London, United Kingdom, April 3 1992*.

Figure 7: Time-Based Bus Service Area Calculation from Origin "A"

However, as can be seen in Figure 7 (representing the TBSAT methodology, which includes the time-limit budget constraint), more remote bus stops are assigned a smaller service area measurement. Under a predetermined travel-time limit, if the traveler chooses to take the time to bus-travel to a more distant bus stop, he will have less time to access destinations around that distant stop. As a result, the size of the service area around distant bus stops is smaller than the size of the service area around bus stops nearer the bus stop of embarkation.

This scenario demonstrates that all traditional service area measurements *overestimate* the bus service area from point A, since these methods ignore the rider's budgeted travel-time limit (a very important factor that affects a traveler's willingness to use a bus service). The actual bus service area from point A is more realistically indicated by the time-based bus service area generated by TBSAT, since it incorporates the rider's predetermined time budget. The TBSA concept provides its users with a more realistic way to analyze bus accessibility to and from specific locations.

PART II: DEVELOPMENT OF THE TIME-BASED BUS SERVICE AREA TOOL (TBSAT)

In Part I, Chapter 2 proposes a new service area measurement, the time-based bus service area (TBSA), which can indicate the bus reachable area from a designated location under a given travel time limit, to support planners to evaluate the quality of the bus service in a new viewpoint. However, since the TBSA of a location changes under different conditions, and often times it is these changes about which planners are concerned, it is crucial for planners to possess a tool that can quickly identify the TBSA of the interested location under different conditions. Such a tool is developed in the first part of this research: the **Time-Based Bus Service Area Tool (TBSAT)**.

Chapter 3 : TBSAT CONCEPTS

This chapter discusses the methodology used by TBSAT to generate time-based bus service area maps showing the bus accessibility of a designated location. First, the term “simple bus trip” is defined, because TBSAT only calculates the time-based bus service area which can be achieved by simple bus trips. Second, the term “time-based bus service area” is defined. Third, section 3.2 discusses how time-based bus service area can be identified and drawn on the map. Finally, section 3.3 establishes a step-by-step procedure that allows TBSAT to generate the time-based bus service area of a given location.

3.1 Define a Simple Bus Trip

For this research, TBSAT only identifies the time-based bus service areas that can be developed using simple bus trips. A *simple bus trip* in this research must meet four criteria:

1. **The traveler must access the boarding bus stop using a single travel mode.**

   Although walking is the typical travel mode used to access a bus stop, a reasonable number of bus trips start using a non-walking mode, such as bicycling to the bus stop, driving to the bus stop (park-and -ride), or being drop-off by private vehicle or taxi. Furthermore, sometimes a traveler might use multiple modes to access the boarding bus stop. For example, a person might bicycle to a bicycle storage area near the boarding bus stop and then walk to the boarding bus stop. For simplicity, this research only focuses on bus trips that are accessed by a single mode.

2. **The traveler makes no bus transfers.**

   A bus trip that requires route transfer(s) is not considered a simple bus trip. In TBSAT, the traveler is assumed to board a single bus and to disembark that bus.

3. **The buses arrive according to the published timetable.**

   In this research it is assumed that the buses of all bus routes can always reach their bus stops at the time specified on the timetable. It is assumed that, even when the traffic conditions change, the bus driver will still meet the timetable by adjusting the bus speed.

4. **The traveler uses a single mode of travel to access the final destination after disembarking.**

   Similar to point 1, in this research, TBSAT assumes the traveler uses only one mode to access their final destination after disembarking from the bus.

3.2 Define and Calculate Time-Based Bus Service Area

3.2.1 Define Time-Based Bus Service Area

As discussed in section 2.3, the purpose of TBSAT is to identify the bus service area of a given location X. This area represents the area a traveler can reach by bus from location X within a specified travel-time limit t_{max}. Such an area is defined as the **time-based bus service area (TBSA)** of X in t_{max}.

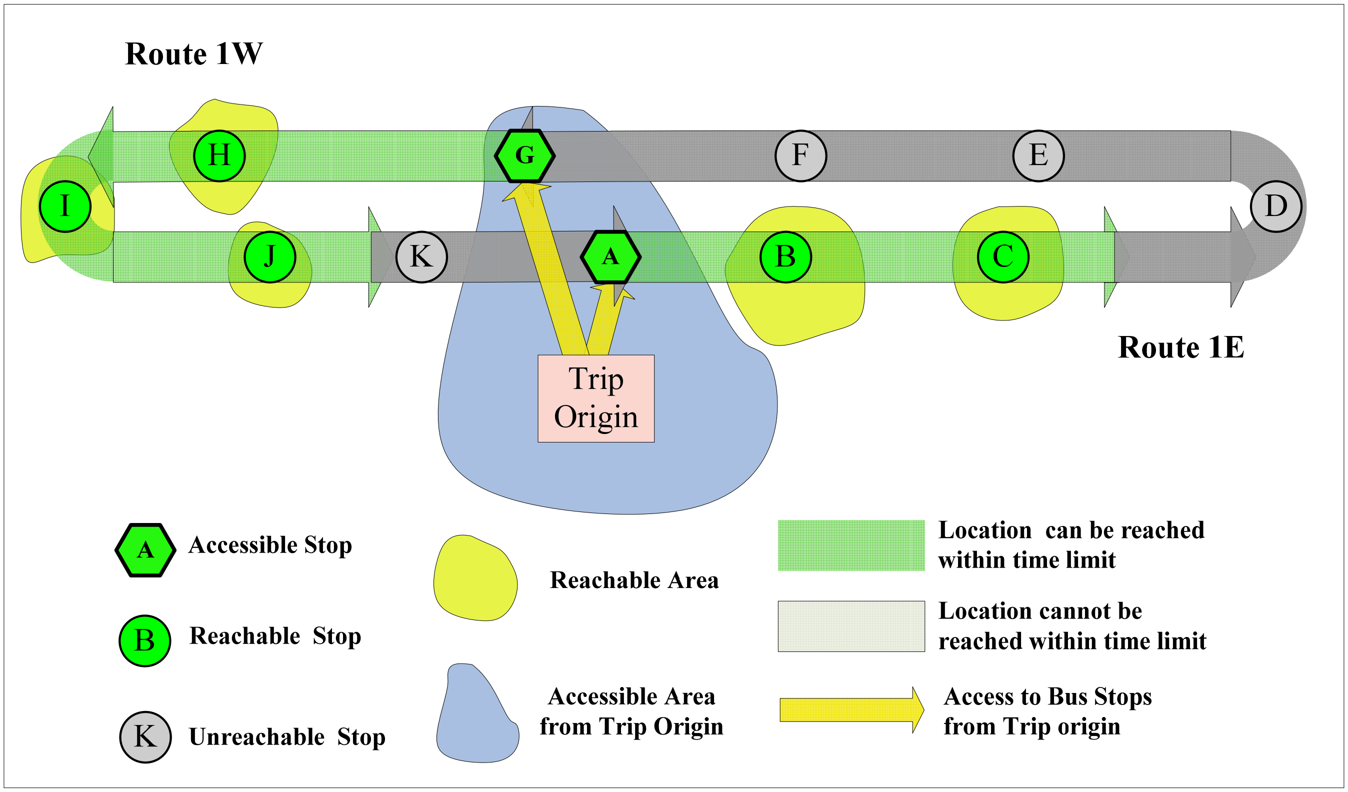


Figure 8: Diagram of Typical Time-Based Bus Service Area

Figure 8 illustrates the TBSA from a fixed trip origin for travel-time limit t_{max}, assuming a simplified condition.

In Figure 8, Route 1 is the only bus route available to the traveler from his trip origin. The green circle bus stops are the bus stops this traveler can reach within time t_{max}. From these bus stops, the yellow shapes are the areas the traveler can reach using the travel-time remaining after disembarking the bus. Since the TBSA represents the total area a bus rider can reach by bus from the trip origin, the TBSA in Figure 8 should be the aggregation of all yellow shapes.

However, besides the yellow shapes, the blue shape, which represents the area that a bus rider can reach *without* taking a bus, should also be included as a part of TBSA. Technically the blue area is not a bus-serviced area. However, since the ultimate goal of showing TBSA is to indicate the area a traveler can reach from the trip origin, to achieve this goal, the blue area should be included as a part of the TBSA map. As a result, the TBSA that TBSAT generates includes the accessible area from trip origin that does not require bus transportation.

The terminology used to describe the calculations of TBSA, including the elements in Figure 8, is discussed in the following section.

3.2.2 Time-Based Bus Service Area Terminology

Accessible Stop

An *accessible stop* is a bus stop that a bus rider can access from the trip origin X within t_{max}. To generalize, accessible stops are the bus stops the travelers can reach within an acceptable access time from trip origin. In chapter 4 the calculation of this acceptable access time will be discussed.

For example, in Figure 8, the green hexagon stops, Stop A and Stop G, are accessible stops because they can be accessed from the trip origin within the acceptable access time.

Accessible Route

An *accessible route* is a bus route that services the traveler’s accessible stops. Accessible routes are the only bus routes that can be utilized by a traveler from the trip origin.

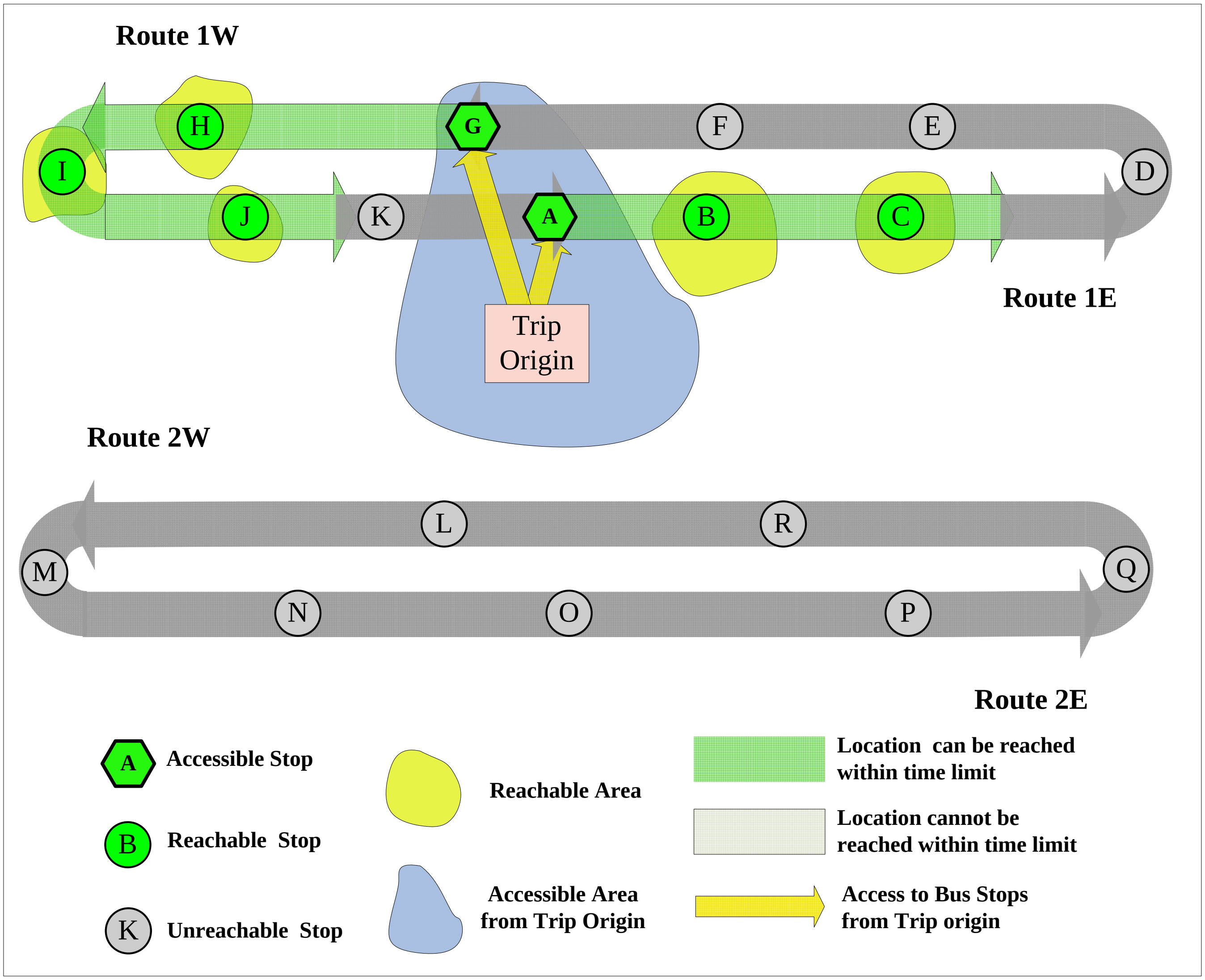


Figure 9: Accessible Route vs. Non-Accessible Route

In Figure 9, Route 1 is the accessible route since its Stop A and Stop G are accessible stops. Route 2 is not an accessible route, because none of its stops is within the accessible area from trip origin.

Disembarkable Stop

A *disembarkable stop* is a bus stop along an accessible route where the traveler can disembark. Each disembarkable stop can be reached from the trip origin within a different amount of time. For example, in Figure 9, all bus stops on Route 1 are disemarkable stops, although Stops D, E, F, and K cannot be reached because it takes too long to reach them from the trip origin.

Note that accessible stops, Stop A and Stop G (in Figure 9), are also disembarkable stops for two reasons. First, an accessible stop can be reached from other accessible stops. For example, in Figure 9, accessible Stop G is also a disembarkable stop because it can be reached if a bus rider chooses to board Route 1 at Stop A. Second, an accessible stop can always be reached from itself after a full round trip. For example, in Figure 9, if a traveler from the trip origin boards Route 1 at Stop A, after a full round-trip through Stop B to Stop K, this bus rider return to Stop A and disembark. Although such a trip does not happen in the real world, TBSAT must include all mathematically possible disembarkable stops in the TBSAT calculation.

Remaining Available Time

The *remaining available time* (T_r) is the remaining time budget that a traveler possesses after leaving the bus at a disembarkable stop. The value of the remaining available time at a disembarkable Stop Z is the difference between the travel-time limit t_{max} and the total travel time from the trip origin to that disembarkable stop. The total travel time from the trip origin to disembarkable Stop Z must include these trip components:

1. *Time needed for a traveler to access an accessible stop, at which an accessible Route R that reaches Stop Z is available.*
2. *Waiting time for the arrival of the accessible Route R bus.*
3. *Travel time on-board the bus until the bus reaches Stop Z.*

There is one case where the value of T_r must be adjusted. When T_r is longer than the amount of time that a traveler is *willing* to spend accessing his final destination after disembarking, T_r must be set to this value. For instance, say a traveler chooses to walk after disembarking, yet he does not wish to walk more than 15 minutes. In such a case, even if he possesses a T_r longer than 15 minutes, the T_r is limited to 15 minutes.

In the majority of cases, however, multiple T_r values are generated for one disembarkable bus stop because there are, normally, multiple ways by which a traveler could reach that disembarkable stop from the trip origin. The following discussion illustrates the two conditions that multiple T_r values are generated for a single disembarkable bus stop:

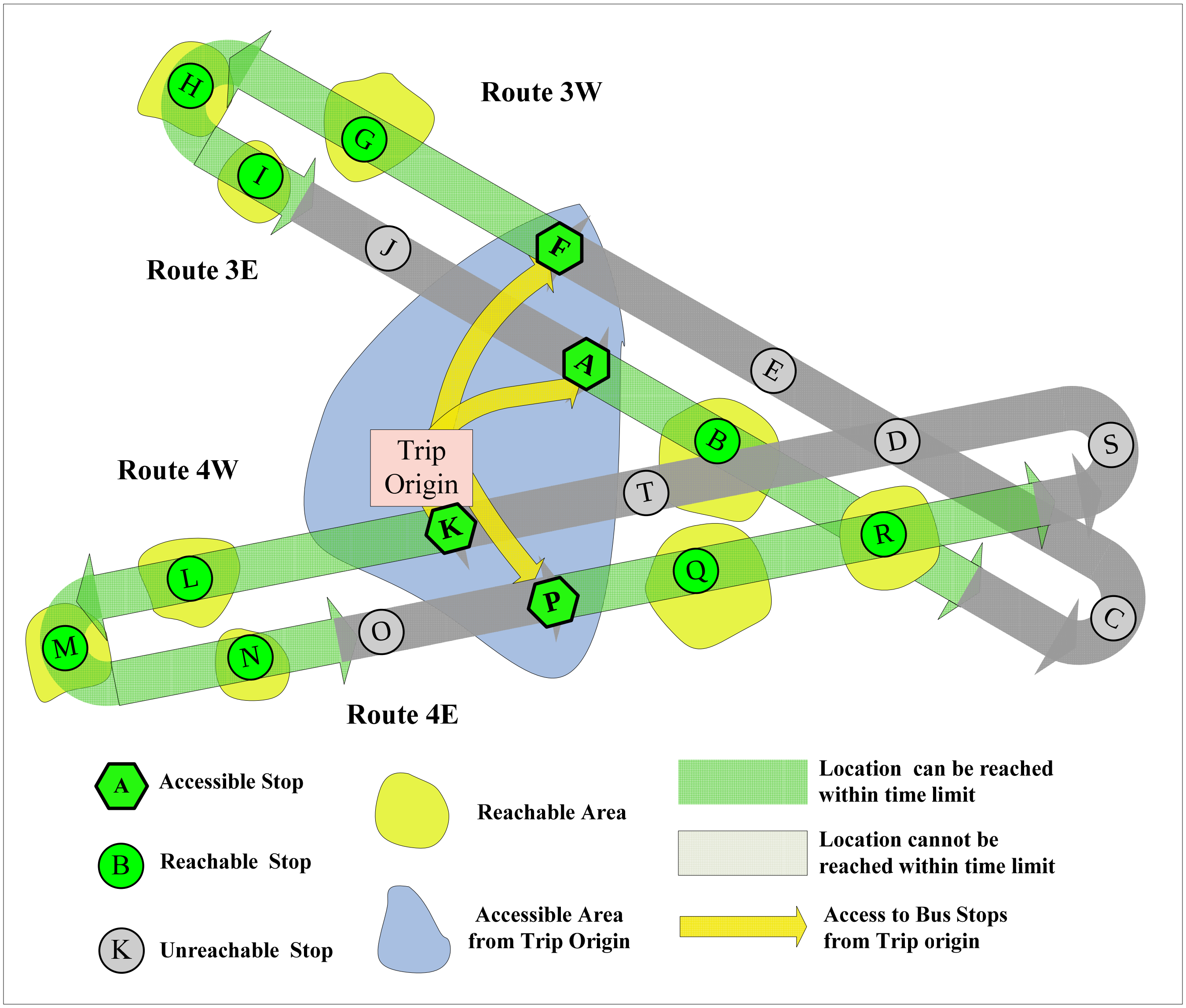


Figure 10: Multiple T_r Due to Reaching the Same Bus Stop through Different Routes

1. **A *disembarkation stop* that can be reached through more than one accessible *route* generates multiple T_r values.**

Figure 10 shows that Stop R can be reached through either Route 3 or Route 4 from the trip origin. Thus, the remaining available time (T_r) at Stop R may vary depending on which route a traveler utilizes to reach Stop R. In such a case, TBSAT assumes that a traveler from the trip origin will attempt to maximize the area he can reach from disembarkable stops. That is, he will want to maximize his remaining available time at Stop R.

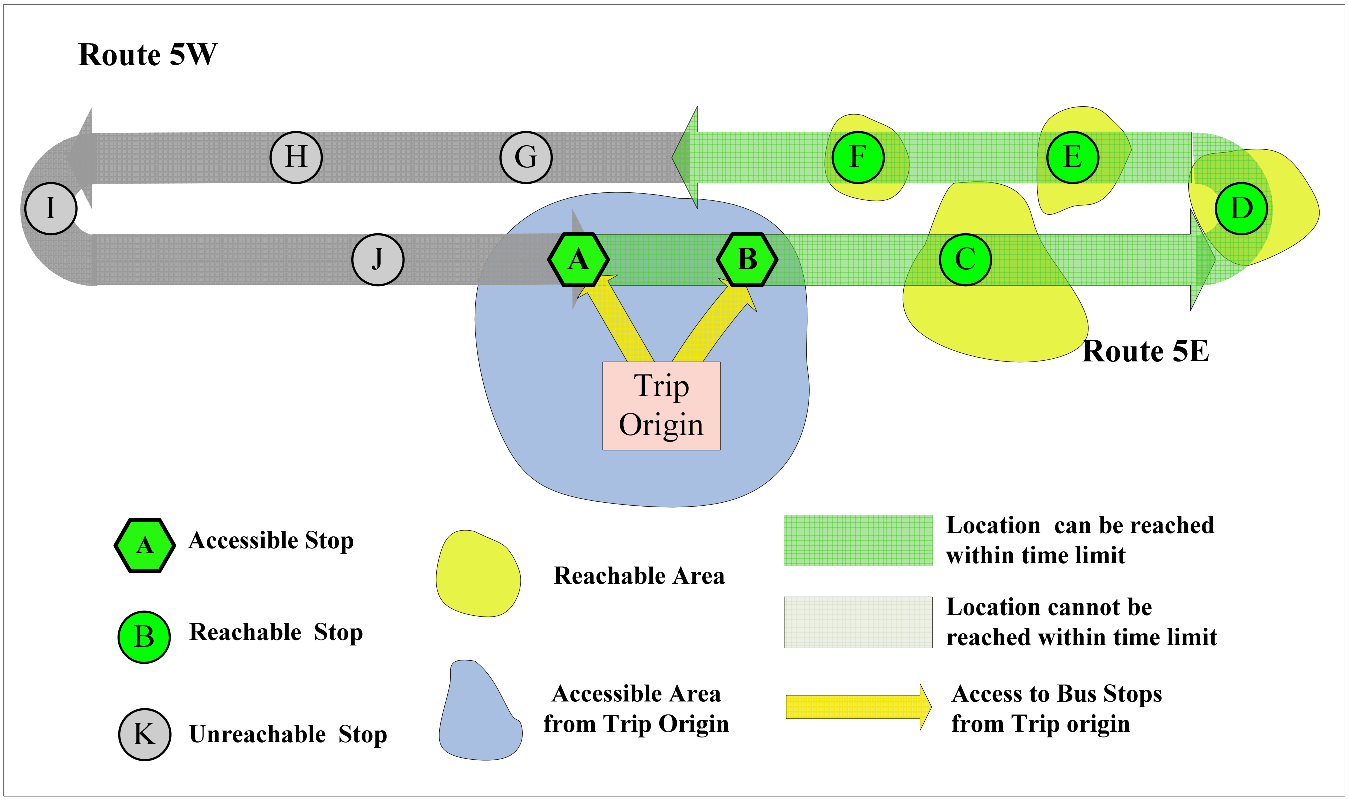


Figure 11: Multiple T_r Due to the Same Bus Route through Different Accessible Stops

2. A *disembarkation stop* that can be reached through more than one accessible *boarding* stop on the same bus route generates multiple T_r values.

Figure 11 illustrates that both Stop A and Stop B are accessible stops on Route 5. That means a traveler from the trip origin can access Route 5 at either Stop A or Stop B. This traveler's remaining available time varies according to which accessible stop he chooses to board Route 5. In such a case, TBSAT also assumes that a traveler from the trip origin will attempt to maximize his reachable area from any disembarkable stops. That is, he will maximize his remaining available time at Stop C, D, E, or F.

In both cases above, TBSAT calculates and uses the maximum remaining available time that a traveler could possibly have at that disembarkable stop as the remaining available time of that bus stop.

Reachable Stop

A *reachable stop* is a bus stop that a traveler from the trip origin can reach through an accessible route within $t_{max.}$

Since a T_r with a value less than zero at a disembarkable stop means a traveler cannot reach that bus stop within the travel-time limit t_{max}, TBSAT decides if a disembarkable stop is a reachable stop by verifying that T_r for that bus stop is greater than zero. If a traveler can bus-travel to a disembarkable stop and possesses a T_r that is larger than zero when disembarking at that stop, that stop then qualifies as a reachable stop.

Reachable stops represent the possible locations a traveler can reach within t_{max}. From each of the reachable stops, a reachable area can be calculated according to the remaining available time at each reachable stop.

In Figure 8, Figure 9, Figure 10, and Figure 11, green circle bus stops are reachable stops. Grey circle bus stops are not reachable stops because it takes more than t_{max} to reach them from the trip origin. Note that accessible stops, which appear as green hexagons, are also be reachable stops.

Reachable Area

The area a traveler can reach from a reachable stop within the remaining available time (T_r) is called the *reachable area*. TBSAT calculates the geometry of the reachable area around a reachable stop according to the T_r the traveler possesses after dismbarking at that stop and the existing paths around that reachable stop along which the bus rider can move away from that bus stop.

3.2.3 The Processes to Estimate Time-Based Bus Service Area

TBSA indicates the geographical area a traveler can reach from his trip origin within the total travel-time limit. To find the TBSA, TBSAT computes the reachable areas for each reachable stop according to the maximum remaining available time that a traveler could possibly possess at each reachable stop. Since each reachable area represents the area a traveler can reach from each reachable stop, TBSAT merges all reachable areas to generate the TBSA for time t_{max} from the designated trip origin. To summarize, to estimate TBSA means to find all reachable stops and their corresponding T_r.

However, according to the discussion above all reachable stops can be identified only after accessible routes are found. Furthermore, accessible routes can only be found at accessible stops. Thus, the entire procedure of estimating TBSA becomes a series of tasks of:

1. Find accessible stops.

2. Find accessible routes that are available at accessible stops.

3. Calculate remaining available time at each disembarkable stop along accessible routes.

4. Mark disembarkable stops along accessible routes as reachable stops if the remaining available time at them is greater than zero.

5. Develop reachable areas around each reachable stop according to remaining available time at each reachable stop.

6. Merge all reachable areas into a complete time-based bus service area map.

3.3 Generate the Time-Based Bus Service Area Map by Steps

The TBSA is calculated using the six-step process outlined above. The following discussion provides more detail about this step-by-step procedure, particularly the calculations that allow TBSAT to identify reachable stops and their corresponding T_r, and those calculations that ultimately generate the time-based service area map.

1. Step 1: Find Accessible Stops

Find all accessible bus stops that can be accessed within the **acceptable access time (AAT)**.[10] The time required to access a bus stop from trip origin is defined as the **access time t_a**. A bus stop is recognized as an accessible stop if its access time t_a <= AAT.

2. Step 2: Find Accessible Routes

All bus routes available at accessible stops are accessible routes. Only bus stops along accessible routes are disembarkable stops and potential reachable stops. Thus, only the remaining available time at bus stops along accessible routes need to be calculated in next step.

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[10] The maximum time a traveler is willing to spend accessing nearby bus stops. Through research (see Appendix B: DEFAULT ACCESS SPEED), TBSAT suggests a default AAT of 15 minutes when the mode used to access the boarding bus stop is walking (see section 4.1.7).

3. **Step 3: Calculate Remaining Available Time at Disembarkable Stops along Accessible Routes**

According to the definition of remaining available time, the value of the remaining available time at a disembarkables stop is the difference between the travel-time limit t_{max} and the total travel time from the trip origin to that bus stop.

Thus, to calculate the remaining available time at Stop Z on an accessible Route R, the following information is required:

1. The access time t_a from the trip origin to the accessible stop where the accessible Route R is available.
2. The **waiting time (t_w)** before the arrival of the accessible Route R.
3. **The bus travel time (t_b)** between the accessible stop (boarding stop) and Stop Z through the accessible Route R. In TBSAT, the time a bus spends stopped at each bus stop to load/unload passengers is included in t_b.

The total travel time from the trip origin to Stop Z is (t_a+t_w+t_b). Thus, the value of the **remaining available time (T_r)** at bus stop Z is:

$$T_r = t_{max} - (t_a+t_w+t_b)$$

Equation 1: Calculate Remaining Available Time

For a T_r longer than the **acceptable destination access time (ADAT)**, which is the maximum time a bus rider is willing to spend accessing possible destinations after disembarking, the value of this T_r should be constrained to be equal to ADAT:

$$T_r = ADAT, (If\ T_r > ADAT)$$

Equation 2: Constrain Remaining Available Time

4. **Step 4: Find Reachable Stops**

By definition, the remaining available time T_r a bus rider possesses after disembarking at a reachable stop must be greater than zero. Thus, of all disembarkable stops along the accessible routes, TBSAT marks only the bus that can be reached with a positive remaining available time as reachable stops.

5. **Step 5: Generate Reachable Areas from Reachable Stops**

With all reachable stops and the corresponding remaining available time (T_r) a traveler can possess at each stop identified, TBSAT calculates the reachable areas from each reachable stop along the existing paths. TBSAT calculates the reachable areas by utilizing the ArcGIS *Network Analyst* function.

6. **Step 6: Merge Reachable Areas into a Complete Time-Based Bus Service Area Map**

By merging reachable areas that are generated from each reachable stop, TBSAT generates a large polygon that covers all possible areas that can be reached via a single bus trip from trip origin. This polygon indicates the bus service area of the given trip origin within given total travel time limit t_{max}.

Figure 12 illustrates these six steps in the form of a flowchart. In the next chapter, factors and variables that are required for completing these steps are defined and discussed.

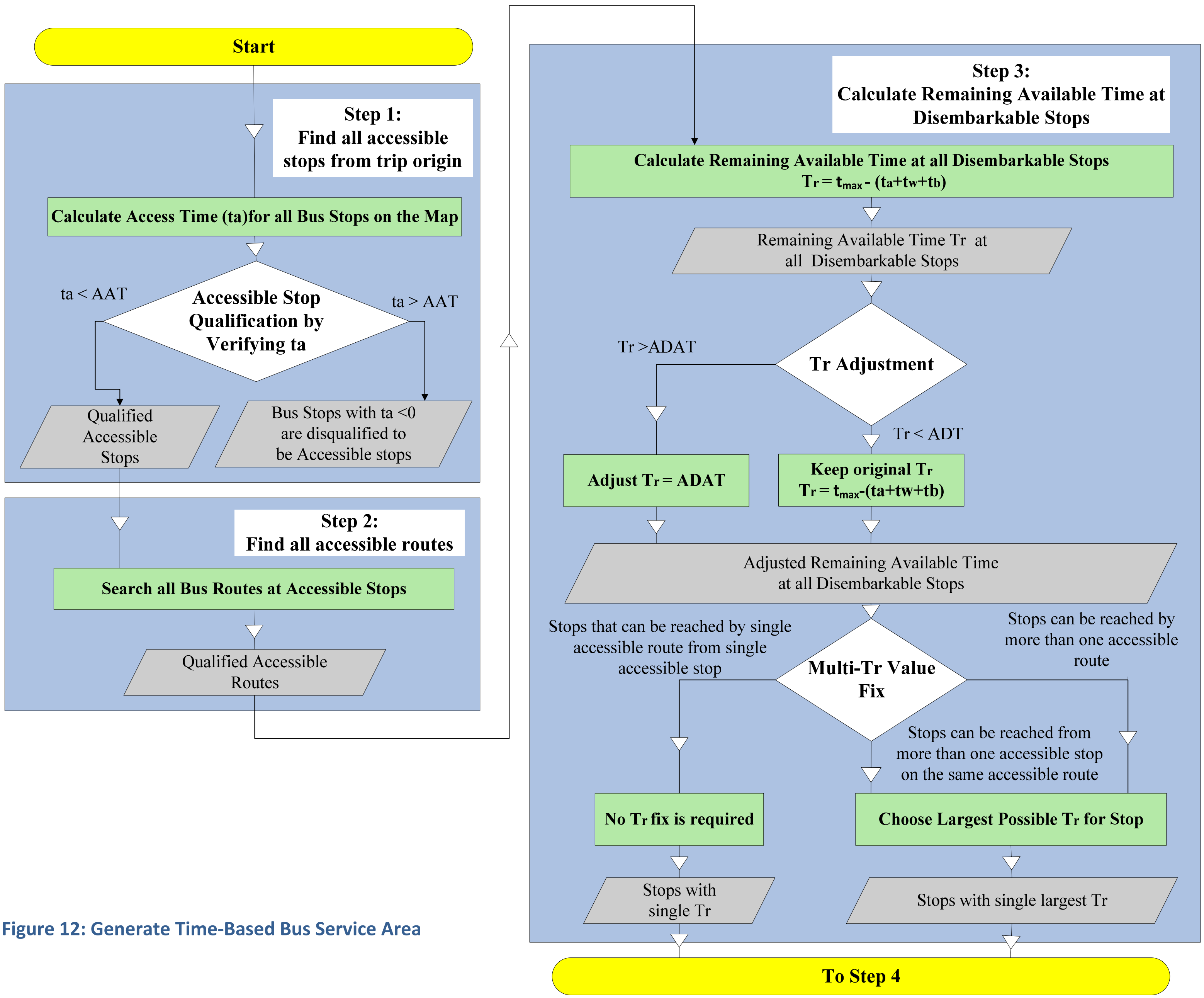

Figure 12: Generate Time-Based Bus Service Area

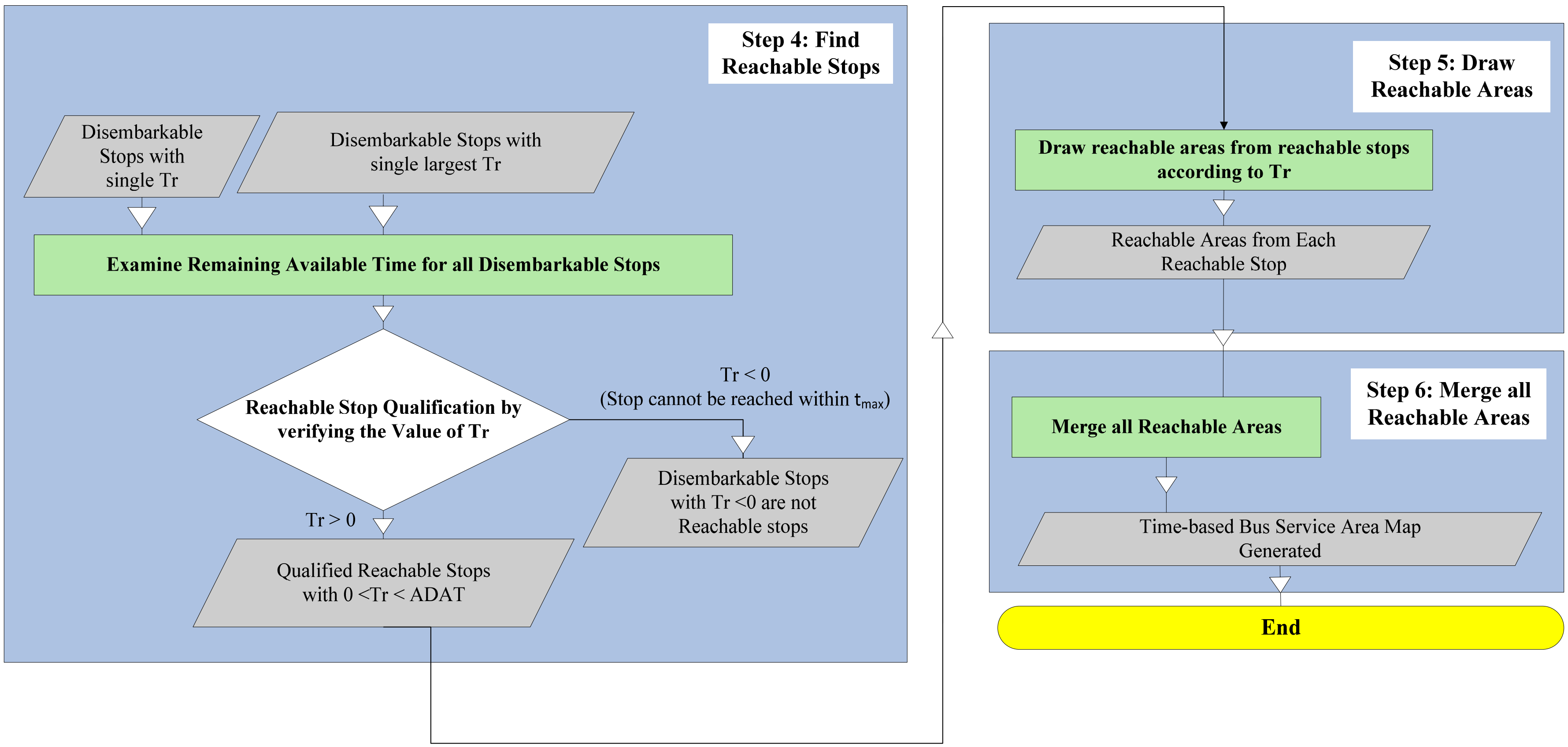

Figure 12: Generate Time-Based Bus Service Area (Cont'd)

In the flowchart in Figure 12, the green rectangles represent the processes to be executed within a step. The parallelograms are the data input that are required to complete each process or the output that is generated by the execution of the processes. The white diamond shapes are a special type of process that is executed. They represent a decision point in the process. Unlike general processes (green squares), which generate new types of output from the input, decisions only separate the input into two or more outputs according to the given criteria without generating new results.

Chapter 4 FACTORS AND VARIABLES IN TBSAT

The six-step process developed in Chapter 3 describes the logical processes that the TBSAT program follows to generate the time-based bus service area for the user defined trip origin and travel-time limit. However, as shown in the flowchart Figure 12 in section 3.3, the processes in the six-step process can generate different outputs according to different values of user input. These inputs are categorized into two types: factors and variables. In each of the following sections, the factors and the variables that are involved in each of the six-step process are described.

In this report, *factors* represent the "facts" that are required as the input(s) during the various process steps in the execution of TBSAT. Factor values in a run are pre-determined by the scenario of the TBSAT run. Factors include the condition of the bus service system, such as the headway (frequency) of bus routes; and the bus rider's behavior, such as the walking speed that is pre-determined by the TBSAT user. The value of the factors cannot be changed during the execution of a TBSAT run. For example, both the location of bus stops and the street layout are factors used by TBSAT in order to calculate the distance from the trip origin to bus stops. This distance can be converted into access time later. The location of bus stops and the street layout must be loaded into the TBSAT database *before* the user runs TBSAT and cannot be modified during the execution of TBSAT. However, this underlying information substantially influences the output of TBSAT.

By contrast, *variables* in TBSAT represent specific parameters whose values are calculated during the execution of specific processes, rather than being pre-set by the TBSAT user. For example, the remaining available time at a reachable stop (which determines the size of the service area segment that can be generated around that reachable stop) is a variable because its value is calculated by referring to other inputs during the execution of the Step 3 of TBSAT.

Both factors and variables are considered inputs to TBSAT. However, the output of a process is always termed a variable, since the value of the output is calculated instead of pre-determined.

4.1 Step 1: Find Accessible Stops

Nine factors and variables (displayed in Figure 13) are involved in the first step, which is finding accessible stops (See Figure 12):

1. Trip Origin Location (Factor)
2. Bus Stop Locations (Factor)
3. Existing Path Map (Factor)
4. Distance between the trip origin and each bus stop (Access Distance) (Variable)
5. Access Speed (Factor)
6. Access time from trip origin to each bus stop (Variable)
7. Acceptable Access Time (AAT) (Factor)
8. Acceptable Access Distance (Factor)
9. List of Accessible Stops (Variable)

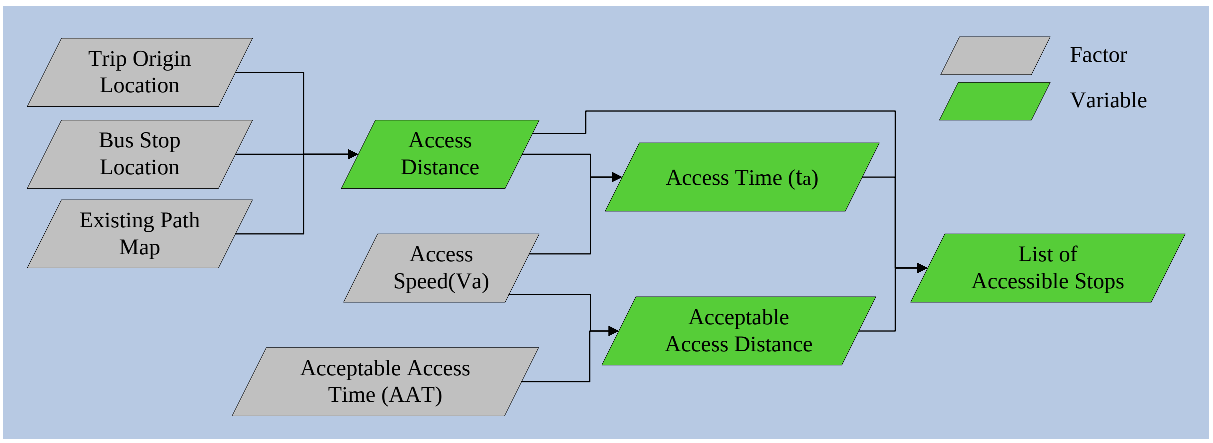

Figure 13: Factors and Variables in Step 1

As shown in Figure 13, with the location of the trip origin, the bus stop locations, and the existing path map known, TBSAT can calculate the variable of the access distance from the trip origin to each bus stop along existing paths. TBSAT calculates this by executing a network analysis session in ArcGIS using the Network Analyst extension.[11]

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[11] The ArcGIS Network Analyst extension is an extension program that allows ArcGIS to perform four types of network analysis: 1) finding the best route the passes all required locations; 2) finding the closest facility from a location; 3) calculating the service area from a location; and 4) creating a origin/destination matrix that estimates the travel cost between a group of origins and a group of destinations. TBSAT utilize the closest facility analysis and the service area analysis functions to generate the time-based bus service area.

This distance is defined in TBSAT as *Access Distance*. If the access distance to a bus stop is greater than the *Acceptable Access Distance* (the user input longest distance that the traveler is willing to travel from trip origin to a boarding bus stop), this bus stop then fails to be an accessible stop.

However, a person normally measures his travel cost of accessing a bus stop by *Access Time*. This is the time the person spends reaching the bus stop traveling at his typical pace, also known as *Access Speed* (V_a). In order to adapt to both the user's demand of using access time and the user's input acceptable access travel cost, and the ArcGIS's demand of determining if a bus stop is accessible within the acceptable access distance, TBSAT requires the user to input his *Acceptable Access Time (AAT)*, instead of his acceptable access distance, and the access speed. By doing so, TBSAT users are able to provide acceptable access distance to TBSAT by multiplying V_a with AAT, thus, allow TBSAT to differentiate the accessible stops, which are the bus stops within the acceptable access distance of the trip origin, from other non-accessible stops through ArcGIS processes.

After TBSAT identifies the accessible stops within the acceptable access distance of the trip origin, the access distance between trip origin and each accessible bus stop is converted into access time. This is done so that TBSAT may generate a list of accessible stops and the access time to each. This list is the final output of Step 1 and one of the inputs to Step 3.

4.1.1 Trip Origin Location (Factor)

The user may choose any point on the map as the location of the trip origin. The origin normally depends on the purpose of the TBSAT run. For example, to generate the 1-hour bus service area from a transit center, the trip origin should be set at the location of this transit center.

4.1.2 Bus Stop Locations (Factor)

The spatial location of all bus stops in the bus system should be prepared as a dot feature class[12] in ArcGIS format and then be added to the TBSAT *Accessible Stops Network Analysis Layer*[13] as its facility information.[14]

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[12] A *dot feature class* specifies the location of a series of points to ArcGIS. In this case, a dot feature class of bus stops tells ArcGIS about the location of each bus stop.

[13] The *Accessible Stops Network Analysis Layer* in TBSAT is a closest facility analysis layer in ArcGIS. This facilitates the finding of accessible stops (see section E.2.1).

[14] Facilities in the *Accessible Stops layer* in TBSAT represent all bus stops in the current bus service system. Accessible stops are identified among these facilities (bus stops).

4.1.3 Existing Path Map (Factor)

To access the accessible stops from the given trip origin, a traveler must move along an existing, passable path. For example, the street map is one type of most frequently used existing path map used to indicate the shortest path from the trip origin to each bus stop.

In order for TBSAT to function correctly, the existing path map must be prepared in the format of a *Network Dataset*[15] and then imported into the ArcGIS component of TBSAT.

4.1.4 Distance between the trip origin and bus stop (Access Distance) (Variable)

With the location of the trip origin, the location of the bus stops, and the existing path known, the TBSAT *Finding Accessible Stops* tool can calculate the distance between the trip origin and each bus stop. [16]

4.1.5 Access Speed (V_a) (Factor)

As discussed above, the access speed is used to convert the access distance into access time. However, access speed is controlled by numerous factors, such as the travel mode, street layout, street grade, weather, and physical condition of the traveler. For example, a traveler who bicycles to a bus stop, his an access speed much faster than another traveler who walks to the bus stop. Thus, the user must provide the appropriate access speed to TBSAT, according to the scenario of that specific run.

Transportation research suggests that walking is the most commonly used mode to access bus stops in urban areas. Further, such research suggests typical speeds for walking or bicycling in urban areas (as discussed in Appendix B: DEFAULT ACCESS SPEED). TBSAT uses a default walking speed of 2.05 mph, based on this research. The user may override this value by modifying the Access Speed factor.

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[15] A *network dataset* is a special format of ArcGIS layer that indicates the passable paths that are available in a geographic region. A network dataset contains information including the shape the path network, the junctions of the crossed paths, and all other optional information, such as the turn limitation at specific junctions and the gradient of paths. A network analysis is always performed on top of a network data set. In this case, finding accessible stops from trip origin is performed on top of the network data set of the current street map.

[16] See section E.2.2.

4.1.6 Access Time (t_a) (Variable)

Once the access speed and the access distance are determined, TBSAT can calculate the access time from the trip origin to each bus stop. As discussed above, the access time from the trip origin to a bus stop is calculated by dividing the access distance between the trip origin and this bus stop with the access speed (V_a).

$$t_a = \text{Access Distance} / V_a$$

Equation 3: Access Time Calculation

4.1.7 Acceptable Access Time (AAT) (Factor)

Acceptable access time represents the maximum time the user is willing to spend accessing nearby bus stops from the trip origin. A bus stop with an access time (from the trip origin) less than the AAT is defined as an accessible stop. Similar to access speed, AAT may vary depending on the values of other factors, such as access mode to the boarding bus stop, the physical condition of traveler, weather conditions, and the street gradient. Thus, the value of AAT also must be specified in each TBSAT run.

TBSAT uses a default acceptable access time of 15 minutes. This assumes that the traveler walks to the bus stop. This is based on research conducted to quantify typical pedestrian walking behavior. See Appendix C: DEFAULT ACCEPTABLE ACCESS TIME for a discussion.

4.1.8 Acceptable Access Distance (Factor)

Once the access speed and the acceptable access time are determined, the acceptable access distance is easily calculated with Equation 4.

$$\text{Acceptable Access Distance} = \text{AAT} \times V_a$$

Equation 4: Covert AAT into Acceptable Access Distance

4.1.9 List of Accessible Stops (Variable)

The list of accessible stops is the final output of Step 1. TBSAT uses the *Finding Accessible Stops* tool to obtain the access time from the trip origin to each of bus stops. Then, TBSAT generates the list of accessible stops. This list includes the name of and the access time to each bus stop that has an access time less than the acceptable access time.

4.2 Step 2: Find Accessible Routes

Once TBSAT has executed all the Step 1 processes documented in Figure 12 in section 3.3, the tool proceeds to Step 2: find accessible routes. These are the bus routes available at each accessible stop. Three factors and variables are involved in this step:

1. Bus stop names along each bus route (Factor)
2. List of Accessible Stops (Variable)
3. List of Accessible Routes (Variable)

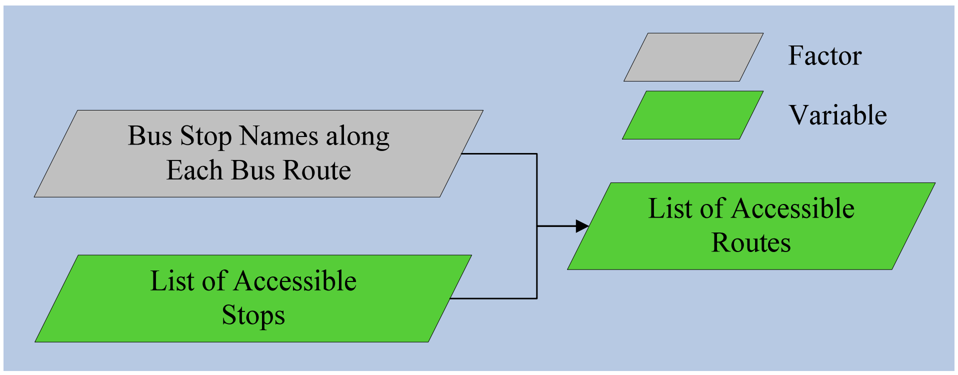

Figure 14: Factors and Variables in Step 2

With the bus stop names along each bus route and the list of accessible stops available, TBSAT identifies which bus routes are available at each accessible stop.

4.2.1 Bus Stop Names along each Bus Route (Factor)

TBSAT decides whether a bus route is available from at least one of the accessible stops by checking whether this route stops at at least one of the accessible stops. Such information is easily obtained from the route schedule for each bus route. In TBSAT, the bus stop names along each bus route are stored in the *Route Schedule* table in the TBSAT database component.

4.2.2 List of Accessible Stops (Variable)

The list of accessible stops is generated as the final output in Step 1 of TBSAT, discussed in section 4.1.9.

4.2.3 List of Accessible Routes (Variable)

By cross-referencing the list of accessible stops with the route schedule, TBSAT creates a list of accessible routes. This list contains the bus routes that are available at each accessible stop. The list of accessible routes is generated by, and stored in, the *Accessible Routes* query in the TBSAT database component.

Table 1: Example of List of Accessible Routes

STOP	Route	Direction	ATTD	Access Distance
326910	32	E	47.00	0.40
336903	32	E	48.00	0.45
326901	60	N	26.00	0.39
326906	60	N	25.20	0.43
326802	60	S	31.63	0.33
326907	60	S	29.88	0.50
326915	81	E	21.10	0.33
326901	81	W	29.00	0.39
316909	81	W	32.60	0.40

Table 1 is an example list of accessible routes generated by TBSAT. Each entry in the list contains the bus stop number, the route number, and the route's direction. For example, the two routes available at stop 326901, are 60N and 81W. These appear as two separate records for that bus stop. As another example, route 60N is available at both stops 326901 and 326906, so that route 60N also appears twice in the list of accessible routes. The ATTD refers to the time point along the bus route at the stop (see section 4.3.1). Finally, the access distance from the trip origin to each accessible stop is recorded in the list of accessible routes.

4.3 Step 3: Calculate Remaining Available Time at Disembarkable Bus Stops

Step 3 in section 3.3 calculates the remaining available time (T_r) at all disembarkable stops. The value of T_r is the output of Step 3. Equation 1 is that used to calculate the base T_r . Equation 2 is a constraint placed on T_r to keep it within the defined range according to the discussion in section 3.3.

$$T_r = t_{max} - (t_a+t_w+t_b)$$

Equation 1: Calculate Remaining Available Time

$$T_r = ADAT \quad (\text{If } T_r > ADAT)$$

Equation 2: Constrain Remaining Available Time

The value of remaining available time at any disembarkable stop is controlled by factors and variables including *total travel-time limit* (t_{max})*, access time* (t_a)*, waiting time* (t_w)*, bus travel time* (t_b)*, and acceptable destination access time (ADAT).* Six pieces of information are required to calculate the T_r at each disembarkable stop:

Variables

1. The Arrival Timetable
2. The access time (t_a) from the trip origin to the accessible stops where each accessible route is available
3. Peak/Off-peak waiting time (t_w) before the arrival of each accessible route's bus
4. The bus travel time (t_b) from the accessible stops to each possible disembarkable stop.

Factors

1. Total travel-time limit (t_{max})
2. Acceptable destination access time (ADAT)

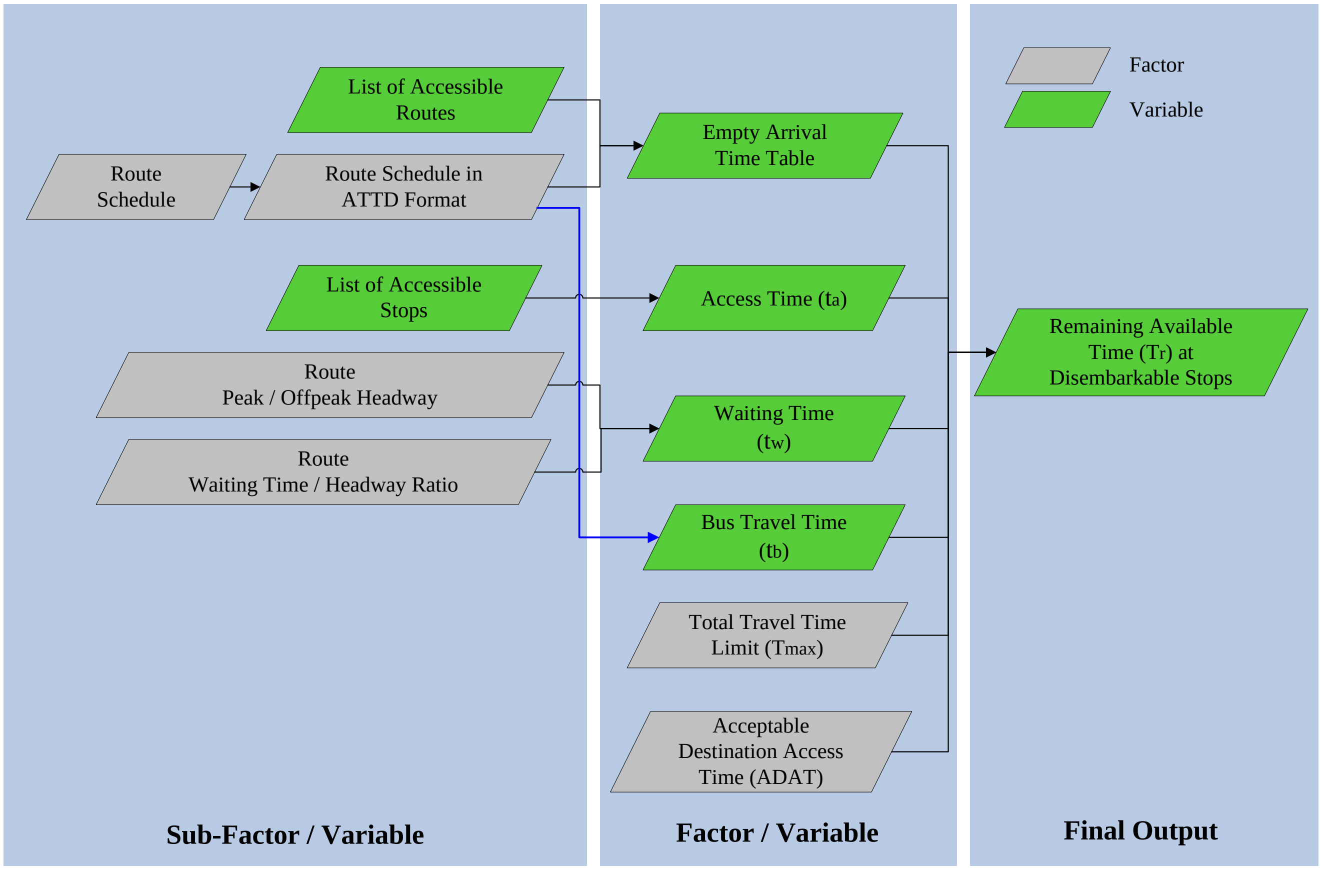

Figure 15: Factors and Variables in Step 3

As shown in Figure 15, to obtain the value of each of the four variables listed in the center column, TBSAT must refer to more sub-factors or sub-variables. The following sections discuss how the access time, the waiting time, and the bus travel time are calculated according to the sub-factors and sub-variables. It then discusses how the remaining available time is calculated according to the factors and variables.

According to the discussion of remaining available time in section 3.2.2, the traveler may reach the same disembarkable stop with different amounts of remaining available time T_r, if he takes a different route to that stop, or uses a different accessible stop. Because a traveler may choose different boarding stops or different bus routes to reach the same bus stop, TBSAT must identify all possible values for T_r that the traveler might use at each disembarkable stops. From all the possible choices, TBSAT identifies the maximum T_r that the traveler has at each disembarkable stop (as discussed in section 3.2.2).

4.3.1 Arrival Timetable

The arrival timetable is a “container” that records all possible combinations of a traveler’s choice of: accessible bus **S**top to board the bus, accessible **R**oute to take, and bus stops to **D**isembark. Such combinations are defined as **SRD plans**. Each SRD plan represents a unique trip plan that a traveler can take from the trip origin to a disembarkable stop.

Table 2: Example of Arrival Timetable

SRD #	Boarding Stop	Route	Board Dir	Arrival Stop	Direction	Access Time	Passeneger Waiting Time	Bus Travel Time	Remaining Available Time
1	316909	81	W	**286802**	W	See Section 4.3.2	See Section 4.3.3	See Section 4.3.4	See Section 4.3.7
2	316909	81	W	346805	E				
3	316909	81	W	276802	W				
4	316915	81	E	**286802**	W				
5	316915	81	E	406811	W				
6	316915	81	E	376607	W				
7	316915	81	E	386613	W				
8	326801	60	N	326101	S				
9	326801	60	N	347001	N				
10	326801	60	N	327022	N				
11	326802	60	S	326101	S				
12	326802	60	S	347001	N				
13	326810	60	N	326101	S				
14	326810	60	N	347001	N				
15	326810	60	N	327022	N				
16	326901	32	W	237416	W				
17	326901	32	W	277204	W				
18	326901	81	W	**286802**	W				
19	326901	81	W	346805	E				
20	326901	60	N	326101	S				
21	326901	60	N	347001	N				
22	326901	60	N	327022	N				

Table 2 shows an excerpt from an arrival timetable. Note that each SRD plan in this table is unique because of its combination of boarding (accessible) stop, the bus route, and the disembarkable bus stop. TBSAT calculates all SRD plans possible from the trip origin, and then lists them in the empty arrival table. Since all

SRD plans are recorded in the arrival timetable, all disembarkable stops that can be reached from trip origin are listed in the Arrival Stop column of the arrival timetable.

The arrival timetable allows TBSAT to record the access time, the waiting time, and the bus travel time of each possible SRD plan. Note that stop 286802 (the entries shown in bold font) can be reached through Route 81 at either boarding stop 316909 (SRD #1), 337006 (SRD #4), or 326901 (SRD #18). As a result, a traveler from the trip origin may choose one of the three different sets of remaining available times at station 286802, depending on the SRD plan chosen.

TBSAT identifies all possible SRD plans and generates the empty arrival timetable by referring to following information:

(1) List of Accessible Routes

The list of accessible routes, which is a table similar to Table 1 that is described in section 4.2.3, records the name of all accessible stops and the access distance from trip origin to each. The access distance is converted into access time automatically by TBSAT.

(2) Absolute Travel Time Differential (ATTD) Format Route Schedule

The route schedule includes two types of important information about the bus service system. First, it specifies the stops along a bus route, and so a list of bus stops that can be reached by this route. Second, it specifies the sequence of the bus stops and the bus travel time interval between bus stops along the bus route. From this, TBSAT determines the bus travel time between any two stops on the same bus route. Both types of information described above are critical to generating the empty arrival timetable.

However, instead of generating the empty arrival timetable directly from a traditional bus route schedule (which records the travel time between stops using standard time format), TBSAT refers to the **Absolute Travel Time Differential (ATTD)** at each bus stop on a bus route in order to decide the sequence and the bus travel time between two bus stops on the same bus route.

Derived from its bus route schedule timetable, the bus route's ATTD at a bus stop records the time duration a bus needs to travel from the first stop of this route to that stop. This value is route, direction, and bus stop specific. For example, as shown in Figure 16, if Route 10E begins at its first stop, Stop A, at 7:00 a.m. and arrives at Stop B at 7:23 a.m., the ATTD of Route 10E at Stop B is 23 minutes. Note that the ATTD at the first stop of a direction of any route is always zero. For example, in Figure 16, Stop A is the first stop of the eastbound Route 10, thus, the ATTD of Route 10 E at Stop A is zero. However, Route 10W - Stop A has an ATTD of 60 minutes because it takes 60 minutes for a route 10W bus travel to travel from its first stop (Stop D) to Stop A. Similarly, Route 10W - Stop D has an ATTD of zero because it is the first stop of westbound Route 10.

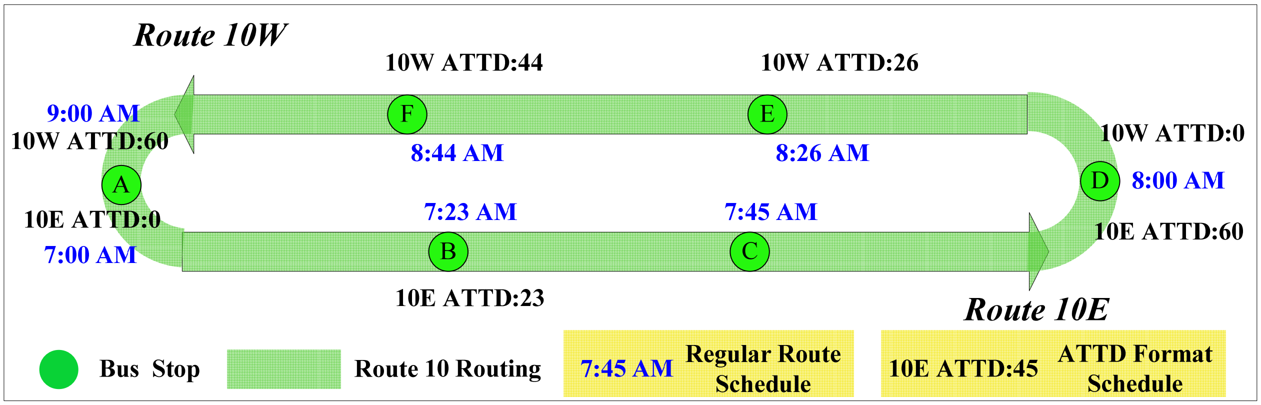

Figure 16: ATTD Format Route Schedule vs. Regular Route Schedule

TBSAT uses ATTD to record the sequence of bus stops along a bus route and to calculate bus travel time rather than directly subtracting the time points between two stops. This is because multiple buses along the same route pass through the same bus stop multiple times during different times of a day. However, there is no information that supports the prioritization of time points. For example, Route 10E may pass through Stop A at 7:00 a.m., 8:00 a.m., and 9:00 a.m. every day. It is difficult for TBSAT to decide which time point should be recorded as the reference time point of Stop A of Route 10E. On the other hand, the ATTD of a bus route at a bus stop is always fixed (assuming no schedule change). Following the example above, regardless of whether the bus arrives at 7:00 a.m., 8:00 a.m., or 9:00 a.m., Route 10E – Stop A has an ATTD of 0 (as long as Stop A remains the first stop of Route 10E).

ATTD is also an ideal format, since it is stored as a “general number,” rather than in “time” format in the TBSAT database component. Storing time values, including access time and waiting time, using the “general number” format in the TBSAT database component simplifies programming and the calculation.

Table 3: Example of ATTD Style Route Schedule

Route	Dir	STOP	ATTD
10	E	347011	0.00
10	E	357203	11.00
10	**E**	**357201**	**13.00**
10	E	367206	15.00
10	E	357301	16.00
10	**E**	**367308**	**17.00**
10	E	367209	18.00
10	W	367209	0.00
10	W	357302	2.00
10	W	357203	5.00
10	W	357201	7.00
10	W	337010	15.00
10	W	347011	18.00

Table 3, an example of an ATTD style route schedule, displays the bus travel time between two successive stops on the same direction of the same route. For example, if Stop 357201 is the boarding stop, the bus travel time from Stop 357201 to Stop 367308 via Route 10E is 4 minutes (17 minutes minus 13 minutes). Likewise, the bus travel time from the boarding stop to a bus stop going the opposite direction of the same route, can also be calculated. The details concerning the method of calculating bus travel time are discussed in section 4.3.4.

Based on the *list of accessible routes* and the *ATTD format route schedule*, TBSAT creates a list of SRD plans. The SRD plans are recorded in the arrival timetable. Figure 17 is an example of how TBSAT uses the accessible route list and the ATTD schedule to create an arrival timetable.

Accessible Stops			
Route	Dir	STOP	ATTD
10	**E**	**357201**	**13.00**
10	**W**	**357203**	**5.00**

ATTD Route Schedule			
Route	Dir	STOP	ATTD
10	E	347011	0.00
10	E	357203	11.00
10	E	357201	13.00
10	E	367206	15.00
10	E	357301	16.00
10	E	367308	17.00
10	E	367209	18.00
10	W	367209	0.00
10	W	357302	2.00
10	**W**	**357203**	**5.00**
10	W	357201	7.00
10	W	337010	15.00
10	W	347011	18.00

Arrival Timetable					
SRD #	Boarding Stop	Route	Board Dir	Arrival Stop	Dir
1	357201	10	E	347011	E
2	357201	10	E	357203	E
3	357201	10	E	367206	E
4	357201	10	E	357301	E
5	357201	10	E	367308	E
6	357201	10	E	367209	E
7	357201	10	E	367209	W
8	357201	10	E	357302	W
9	357201	10	E	357203	W
10	357201	10	E	357201	W
11	357201	10	E	337010	W
12	357201	10	E	347011	W
13	357203	10	W	347011	E
14	357203	10	W	357203	E
15	357203	10	W	357201	E
16	357203	10	W	367206	E
17	357203	10	W	357301	E
18	357203	10	W	367308	E
19	357203	10	W	367209	E
20	357203	10	W	367209	W
21	357203	10	W	357302	W
22	357203	10	W	357201	W
23	357203	10	W	337010	W
24	357203	10	W	347011	W

Figure 17: Create Arrival Timetable

The arrival timetable in Figure 17 shows that each SRD plan represents a possible combination of an accessible boarding stop and a disembarkable stop. Since the example above shows two accessible stops and 13 bus stops along Route 10, excluding the SRD plans which have their boarding stop the same as their disembarking stop, the total number of possible SRD plans is 2*(13-1)=24.

Once a "clean" arrival timetable (see Table 2) is created, critical time estimates for each SRD plan are computed by TBSAT. These estimates include access time, waiting time, and bus travel time. Once calculated these are stored in this arrival timetable in the TBSAT database component. Then, TBSAT calculates the remaining available time that each SRD plan offers at its disembarkable stop.

4.3.2 Access time (t_a)

The access time for each SRD plan depends on which accessible stop an SRD plan contains.

Table 4: Designate Access Time to SRD combinations

SRD #	Boarding Stop	Route	Board Dir	Arrival Stop	Direction	Access Time
1	316909	81	W	286802	W	11.78
2	316909	81	W	346805	E	11.78
3	316915	81	E	406811	W	12.64
4	316915	81	E	376607	W	12.64
5	316915	81	E	386613	W	12.64
6	326801	60	N	326101	S	10.15

Table 4 shows the access time of an SRD plan is exclusively dependent on this SRD plan's boarding stop. This is because the access time is controlled only by the distance from the trip origin to the accessible boarding stop. For example, although SRD numbers 1 and 2 disembark at different stops, as long as they contain the same boarding stop, the value of their access time should be equal.

As for the value of access time, the access time to all accessible stops is calculated in Step 1. The computation of access time is illustrated in section 4.1.6.

4.3.3 Peak/off-peak waiting time (t_w) before the arrival of each accessible route

The passenger waiting time for each SRD plan is dependent upon which bus route each SRD plan uses. To estimate the waiting time for each bus route, two factors are required.

(1) Peak/off-peak scheduled headway of each bus route (Factor)

The **scheduled headway** is the scheduled time-interval between two successive buses of a bus route. The scheduled headway represents the maximum time a bus rider must wait at the bus stop before the arrival of the next desired bus. The scheduled headway can be obtained easily from the transit operator.

TBSAT requires the scheduled headway for both peak and off-peak hours of each bus route. This is because TBSAT generates the time-based bus service area map of a location during both peak and off-peak hours in a single run. The peak and off-peak scheduled headway of all bus routes is stored in the *Route Headway Table* in the TBSAT database.

(2) Waiting time/headway ratio of each bus route (Factor)

Time spent waiting for a bus at a bus stop may be measured in terms of the bus route's scheduled headway. This ratio, **waiting time/headway ratio**, takes on values from zero to one. Zero represents the case when the traveler arrives at the bus stop just at the same time as his bus. He waits zero (0% portion) amount of time for that bus. At the other extreme, a ratio of one, the traveler arrives just as the bus is leaving the bus stop. He misses the bus. This traveler must wait the full (100% portion) of time for the next scheduled bus to arrive.

To simplify the computation, many studies or models use half of the scheduled headway as the estimated passenger waiting time.[17]

However, some other studies, such as David O'Sullivan's and Qiong Tian's studies, suggest that the estimated waiting time should be equal to or less than half of the scheduled headway. The stated reason is that some people, especially the daily commuter, know the bus schedules and manage their time so as to arrive at the bus stop close to the scheduled bus arrival

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[17] Lazar N. Spasovic, Maria P. Boile, and Athanassios K. Bladikas, "A methodological framework for optimizing bus transit service coverage," in *73rd Annual Meeting of the Transportation Research Board Congress Held in Washington D.C. January 1993, 6.*

Mark Wardman, "Public transport values of time,"*Transport Policy* 11, no. 4 (2004).

time. In this way, the traveler waits for the bus for less than half of the bus scheduled headway amount of time.[18]

Jeffrey M. Casello proposed that the estimated waiting time could be half of the scheduled headway for a route which has less than 30 minute scheduled headway. For a route with a scheduled headway longer than 30 minutes, the estimated waiting time is assumed to be 1/3 of the scheduled headway, with a maximum waiting time of 15 minutes.[19] This assumption makes intuitive as well as logical sense. For a route with a scheduled headway less than 30 minutes, the average waiting time is less than 15 minutes. In this case, the bus rider might consider the precision in waiting time tolerable or unimportant. However, if a scheduled headway is longer than 30 minutes, by using Casello's first formula the estimated waiting time for such a route will be more than 15 minutes. In this case, the bus rider may become aware of the time spent on waiting. As a result, this rider is more likely to manage his time and attempt to reach to the bus stop closer to the expected bus arrival time.

Another way to estimate waiting time more precisely is by taking traffic conditions into consideration. The *Coefficient of Variation of Headways* is used commonly to in order to represents the influence that traffic conditions contribute to waiting time. The coefficient of variance of headways is defined (see Equation 5) as the standard deviation of the scheduled headway divided by the mean of the scheduled headway.[20]

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[18] David O'Sullivan, Alastair Morrison, and John Shearer, "Using desktop GIS for the investigation of accessibility by public transport: An isochrone approach," *International Journal of Geographical Information Science* 14, no. 1 (2001).

Qiong Tian, Hai-Jun Huang, and Hai Yang, "Equilibrium properties of the morning peak-period commuting in a many-to-one mass transit system," *Transportation Research Part B: Methodological* (2006), 618.

[19] Jeffrey M. Casello, "Transit competitiveness in polycentric metropolitan regions," *Transportation Research Part A: Policy and Practice* 41, no. 1 (2007).

[20] Liping Fu, Qing Liu, and Paul Calamai, "Real-time optimization model for dynamic scheduling of transit operations," *Transportation Research Record* 1857, no. 7 (2003).

Christopher Pangilinan, et al, "Bus supervision deployment strategies and the use of real-time AVL for improved bus service reliability," in *87th Transportation Research Board Annual Meeting Congress Held in Washington D.C. January 2008*.

P. Chandrasekar, Ruey Long Cheu, and Hoong Chor Chin, "Simulation evaluation of route-based control of bus operations," *Journal of transportation engineering* 128, no. 6 (2002).

$$\text{Coefficient of Variation of Headways} = \frac{\text{Standard Deviation of Headway Deviations}}{\text{Mean Schedule Headways}}$$

Equation 5: Coefficient of Variation of Headways

The simple waiting time equation with coefficient of variation of headways can be expressed as:[21]

$$t_W = \frac{H}{2} \times (1 + C_v)$$

Where t_w stands for waiting time and C_v stands for coefficient of variation of headways.

Equation 6: Waiting time with coefficient of variation of headways

The coefficient of variation of headway reflects the impact on waiting time due to traffic conditions. The Transportation Research Board (TRB) identifies the relationship between the coefficient of variation of headway and the level of service (LOS) of the street where the bus route runs.[22]

Table 5: Relationship between LOS and Cv, coefficient of variance of headways

LOS	c_{vh}	**$P(\lvert h_i - h \rvert > 0.5h)$**	Comments
A	0.00-0.21	"1%	Service provided like clockwork
B	0.22-0.30	"10%	Vehicles slightly off headway
C	0.31-0.39	"20%	Vehicles often off headway
D	0.40-0.52	"33%	Irregular headways, with some bunching
E	0.53-0.74	"50%	Frequent bunching
F	>0.75	>50%	Most vehicles bunched

Source: Transportation Research Board (TRB), *Transit Capacity and Quality of Service Manual*, 2nd ed. (Washington D.C.: Transportation Research Board, 2003).

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[21] Majid M. Aldaihania, et al, "Network design for a grid hybrid transit service," *Transportation Research Part A: Policy and Practice* 38, no. 7 (2004).

Junsik Park and Seung-Young Kho, "A new method to determine level of service criteria of headway adherence," in *85th Transportation Research Board Annual Meeting Congress Held in Washington, D.C. 2005.*

[22] Transportation Research Board (TRB), *Transit capacity and quality of service manual*, 2nd ed. (Washington D.C.: Transportation Research Board, 2003).

As shown in Table 5, the coefficient of variation of headways is zero when the traffic achieves free flow, which means all buses arrive at all stations exactly at the scheduled time. Under this condition, the waiting time is equal to half of the headway.

If, in Equation 6, the headway is transferred to the left of the equal sign, the resulting function is the ratio between passenger waiting time and scheduled headway (shown in Equation 7).

$$\frac{t_W}{H} = \frac{(1+C_v)}{2}$$

Equation 7: Calculate Waiting time/Headway Ratio

This waiting time/headway ratio describes the relationship between the estimated passenger waiting time and the schedule headway in a more direct manner. For example, if the waiting time/headway ratio is 0.5, that means it is assumed that people must wait for half of the scheduled headway at the bus stop before the arrival of their desired bus.

By inserting the coefficient of variation of headways for different traffic conditions into Equation 7, TBSAT creates a list of probable waiting time/headway ratios for identification of time-based bus service areas under different traffic conditions. The following table lists the default waiting time/headway ratios that can be chosen directly in TBSAT. These ratios are stored in the *Waiting Time/Headway Ratio* table in the TBSAT database.

Table 6: TBSAT Default Waiting Time/Headway Ratio

TBSAT Default Waiting Time/Headway Ratio	Traffic Condition	Coefficient of Variance of Headways
0.5	LOS A	0
0.63	LOS B	0.26
0.675	LOS C	0.35
0.73	LOS D	0.46
0.8175	LOS E	0.635
0.875	LOS F	0.75

Furthermore, TBSAT also allows a user to input manually the waiting time/headway should the user wish to use a value different other than the default ratios.

With the scheduled headway available and the waiting time/headway ratio specified, TBSAT can estimate the waiting time for each accessible stop along available bus routes.

$$\text{Waiting Time } t_w = (\text{Scheduled Headway}) \times (\text{Waiting Time/Headway Ratio})$$

Equation 8: Waiting Time Estimate in TBSAT

As mentioned above, the waiting time for each SRD plan is dependent on which bus route each SRD plan takes. In Table 7, the waiting time for SRD #1 through SRD #5 is the same (15 minutes) because each uses the same route (Route 81) for its accessible route.

Table 7: Add Waiting Time to Arrival Timetable

SRD #	Boarding Stop	Route	Board Dir.	Arrival Stop	Direction	Access Time	Passenger Waiting Time
1	316909	81	W	286802	W	11.78	15
2	316909	81	W	346805	E	11.78	15
3	316915	81	E	406811	W	12.64	15
4	316915	81	E	376607	W	12.64	15
5	316915	81	E	386613	W	12.64	15
6	326801	60	N	326101	S	10.15	7.5

After both the access time and the waiting time for an SRD plan is calculated, only the bus travel time remains to be identified before the remaining available time for each SRD plan's disembarkable stop can be calculated.

4.3.4 The bus travel time (t_b) from accessible stops to each disembarkable stop

As mentioned in section 4.3.1, TBSAT refers to the Absolute Travel Time Differential (ATTD) for each bus stop along each route in order to determine the sequence and the bus travel time between two bus stops on the same bus route. Since the accessible (boarding) stop, the accessible route, and the disembarkable stop that each SRD plan chooses are known after the step described in section 4.3.1, TBSAT can calculate the bus travel time of each SRD plan by referring to the ATTD format route schedule. However, there are three types of relative location relationships between the accessible stop and the disembarkable stop an SRD plan chooses. Depending on the type of this relationship, the bus travel time of an SRD plan is calculated according to one of the following three functions:

(1) Type I: SRD plans which disembark at a bus stop that is sequenced after the boarding stop and traveling the same direction as the boarding stop.

When the disembarkable stop of an SRD plan is sequenced after the accessible stop of this SRD plan in the same direction of a bus route, the bus travel time of this SRD plan can be calculated by simply subtracting the ATTD of the disembarkable stops from the ATTD of the accessible stop.

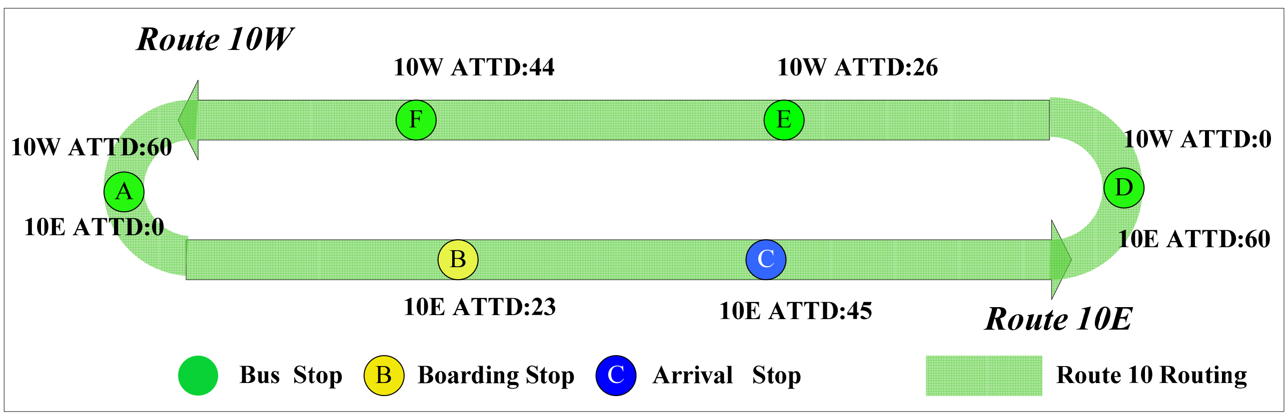

Figure 18: Calculate Bus travel Time (Type I)

As shown in Figure 18, if an SRD plan boards at Stop B and disembarks at Stop C, which is in the same direction as Stop B and sequenced after Stop B, the bus travel time from B to C will be 45-23=22 minutes. As a result, the bus travel time for a Type I SRD plan is:

$$\text{Bus Travel Time} = ATTD_D - ATTD_A$$

Equation 9: Calculate Bus Travel Time (Type I)

$ATTD_A$ is the ATTD of the bus route an SRD plan chosen at this SRD plan's accessible stop. $ATTD_D$ is the ATTD of this SRD plan's chosen bus route at this SRD plan's disembarkable stop.

(2) Type II: SRD plan which boards and disembarks at different directions along a bus route.

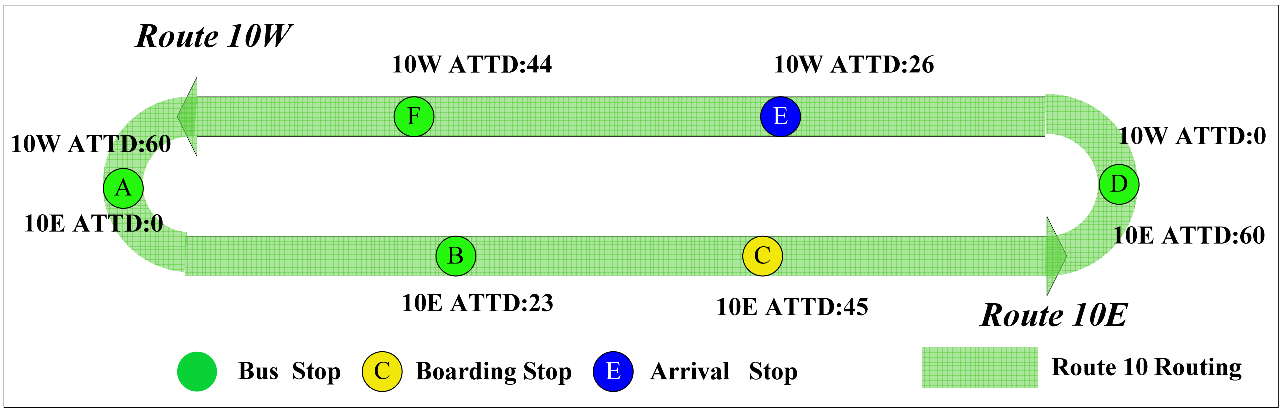

Figure 19: Calculate Bus Travel Time (Type II)

As shown in Figure 19, if an SRD plan boards at Stop C and disembarks at Stop E, the traveler who takes this SRD plan will board Route 10E at Stop C, switch direction from eastbound to westbound at Stop D, and finally reach Stop E and then disembark. As shown in the figure, Stop E does not include 10E ATTD because this leg of the trip travels in the opposite direction of 10W. Thus, the calculation of the bus travel time from Stop B to Stop E should be:

Bus Travel Time = (10E ATTD at D -10E ATTD at C) + 10W ATTD at E

The first two items on the right side of the equation calculate the bus-travel time from Stop C to Stop D, which is the terminus of Route 10E. Then, the third item 10W ATTD at E represents the bus travel time form Stop D to Stop E. As a result, for an SRD plan which has its accessible stop and its disembarkable stop at two opposite directions of a bus route, the bus travel time is:

$$\text{Bus Travel Time} = ATTD_{MAX} - ATTD_{A} + ATTD_{D}$$

Equation 10: Calculate Bus Travel Time (Type II)

$ATTD_{MAX}$ represents the ATTD of the final stop in the same direction as the boarding stop. $ATTD_{A}$ is the ATTD of this SRD plan's boarding stop. $ATTD_{D}$ is the ATTD of this SRD plan's chosen bus route at this SRD plan's disembarkable stop.

Thus, $ATTD_{MAX} - ATTD_{A}$ is the bus travel time from the accessible stop to the terminus stop where the bus switches direction. And $ATTD_{D}$ represents the bus travel time from the direction-switching terminus stop to the disembarkable stop.

(3) Type III: SRD plan with a disembarkation bus stop that is sequenced before the boarding stop along the same direction as the boarding stop.

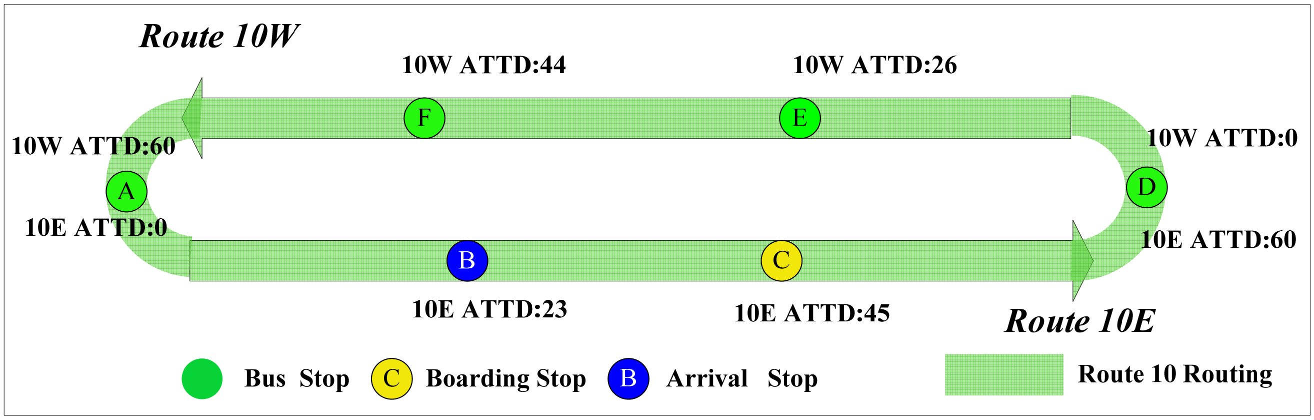

Figure 20: Calculate Bus travel Time (Type III)

As shown in Figure 20, if the traveler can only board Route 10 at Stop C, to reach Stop B, the traveler must board at Stop C and travel through Stops D, E, F, and A. Thus, the bus travel time from Stop C to Stop B is:

$$\text{Bus Travel Time} = (ATTD_{MAX\text{-}East} - ATTD_{C}) + ATTD_{MAX\text{-}West} + ATTD_{B}$$

$ATTD_{MAX\text{-}East}$ is the maximum ATTD of the eastbound Route 10E, which is also the ATTD of the last stop of Route 10E. In this case, the $ATTD_{MAX\text{-}East}$ is the Route 10E ATTD at Stop D. The $ATTD_{MAX\text{-}East}$ –

$ATTD_C$ is the bus travel time from Stop C to Stop D, which is the ATTD difference between the final bus stop of the eastbound Route 10E and the ATTD at Stop C. $ATTD_{MAX\text{-}West}$ in this equation represents the bus travel time of the entire westbound trip from Stop D to Stop A. The value of $ATTD_{MAX\text{-}West}$ equals to the Route 10W ATTD at Stop A since the value of 10W ATTD at Stop A represents the bus travel time from Stop D to Stop A according to the definition of ATTD. As a result, the calculated bus travel time from Stop C to Stop B is (60-45) + 60 + 23 = 98 minutes.

$$\text{Bus Travel Time} = (ATTD_{MAX} - ATTD_A) + ATTD_{MAX\text{-}Opposite} + ATTD_D$$

Equation 11: Calculate Bus travel Time (Type III)

According to the example above, the bus travel time of a type III SRD plan can be calculated according to Equation 11. $ATTD_{MAX} - ATTD_A$ represents the travel time from the boarding stop to the final stop of this direction where the route switches direction. $ATTD_{MAX\text{-}Opposite}$ represents the bus travel time for the bus to travel the route through the entire opposite direction. Finally, $ATTD_D$ represents the bus travel time from the first stop of the same direction to the disembarkable stop.

Depending on the combination of the accessible stop and the disembarkable stop an SRD plan chooses, the bus travel time of this SRD plan is calculated according to one of the three methods identified above.

4.3.5 Total Travel Time Limit (t_{max}) (Factor)

Total Travel time limit represents the travel-time budget a traveler possesses from trip origin. The time-based bus service area that TBSAT generates represents the t_{max} minute bus service area from the designated trip origin. This t_{max} is pre-determined and input by the user.

4.3.6 Acceptable destination access time (ADAT)

As mentioned in Step 3 in section 3.3, a constraint is placed on the value of remaining available time to be sure that it remains below or equal to ADAT. Similar to AAT, introduced in section 4.1.7, ADAT varies depending on factors such as the travel means a traveler chooses to move from his point of disembarkation to his final destination. In TBSAT, ADAT can be specified separately and does not have to be the same as AAT. For example, the TBSAT user may wish to ride a bicycle to the boarding stop and then walk to the final destination after disembarking. In this case, the user specifies an AAT that is his tolerable amount of time to bicycle and an ADAT that is his tolerable amount of time to walk.

TBSAT assumes that walking to final destination is the most common mode. By default, TBSAT sets ADAT to 15 minutes. This is based on the same reliable acceptable walking speed as that determined in section 4.1.7 and Appendix C: DEFAULT ACCEPTABLE ACCESS TIME.

4.3.7 Remaining Available Time (T_r) (Variable)

With all variables and factors, above, determined, TBSAT now uses Equation 1 and Equation 2 to calculate the remaining available time at each of the disembarkable stops for each SRD plan. TBSAT then prunes this list. If a disembarkable stop can be reached through multiple SRD plans, TBSAT keeps only the SRD plan that offers the greatest amount of remaining available time to this diembarkable stop. This method retains the one-to-one relationship between disembarkable stops and their corresponding remaining available time.

4.4 Step 4: Find Reachable Stops

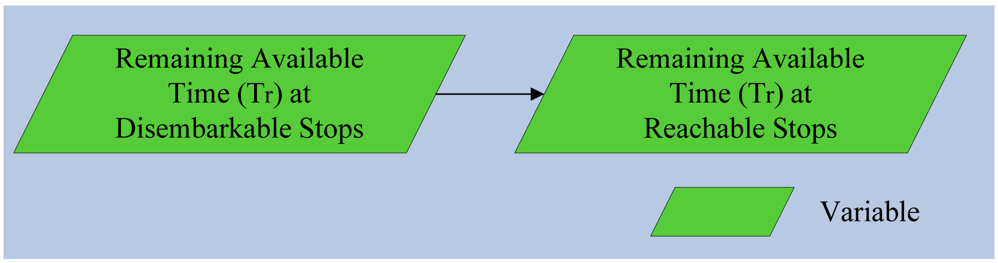

Figure 21: Factors and Variables in Step 4

Since the arrival timetable records all SRD plans possible from the trip origin, TBSAT can now check the value of T_r for each SRD plan to find all plans with a T_r greater than zero. The disembarkable stops of non-zero SRD plans are qualified as the reachable stops. There is no additional factor or variable required as the input to this step, as shown in Figure 21.

Table 8: Example of Excluding Non-Reachable Stop

Boarding Stop	Route	Board Dir	Arrival Stop	Direction	Access Time	Passenger Waiting Time	Bus Travel Time	Remaining Available Time
316909	81	W	286802	W	11.78	15	8.2	15
316909	81	W	346805	E	11.78	15	46.31	-13.09
316909	81	W	276802	W	11.78	15	10.07	15

316915	81	E	286802	W	12.64	15	69.6	-37.24
316915	81	E	406811	W	12.64	15	28.8	3.56

In Table 8, disembarkable Stop 346805 fails to qualify as a reachable stop because the remaining available time for its SRD plan(s) is less than zero. Note that Stop 286802, however, can be reached by the first SRD plan but not the fourth SRD plan in the remaining time. In this case, Stop 286802 remains a reachable stop since it can be reached from the trip origin within the total time limit through at least one SRD plan.

With both of the reachable stops and their corresponding T_r identified, and the list pruned to eliminate unreachable stops, TBSAT is ready to calculate the reachable area from each destination stop. This is the next step.

4.5 Step 5: Generate Reachable Area from Reachable Stops

At this point, TBSAT has generated the list of reachable stops, each with its corresponding T_r. TBSAT requires several more pieces of information before it can calculate the reachable area from each reachable stop. Following is a list of the required information. Figure 22 shows how this information is used in Step 5 to create the output list.

1. Location of reachable stops (Variable)
2. Existing path map (indicating all passable paths around reachable stops) (Factor)
3. Destination Access Speed (DAS) (Factor)
4. Remaining Available Length (Variable)

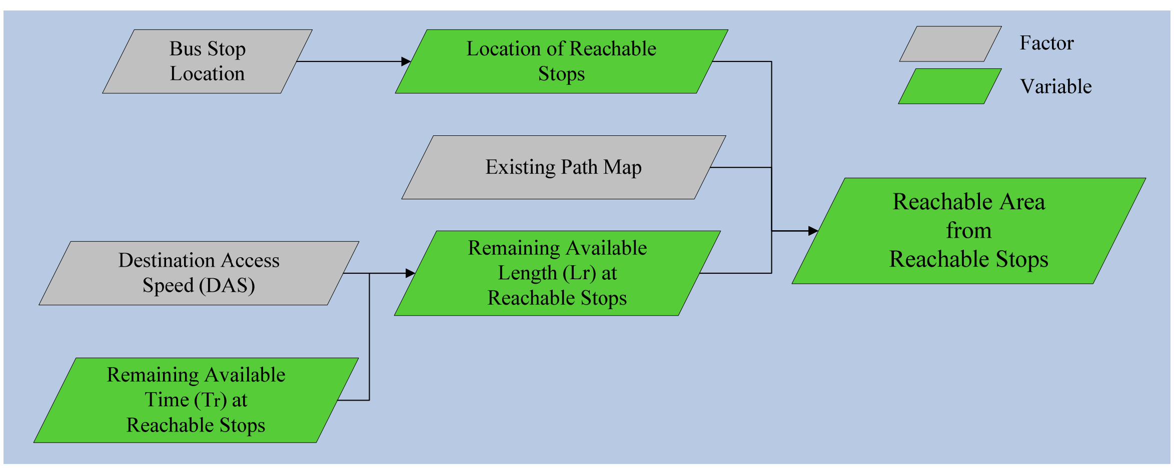

Figure 22: Factors and Variables in Step 5

4.5.1 Location of Reachable Stops (Factor)

To develop reachable areas from reachable stops, it is essential to know the location of reachable stops because the reachable area from each reachable stop is developed from the point at which the reachable stop is located. Fortunately, the location of all bus stops is already available as a dot feature class in ArcGIS format, as described in section 4.1.2. TBSAT is capable of selecting reachable stops from all bus stops and then adding only these reachable stops to the two Network Analyst layers, *Peak Service Area Analysis Layer* and *Off-Peak Service Area Analysis Layer*,[23] as their facility information[24] in order to develop reachable areas.

4.5.2 Existing Path Map (Factor)

Reachable areas are developed from reachable stops along the existing path (used in section 4.1.3) around reachable stops. Similar to the requirements described in 4.1.3, the street layout map around reachable stops must be prepared in the Network Data Set format and then imported into the ArcGIS component of TBSAT prior to the run. A single network data set, which covers the vicinity around all bus stops of the system, must be prepared.

4.5.3 Destination Access Speed (DAS) (Factor)

Although reachable areas can be generated from reachable stops, according to the available remaining time T_r, in ArcGIS, each T_r must be converted to a spatial distance. This represents the maximum radius distance reachable from a bus stop. ArcGIS generates the reachable area around that bus stop using this radius distance. This distance is defined as the *remaining available length* (L_r) because it represents the maximum distance the traveler can travel from each reachable stop using his remaining available time (T_r) for that stop. However, to convert T_r into L_r, we need to multiply T_r by the destination access speed. *Destination access speed* (DAS) is the speed the traveler uses to move away from a reachable stop to his final destination. For example, if the traveler bicycles to his final destination after disembarking the bus, the destination access speed used is his bicycling speed.

Similar to access speed, the value of the destination access speed may be defined by the user before the TBSAT run. However, TBSAT sets the default destination access speed of 2.05 mph, if the TBSAT users specify walking as the access mode without specifying a speed.

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[23] The *Peak Service Area Analysis Layer* and the *Off-Peak Service Area Analysis Layer* in TBSAT are *service area analysis layers* (See Footnote 71) in ArcGIS. TBSAT generates the peak time-based service area map on the *Peak Service Area Analysis Layer* and the off-peak time-based service area map on the *Off-Peak Service Area Analysis Layer*.

[24] Facilities in the Accessible Stops Network Analysis Layer in TBSAT represent all bus stops in the current bus service system. Accessible stops are identified among these facilities (bus stops) (See E.2.1).

4.5.4 Remaining Available Length (L_r) (Variable)

As discussed above, the remaining available length from a reachable stop is converted from the remaining available time T_r:

$$\text{Remaining Available Length } (L_r) = DAS \times T_r$$

Equation 12: Convert Remaining Available Time into Remaining Available Length

With the L_r during both peak and off-peak hours calculated and the location of reachable stops identified, TBSAT can now calculate the reachable area of both peak and off-peak hours from each of the reachable stops.

4.6 Step 6: Merge All Reachable Areas into the Complete Time-Based Bus Service Area Map

No particular factor or variable need be set in this step. TBSAT merges all reachable areas from reachable stops into the completed time-based bus service area map without importing additional factors or variables.

The next chapter follows the step-by-step procedure developed in section 3.3. It uses the factors and variables identified in Chapter 4 to complete the programming of TBSAT.

PART III: APPLICATION OF THE TBSAT: BUS SERVICE AREA MAP FOR THE SANTA CLARA TRANSIT CENTER

With the development of TBSAT, we now possess a tool that can assist in identifying the TBSA of a location. The third part of this research applies the TBSAT to the Santa Clara Transit Center (SCTC) in Santa Clara, California, using five different scenarios to demonstrate different uses for the TBSAT. The results of each scenario demonstrate different planning implications.

Chapter 5 : HOW FAR CAN I REALLY GO? APPLYING TBSAT TO THE SANTA CLARA TRANSIT CENTER IN SANTA CLARA, CA

Chapter 2 described how the bus service area of a specific location, which is the time-based bus service area, cannot be accurately identified using traditional service area measurement methods. TBSAT is a tool that answers the question: *How far can I really go by bus?* Or, looking at the question from a general perspective: *What is the geographical area from which people can reach a given location by bus, given some maximum acceptable travel time?*

This chapter demonstrates TBSAT's capability to calculate and visualize the time-based bus service area around the Santa Clara Transit Station (SCTC) in Santa Clara, California. The SCTC is an important transit hub in the southern San Francisco Bay Area, served by Caltrain rail routes, Altamont Commuter Express (ACE) heavy rail lines, and Valley Transportation Authority (VTA) bus routes.[25] Furthermore, through the cooperation of multiple authorities and agencies, the San Francisco Bay Area Rapid Transit (BART), which is the main regional rapid transit service in the San Francisco Bay Area, is making efforts to extend its service from the East and West San Francisco Bay Area to the South San Francisco Bay Area. Under this plan, the SCTC will become the southernmost terminus of the 16-mile long BART extension.[26] The BART extension will likely generate an additional 20,000 passengers per day passing through the SCTC.[27] The potential passenger activity generated by this extension will have significant impact on the travel patterns of the South Bay Area region. Thus, in the near future the bus service around the SCTC must react to this development and adjust its operation strategy. As a descriptive and modeling analysis tool, TBSAT applied at the SCTC can provide information indicating the bus service area that the SCTC could cover under five hypothesized scenarios. Such information can be generated only by TBSAT.

Through these five scenarios, this chapter also demonstrates TBSAT's ability to correctly reflect the *change* in time-based service area of the SCTC according to changes in various factors that alter the SCTC's bus accessibility. The five scenarios are described in Table 9.

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[25] Metropolitan Transportation Commission, Santa Clara Valley Transportation Authority, City of San Jose, and City of Santa Clara, "Santa Clara station area plan: Project description,"(2006). <http://www.santaclarasap.com/> [29 April 2008].

[26] Santa Clara Valley Transportation Authority, "BART to Silicon Valley: Project description," < http://www.svrtc-vta.org/projectoverview.asp> [29 April 2008].

[27]Santa Clara Valley Transportation Authority, "Projected ridership volumes at BART alternative stations**,**" *Silicon Valley Rapid Transit Corridor Final EIR*, 4.2-8, (December, 2004). < https://www.communicationsmgr.com/projects/VTA/docs/Vol.1-Ch.04.02-Transportation%20and%20Transit.pdf> [29 April 2008].

Table 9: Five Hypothesized Scenarios

Scenario	Topic
1	**How Early Should You Get Up?**
	Varied Travel-Time Budget
2	**Be Athletic!**
	Varied Acceptable Access Time
3	**Get on the Bicycle!**
	Varied Access/Destination Access Mode
4	**Bad Traffic Is a Drag!**
	Varied Traffic Conditions
5	**Collect More Potential Riders!**
	Potential Rider Estimate through Joint Work between TBSAT and Social Statistics

Scenario 1, "How Early Should You Get Up?," compares the difference among the time-based bus service areas of the SCTC using three different total travel-time budgets of 30, 60, and 90 minutes. Scenario 1 verifies that an increase in total travel-time budget does allow a traveler to reach greater distances by bus from the SCTC.

Scenario 2, "Be Athletic!," compares the difference between the time-based bus service areas of the SCTC using two different acceptable access time/acceptable destination access time settings. This scenario verifies that the time-based bus service areas of the SCTC are larger when the traveler is willing to spend more time accessing (for instance, walking to) the bus stop or reaching the final destination after disembarking from the bus.

Scenario 3, "Get on the Bicycle!," reveals the difference in the size of the time-based bus service areas of the SCTC depending on whether a traveler walks to the bus stop, bicycles to access the bus stop, or uses the "bike-n-ride" method (which means bicycling to the boarding bus stop as well as bicycling to the final destination after disembarking the bus). The results show how riding a bicycle combined with riding a bus can significantly increase the service area from the SCTC.

Scenario 4, "Bad Traffic is a Drag!," focuses on the difference in the size of time-based bus service areas of the SCTC due to increased bus-wait times caused by traffic. TBSAT assumes that a drop in the level of service (LOS) of vehicular traffic increases the total bus trip time by increasing the time the traveler must wait for the bus to arrive. The increase in bus-waiting time thereby reduces the size of the time-based bus service area.

This scenario verifies that the waiting time cost factor is significant for the time-based bus service area calculation of the SCTC.

For each of these first four scenarios, the SCTC's bus accessibility is analyzed in multiple ways. One analysis technique is visual inspection of the TBSA maps. In addition, bus accessibility is analyzed using statistics such as the number of **accessible stops**,[28] the number of **reachable stops**,[29] and the percentage change in the size of the service area.

Unlike the previous scenarios, Scenario 5, "Collect More Potential Riders!," quickly demonstrates the possibility of generating advanced transportation planning-related information through the integration of the time-based bus service areas of the SCTC with other social statistics. Scenario 5 demonstrates how TBSAT can estimate the population covered by the 60-minute bus service area of the SCTC in each census tract of Santa Clara County, California, by integrating the time-based service area map with population data from the U.S. Census. The precision of the underlying data (tract level) makes this a rough estimate. Nevertheless, the resulting maps help the user to visualize how many residents are served by the bus service connecting to the SCTC.

The time-based bus service areas of all five scenarios were generated using the same underlying bus service. The same bus service means there is no difference in bus routing, bus timetable, or bus headway between scenarios. Due to the limited amount of time for this research, the underlying system data includes only 11 bus routes that are available within approximately 3 miles from the SCTC, instead of all bus routes that serve the entire South Bay Area,. The preparation of the bus service information for the five scenarios is discussed in detail in Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION**.**

In addition, the five scenarios were generated using the same existing path map. This means that in all five scenarios the traveler was assumed to travel to and from bus stops using the same routes along the street network. Before generating the five scenarios, the existing path map in Santa Clara and the bus service information around the SCTC had to be prepared in specific formats and inputted into the TBSAT. The preparation of the existing path map for the five scenarios is discussed in detail in Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION**.**

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[28] Bus stops which a bus rider can access from the trip origin within their total travel time budget and within their acceptable access range. See section 3.2.2.

[29] Bus stops which a bus rider from the trip origin can reach through an accessible route within the total travel-time limit. See section 3.2.2.

5.1 Scenario 1: How Early Should You Get Up? Varied Travel-Time Budget

One of the fundamental values of TBSAT is its ability to reveal the strong relationship between a bus rider's travel-time budget and the area that rider can reach. It is intuitively understood that the more time you can spend on a trip, the larger the area you can expect to reach. However, without TBSAT, this general understanding cannot be visualized. TBSAT generates service area maps which precisely indicates whether a particular place is reachable or not within a given travel-time budget.

Scenario 1 identifies the 30-, 60-, and 90-minute time-based bus service areas around the SCTC, showing the area a traveler from the SCTC can reach within 30, 60, and 90 minutes. These three travel-time budgets were chosen because the standard VTA bus headway (frequency) of its routes is typically 15, 30, or 60 minutes. Thus, 30-, 60-, and 90-minute travel-time budgets are the reasonable periods that a bus rider can expect.

All three runs use the same settings for all factors other than the total travel-time limit. All three runs in this scenario assume that the traveler walks to the boarding bus stop and walks after disembarking from the bus. The acceptable walking time is set at 15 minutes, as suggested in section 4.1.7. Finally, the waiting time/headway ratio is set to 0.5, which represents free flow traffic conditions (Level of Service A).

Table 10: Scenario 1 Factor Settings

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#1	30	2.05	15	2.05	15	0.5
#2	60	2.05	15	2.05	15	0.5
#3	90	2.05	15	2.05	15	0.5

Run #2 is considered the *benchmark run*, because its factor settings, which are defined as the *benchmark settings*, represent a typical traveler's expectations:

- 1-hour overall travel-time.
- No more than 15-minute walk to/from a bus stop.
- Free-flowing traffic (LOS A).

These settings are also used for the benchmark runs in Scenario 2, 3, and 4.

Once the 30-, 60-, and 90-minute bus service areas are generated, a quick visual analysis may be performed to see whether the increase in total travel-time budget significantly affects the size of the time-based bus service area of the SCTC.

5.1.1 The Difference between Peak and Off-Peak 30-Minute Bus Service Area

Figure 23 displays an overlay of the peak and off-peak 30-minute bus service area for the SCTC. The dark blue area represents the 30-minute bus service area during the off-peak period. The 30-minute bus service area during the peak period encompasses that dark blue area plus the places shown with the red boundary that denotes the off-peak service area. As Figure 23 shows, the 30-minute bus service area of the SCTC during the off-peak period appears in a horizontal strip running approximately 10 miles in an east-west direction. The 30-minute bus service area during the peak period is somewhat larger than the bus service area during the off-peak, since some bus routes have shorter headway (run more often) during the peak hours.

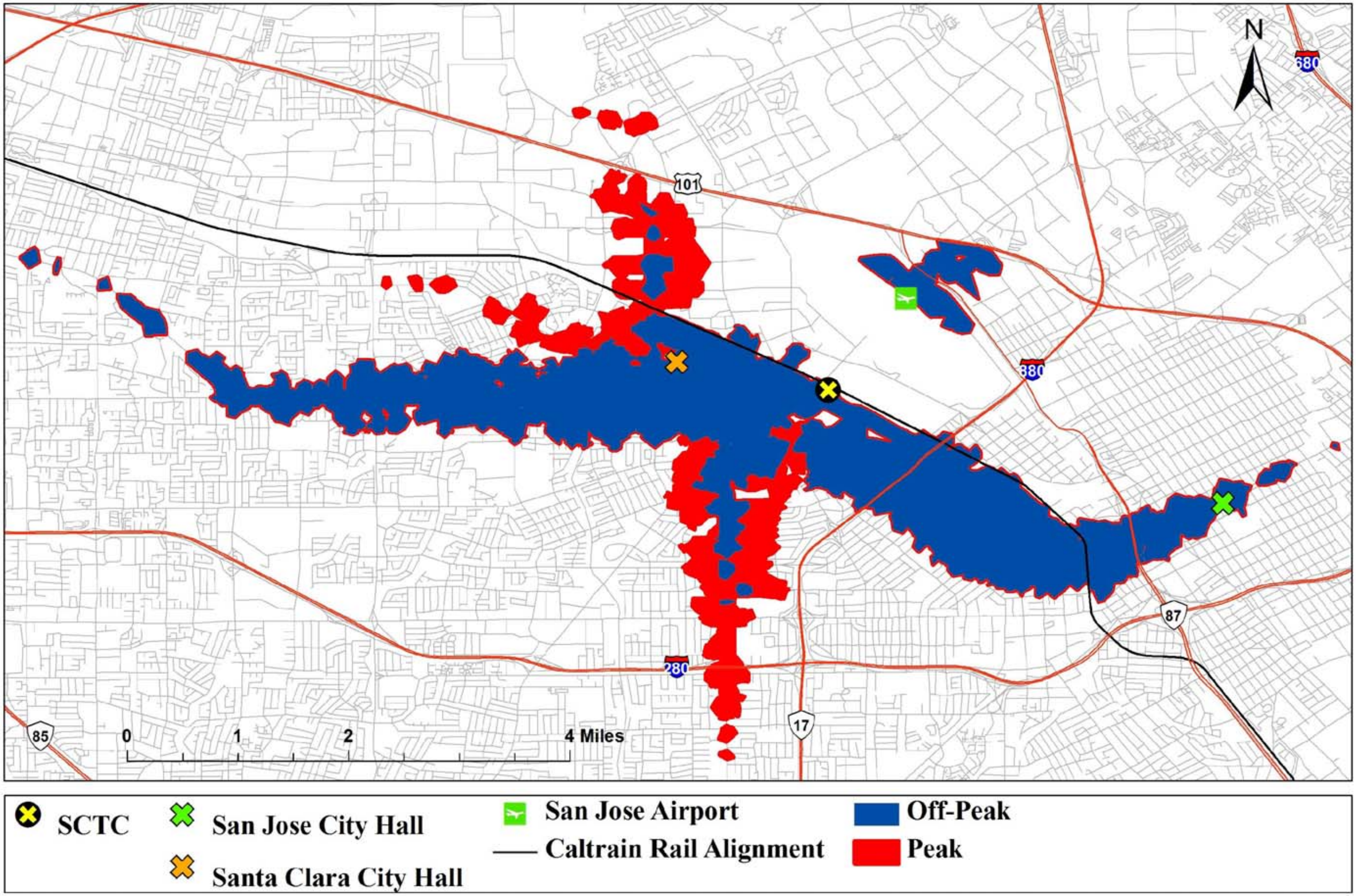

Figure 23: 30-Minute Bus Service Area, Santa Clara Transit Center

Some specific lessons a viewer may learn from viewing Figure 23 are:

(1) The time-based service area around a reachable stop shrinks as the traveler disembarks at stops farther away from the SCTC:

The farther from the SCTC that the traveler chooses to disembark from the bus, the smaller the area that can be reached after disembarking. That is, the area of choice tapers as the distance increases from the point of origin. Under a fixed 30-minute travel-time budget, when a traveler bus-travels to more distant bus stops from the SCTC, less of his travel-time budget remains after disembarking. This smaller remaining travel-time in his budget limits the area the traveler can reach after disembarking. Such a result seems obvious. However, TBSAT is the first tool that allows planners to *see* such a result within a customizable environment.

(2) Some areas cannot be reached during the off-peak period:

Another fact that the time-based service area reveals, that other methods do not, is the service area difference between peak and off-peak service periods. The red area in Figure 23 shows the area the traveler can reach within 30 minutes from the SCTC, only if he travels during peak hours. The 30-minute bus service area of the SCTC during the peak service period is 18% larger than it is during the off-peak period. This demonstrates that the bus service area actually changes under different service conditions and that this change can be quantified and visualized using TBSAT.

5.1.2 Differences Among 30-, 60-, 90-Minute Bus Service Areas of the SCTC

A single time-based bus service area map has already proved that TBSAT achieves the goal of revealing the area a traveler can actually reach within a specified time limit, as well as revealing the difference in that reachable area between two different service periods. However, another key strength of TBSAT is its ability to generate quickly the different time-based bus service area maps for the same trip origin using different settings.

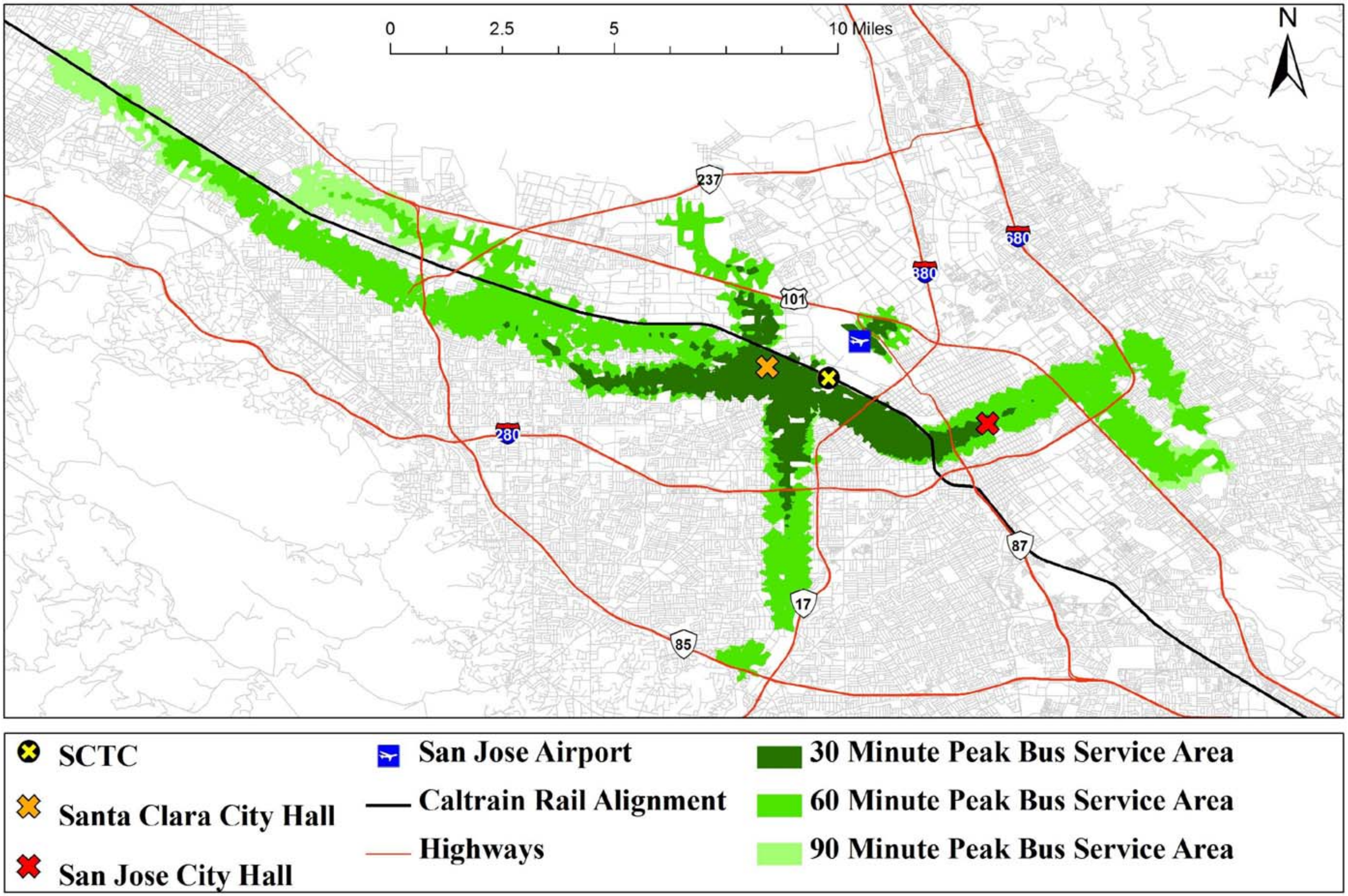

Figure 24: 30-, 60-, 90-Minute Peak Bus Service Area

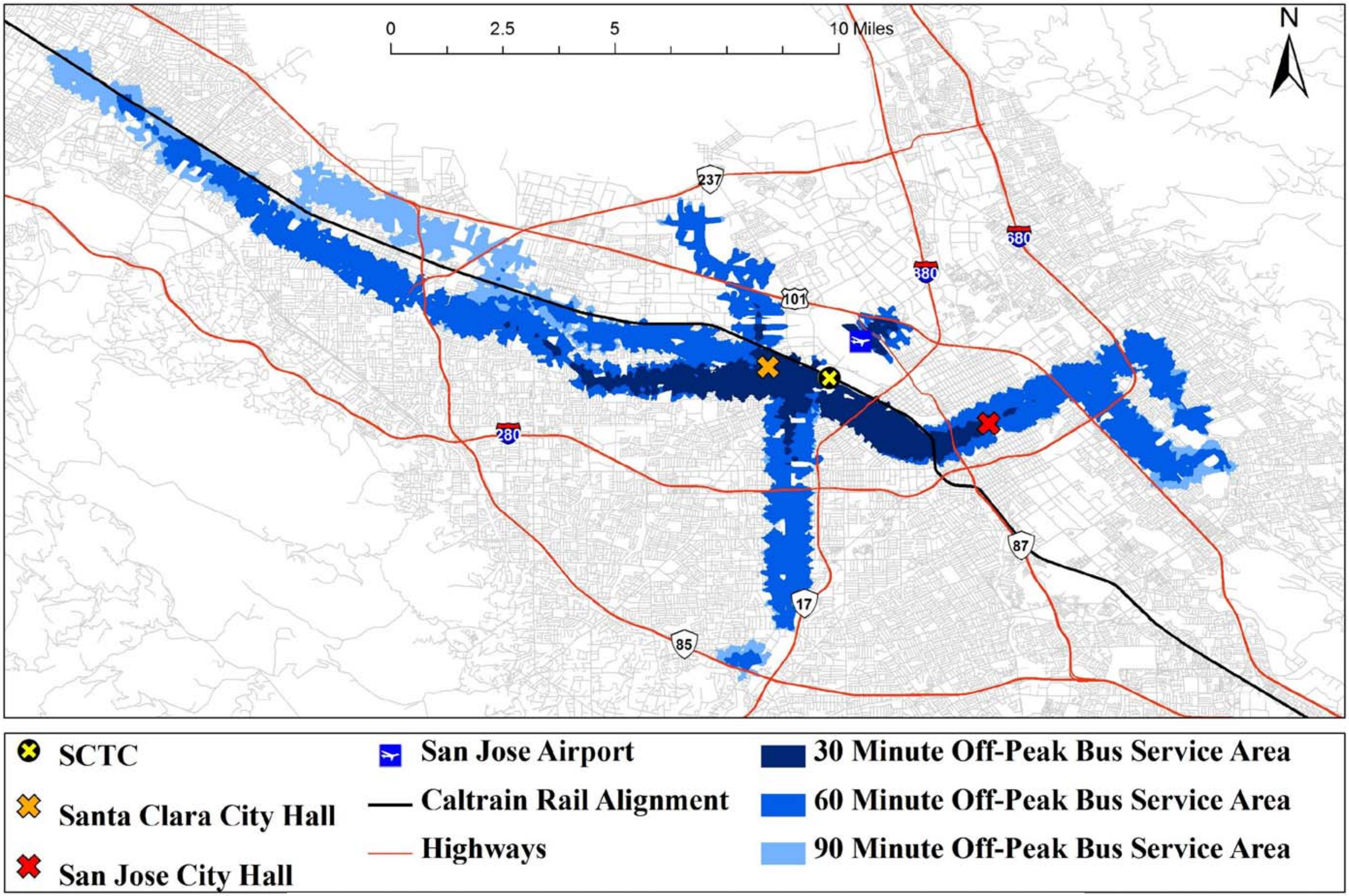

Figure 25: 30-, 60-, 90-Minute Off-Peak Bus Service Area

Figure 24 and Figure 25 compare the difference among the 30-minute, 60-minute, and 90-minute bus service areas of the SCTC for peak and off-peak bus service periods. From these maps, the viewer may derive significant information:

(1) Travel-time budget increases result in a significant increase in the size of both peak and off-peak service areas:

Comparing the time-based bus service area change to the benchmark Run #2 (see Table 12), the peak bus service area decreases by 74% when the travel-time budget decreases from the benchmark 60 minutes to 30 minutes and increases by 17% when the travel-time budget increases from 60 minutes to 90 minutes. On the other hand, the off-peak bus service area decreases by 77% when the travel-time budget decreases from 60 minutes to 30 minutes, and increases by 28% when the travel-time budget increases from 60 minutes to 90 minutes. The east-west strip becomes longer as the total travel-time limit increases because now a traveler has more time to spend on a bus trip from the SCTC. In summary, many areas that are not reachable within 30 minutes become reachable if a longer travel-time budget is allowed.

(2) Service area "strip" widths reach a maximum cap:

Another important fact the can be observed by comparing the time-based bus service area that displays the three different travel-time limits. Note that the increase in the length (longer dimension) of each service area strip is more significant than the increase in the width (shorter dimension) of each service area strip. Furthermore, note that the width of each strip appears to yield to some cap.

A bus service area appears as a *strip* because each time-based bus service area is the merge of the reachable areas of each reachable bus stop (according to the remaining available time the traveler possesses at each reachable stop). However, the maximum size of the service area that can be generated from a reachable bus stop is capped by the 15-minute walkable area (the factor setting from Table 10). This restriction means that in this scenario the mode that people use after disembarking the bus is assumed to be walking, and the acceptable walking time is 15 minutes. That is, once a traveler reaches a bus stop, if he possesses a remaining travel-time budget longer than 15 minutes after disembarking the bus, his reachable area from that bus stop is still capped at the 15-minute walkable area. Since this condition occurs at many bus stops in close proximity to the SCTC, the reachable area from these bus stops is still capped to the size of the area walkable in 15 minutes. Therefore, the merge of these reachable areas appears in a strip that remains a near constant width.

5.1.3 Findings from Scenario 1

In this section, a quick comparison among the time-based bus service areas generated under the three different total travel-time budgets is discussed.

Table 11: Scenario 1 Quick Facts (a)

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#1	30	2.05	15	2.05	15	0.5
#2	60	2.05	15	2.05	15	0.5
#3	90	2.05	15	2.05	15	0.5

Table 12: Scenario 1 Quick Facts (b)

TBSAT Run	# of Accessible Stops	# of Accessible Routes	# of Reachable Stops		Service Area Relative Ratio		Service Area Percentage Change	
			(Peak)	(Off-Peak)	(Peak)	(Off-Peak)	(Peak)	(Off-Peak)
#1	17	5	114	80	26.4%	22.6%	-73.5%	-77.3%
#2	17	5	280	250	100.00%	100.00%	Benchmark	Benchmark
#3	17	5	399	381	117.2%	127.8%	+17.3%	+27.8%

As the quick facts tables show (Table 11and Table 12), a traveler with a 30-minute travel-time budget can access only 80 bus stops along the five routes that are available around the SCTC during the off-peak service period. On the other hand, during the peak period, that same traveler has access to an additional 34 bus stops. Run #2 and Run #3 show a similar pattern.

Table 12 compares the size of the time-based bus service area against the benchmark 60-minute bus service area. During the peak period, the 30-minute bus service area of the SCTC is only 26% of the area covered by the 60-minute service area. On the other hand, the 90-minute service area is larger than the benchmark area by 17%. During the off-peak period, the percentage differences are even greater.

According to the results of Scenario 1, an increase in travel-time budget does, indeed, result in and increased time-based bus service area. Furthermore, TBSAT allows such increases to be visualized as well as presented in numerical terms, including such absolute statistics as the number of reachable stops and the total reachable square miles.

5.1.4 Planning Implications

Two implications are inspired from the results of Scenario 1:

1. Peak versus off-peak schedule management.
2. Bus service design based on human preferences.

First, results shown in Scenario 1 indicate that buses connecting to the SCTC serve a smaller geographic area during the off-peak hours than during the peak hours. It is important for bus service operators to provide corresponding service frequency to specific areas according to the area's characteristics. For example, it is essential to ensure that the bus service can quickly connect the SCTC and the business area in downtown San Jose during the peak hours in order to make the bus a more desirable transportation means to commuters who work in downtown San Jose. As another example, many VTA bus routes terminate at regional shopping centers. Since the travel demand toward these shopping centers does not occur only during the peak hours, the bus service operators may need focus on providing reasonable service accessibility to these shopping centers throughout the day, not just during the peak period.

The second implication is that bus service should provide reasonable accessibility, assuming a reasonable travel-time budget. Based on the findings of Scenario 1, TBSAT identifies that different travel-time budgets generates different time-based bus service areas. As a result, finding the average affordable bus travel-time budget and the design of a bus service system that covers a reasonable service area would be essential to the competitiveness to the bus service.

5.2 Scenario 2: Be Athletic! Varied Acceptable Access Time

Can I reach more areas by bus if I walk more? The answer to this question seems to be *Yes*. However, TBSAT allows people to see the difference in the time-based bus service area when the amount of time the traveler is willing to walk changes. Through the acceptable access time evidence presented in Chapter 4, this research suggests that walking less than 15 minutes is acceptable to most of the public. Scenario 2 tests whether the one-hour bus service area of the SCTC changes as the traveler is willing to walk more or less time to and from the bus stops.

Table 13: Scenario 2 Factor Settings

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#4	60	2.05	10	2.05	10	0.5
#5	60	2.05	15	2.05	15	0.5
#6	60	2.05	20	2.05	20	0.5

Run #4 simulates the condition of a traveler who is less willing to walk. The acceptable access time and the acceptable destination access time of Run #4 are reduced from the benchmark 15 minutes to 10 minutes. Run #5 uses the benchmark settings from Run #2 - Scenario 1 (the assumed standard condition). Run #6 simulates the condition of a traveler who is willing to spend more time walking to/from bus stops. The acceptable access time and the acceptable destination access times of Run #6 are increased from 15 minutes to 20 minutes.

Run #4 simulates the conditions of the traveler who is willing to walk less time than the 15-minute average. His acceptable access time (AAT) and acceptable destination access time (ADAT) is 10 minutes. Run #5 uses the benchmark settings from Scenario 1 - Run #2. Run #6 simulates the conditions of a traveler who is willing to spend more time walking to and from bus stops. The acceptable access time and the acceptable destination access time for Run #6 is set at 20 minutes. Table 13 summarizes these settings.

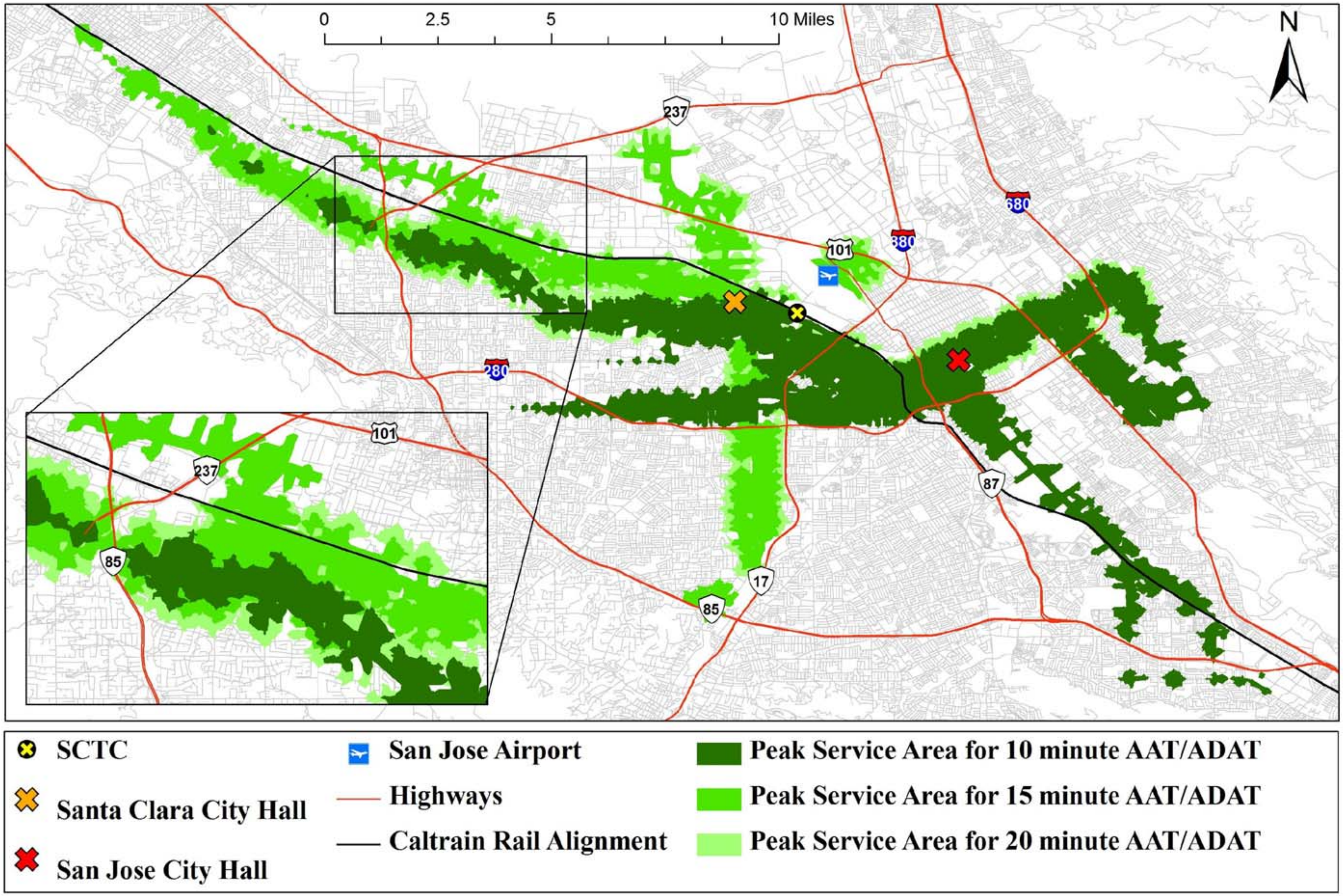

Figure 26: 60-Minute Peak Bus Service Area with 10-, 15-, 20-Minute AAT/ADAT

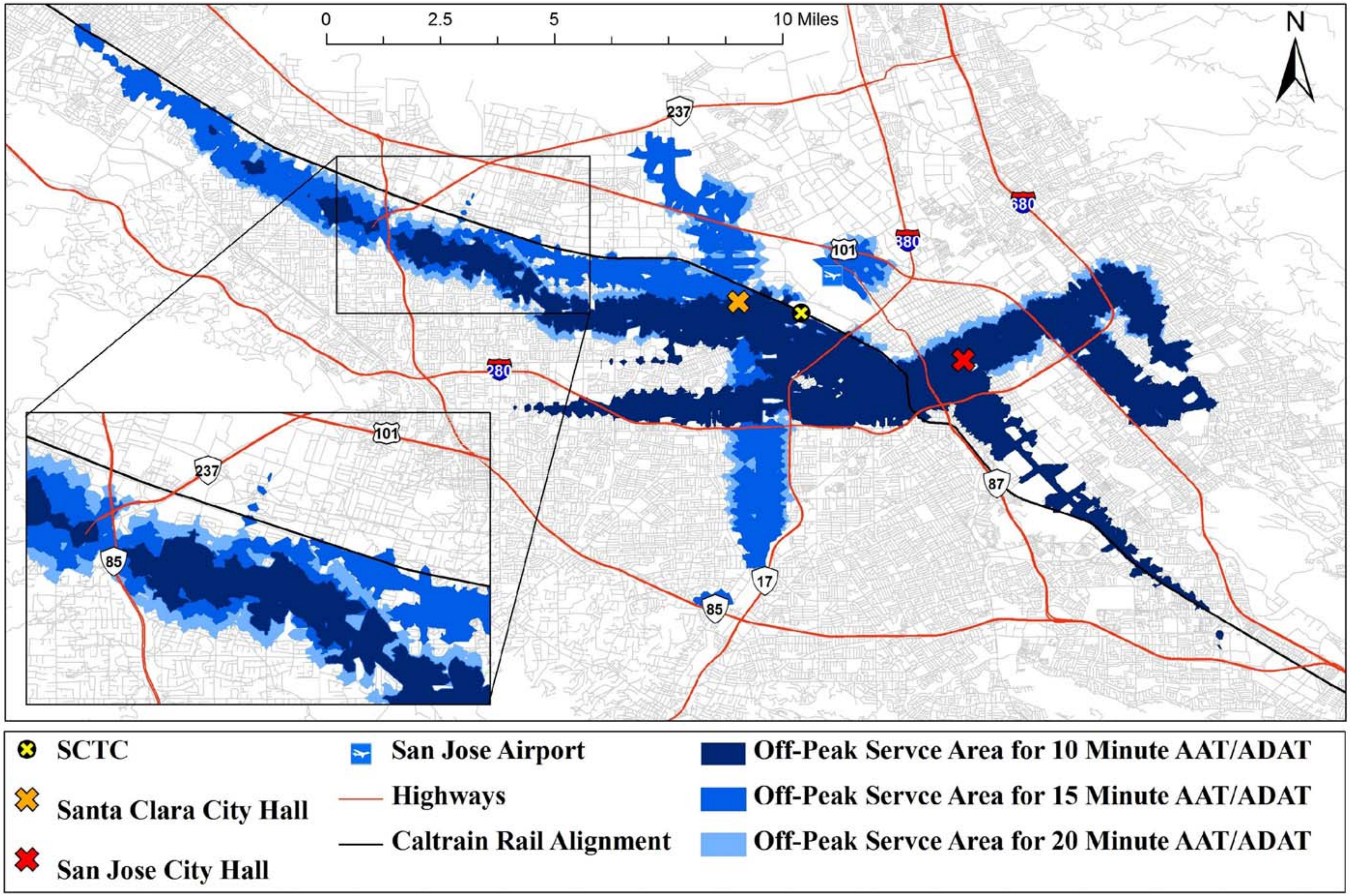

Figure 27: 60 -Minute Off-Peak Bus Service Area with 10-, 15-, 20-minute AAT/ADAT

Figure 26 and Figure 27 show that when the acceptable walking time changes, the service areas around reachable bus stops that are close to the SCTC also change because the acceptable destination access time (the time that the traveler is willing to walk away from a bus stop after disembarking) now changes. On the other hand, the service areas around distant reachable bus stops does not change because by the time the traveler uses to reach these distant stops they would possess a remaining available time less than 10 minutes, which means they don't have too much time walking away from these stops anyway even they are willing to walk more.

As Figure 26 and Figure 27 demonstrate, when the acceptable walking time changes, the service areas around reachable bus stops (closer to the SCTC) change, since the acceptable destination access time (the time that the traveler is willing to walk away from bus stop after disembarking) now changes. Conversely, the service areas around reachable bus stops farther from the SCTC do not change. This is because, by the time the traveler reaches one of these distant bus stops, he has a remaining available travel-time budget of 10 minutes or less in which to walk to the actual destination, even though his ADAT may indicate he is *willing* to walk longer.

5.2.1 Findings from Scenario 2

Table 14: Scenario 2 Quick Facts (a)

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#4	60	2.05	10	2.05	10	0.5
#5	60	2.05	15	2.05	15	0.5
#6	60	2.05	20	2.05	20	0.5

Table 15: Scenario 2 Quick Facts (b)

TBSAT Run	# of Accessible Stops	# of Accessible Routes	# of Reachable Stops		Service Area Relative Ratio		Service Area Percentage Change	
			(Peak)	(Off-Peak)	(Peak)	(Off-Peak)	(Peak)	(Off-Peak)
#4	12	5	277	248	66.2%	65.8%	-33.8%	-34.2%
#5	17	5	280	250	100.00%	100.00%	Benchmark	Benchmark
#6	24	5	285	255	126.7%	125.9%	+26.7%	+25.9%

From the quick facts in Table 14 and Table 15 the reader may derive these interesting findings:

(1) Accessible stops increases as AAT/ADAT increases:

The longer a traveler is willing to walk, the more bus stops he can walk to from his point of origin. For instance, increasing the acceptable access time from the benchmark 15 minutes to 20 minutes, the traveler is able to walk to 24 bus stops instead of 17 (see Table 15) to begin his trip. Conversely, the traveler who is willing to walk only 10 minutes from his point of origin is able to access only 12 of the 17 stops available at the 15-minute benchmark time.

(2) Accessible routes does not change as AAT/ADAT increases:

Although the number of accessible stops varies from 12 to 24 for the 3 runs (see Table 15), the number of accessible routes remains at 5. This finding represents that even if the traveler is willing to spend 20 minutes walking to bus stops, he can still gain access to only 5 bus routes, just as many as the traveler willing to spend 10 minutes walking to bus stops.

Intuitively, one might guess there should be more bus routes available to the traveler willing to walk longer to access bus service. Interestingly, this scenario, which uses VTA route information, does not reflect any change. The reason may be the special characteristics of the SCTC and the VTA route design. Since the SCTC is one of the major transit hubs in the South San Francisco Bay Area, many transit services converge at it. Thus, it makes sense that VTA might make all bus routes that run near the SCTC actually go through the SCTC, or at least run very close to the SCTC. If VTA does apply such route design, then it makes sense that the number of accessible routes remains unchanged through the runs, because all bus routes that are close to the SCTC are already designed to be easily accessed from the SCTC.

(3) Reachable stops increases as AAT/ADAT increases:

Despite the unchanging number of accessible routes, the number of reachable stops (disembarkation bus stops) still increases as the AAT/ADAT increases. The reason is that, while the total travel time of all three runs remain the same, as AAT increases, the traveler can access more stops to get on the bus. He can then reach a greater number of more distant bus stops by "skipping stops."

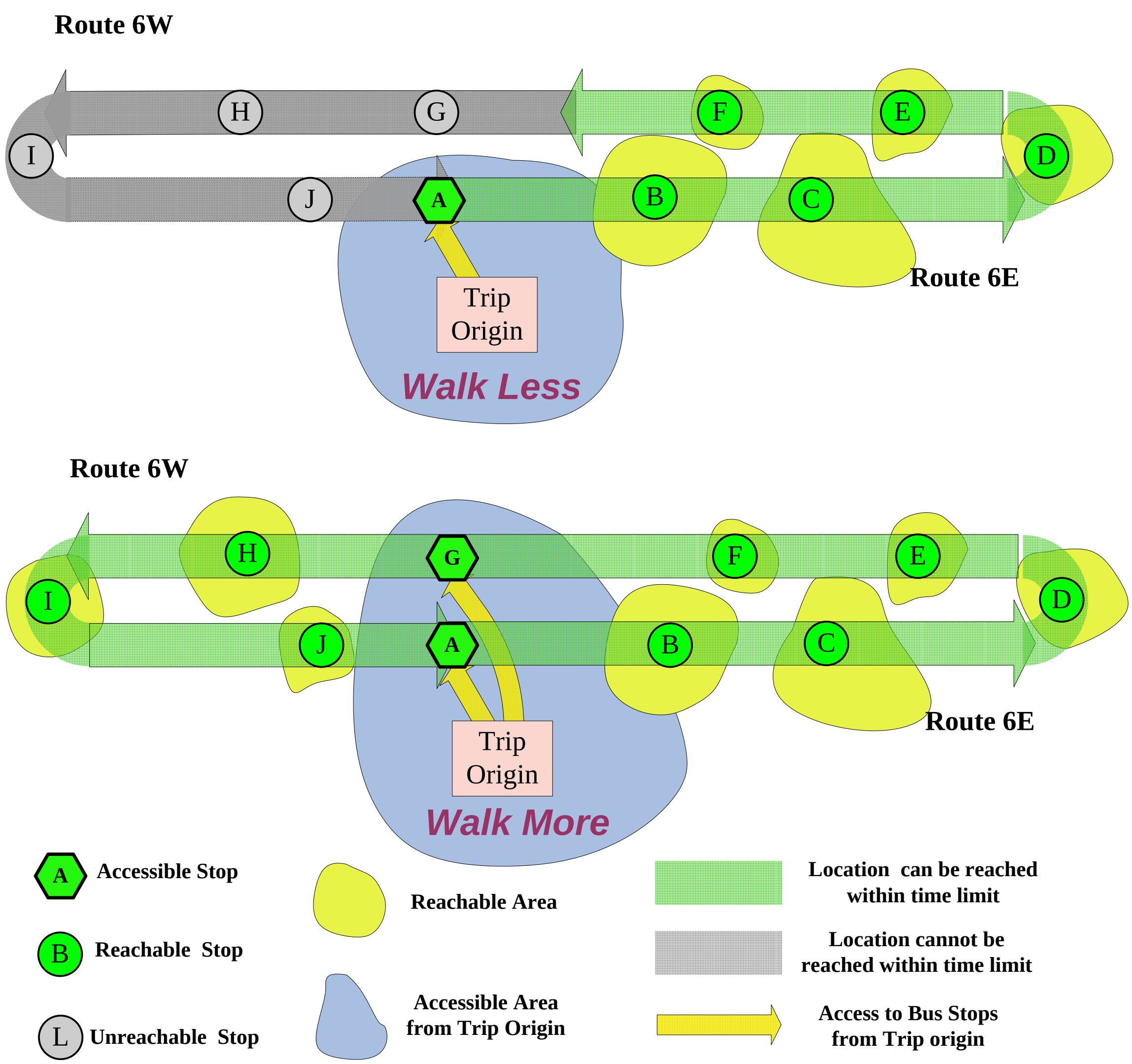

Figure 28: Reachable Stops Increases with Longer Walking Times

An example clarifies this concept. As the upper illustration in Figure 28 shows a traveler who walks less is not able to walk across the street and get to stop G to catch the westbound Route 6. As a result, he can board only Route 6 at stop A (an eastbound bus). In such a case, this traveler will run out of travel-time before reaching stop G. Thus, stops G, H, I, and J are not reachable by this traveler. On the other hand, the lower illustration in Figure 28 represents the condition of the traveler walking longer. If a traveler is willing to walk a little farther to stop G, he will be able to “skip” the bus travel from stop A through stop F, and will reach stops H, I, and J within his travel-time limit. Such an example demonstrates why the greater the acceptable access time a traveler has, the more bus stops he can reach.

(4) Total time-based bus service area changes as AAT/ADAT changes:

As a traveler's willingness to walk increases from the benchmark 15 minutes to 20 minutes, he gains between 26% and 27% (off-peak and peak service periods, respectively) more reachable area than the benchmark area. Conversely, as the traveler's willingness to walk decreases, his reachable area also decreases, as evidenced by the change between the 15-minute walking time benchmark to the 10-minute walking time run. The traveler loses 35% of the reachable area during the off-peak service period and loses 34% area during the service peak period.

From the result of this scenario, we can conclude and confirm that the time-based bus service area of the SCTC is increased if the traveler spends more time walking to and from bus stops. Such an increase is due to two reasons, the increase in the number of accessible bus stops around the SCTC (the point of origin), and the increase in the walkable area from each reachable stop.

5.2.2 Planning Implications

As mentioned above, if a bus customer is willing to walk more during his trip, the overall time-based bus service area increases. Indeed, this is one of the parameters of the service quality of a bus service system, without additional investment in the bus service. However, it is a very challenging task for planners to encourage people to change their walking behavior to walk more to access buses. The bus customers' willingness to walk is determined by numerous factors, weather factors (including the local climate or current weather conditions), the physical condition of the customers (that is, the average fitness of the bus riders in the area), and the environmental factors (including the possible walking experience or safety concerns), which are also known as the walkability of an area.

While the nature factors and the physical condition of the bus riders are less alterable by planners, improving the walkability of the area, such as creating safer streets to walk on and providing a pleasant, comfortable walking experience along the streets, would be a practical way to encourage substantially walking, and hence, increase the bus service area.

5.3 Scenario 3: Get on the Bicycle! Varied Access/Destination Access Mode

Although walking is the most common mode people choose to access bus stops, a fairly large number of people gain access to bus services by other means of transportation. One of the commonly used alternatives is bicycling. In fact, many major VTA bus stops have bicycle racks available. A traveler may bicycle to the bus stop, lock his bicycle at a rack, and then board the bus. Such a pattern is also known as the "Park-and-Ride."

Alternatively, a bus rider may put his bicycle on a special rack on the bus (if one is available), ride the bus, disembark, and then bicycle to the final destination. Many transit operators in the San Francisco Bay Area promote such "Bike n' Ride" behavior by providing transport devices (racks) and space on the transit cars for riders to bring their bicycles with them. Most VTA buses are equipped with either a bicycle rack or seats that convert to make space for bicycles.

Since bicycling to bus stops is an established alternative access mode to bus services, Scenario 3 focuses on the comparison between walking versus bicycling access modes in the calculation of the 60-minute bus service area of the SCTC.

Table 16: Scenario 3 Factor Settings

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#6	60	2.05	15	2.05	15	0.5
#7	60	13.68	15	2.05	15	0.5
#8	60	13.68	15	13.68	15	0.5

As shown in Table 16, Run #7 represents the benchmark setting, which assumes walking as both the boarding stop access mode and the destination access mode. Run #8 assumes the traveler bicycles to the boarding bus stop, but leaves his bicycle at that bus stop. This traveler must then walk to his final destination after disembarking the bus. . Run #9 is the "Bike n' Ride" simulation. The traveler bicycles to the accessing bus stop as well as from the disembarkation bus stop to the final destination.

The walking speed of 2.05 mph is used, as discussed in section 4.1.5. Both Run #8 and Run #9 require an average bicycling speed setting. Rose and Marfurt surveyed 5,577 people about their use of bicycles for commuting and found that the reported bicycling speed averaged 13.68 mph.[30] Run #8 uses this value as its access speed only. Run #9 uses this value as both the boarding stop access speed and the destination access speed.

5.3.1 Calculation of 60-Minute Bus Service Area Using Access by Walking, Access by Biking, and Bike n' Ride

Figure 29 and Figure 30 reveal the 60-minute bus service areas for the SCTC calculated from Run #7, Run #8, and Run #9.

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[30] Geoff Rose and Heidi Marfurt, "Travel behaviour change impacts of a major ride to work day event," *Transportation Research Part A* 41, (2007), 357.

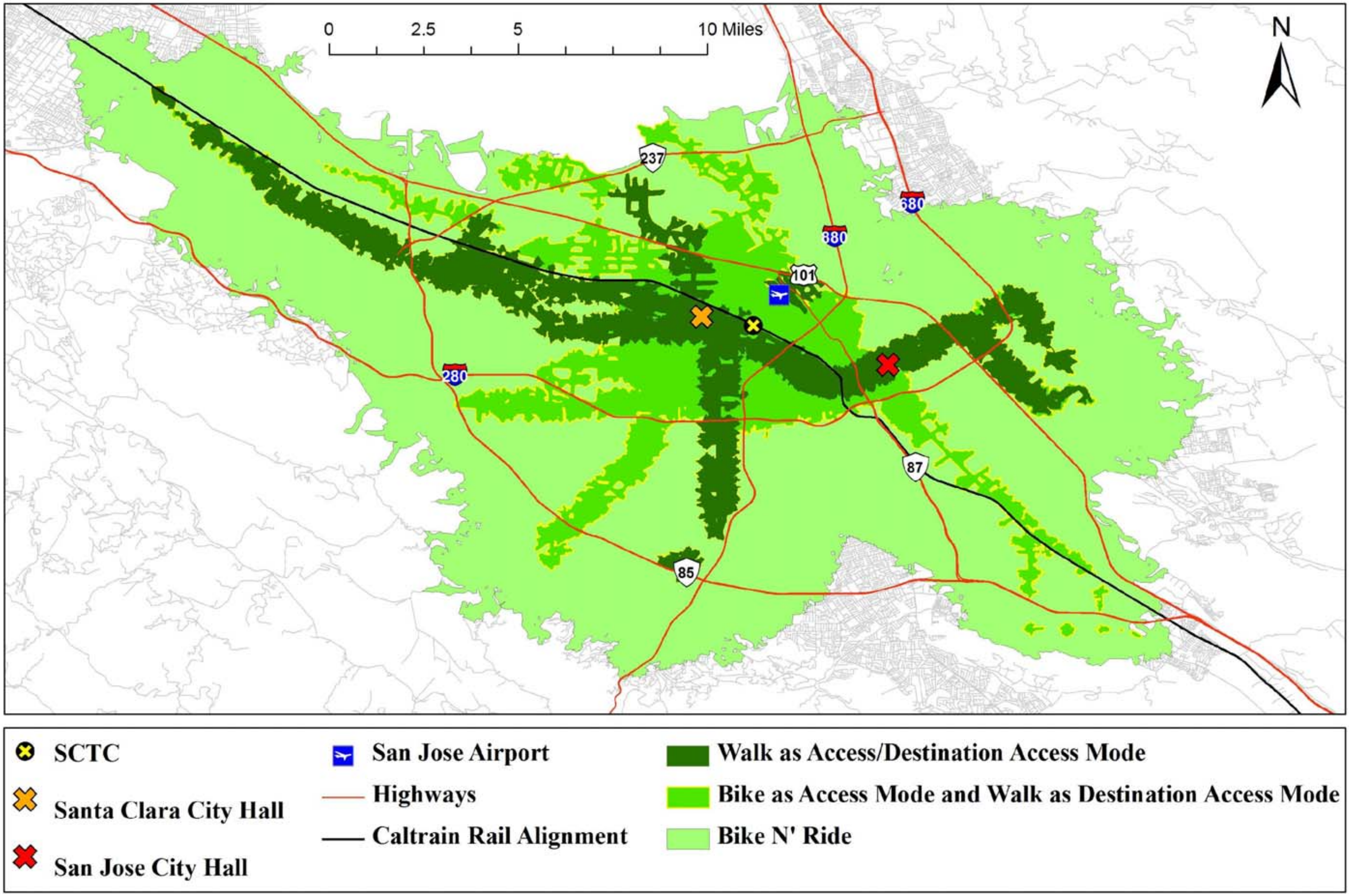

Figure 29: 60-Minute Peak Bus Service Area for Different Access/Destination Access Modes

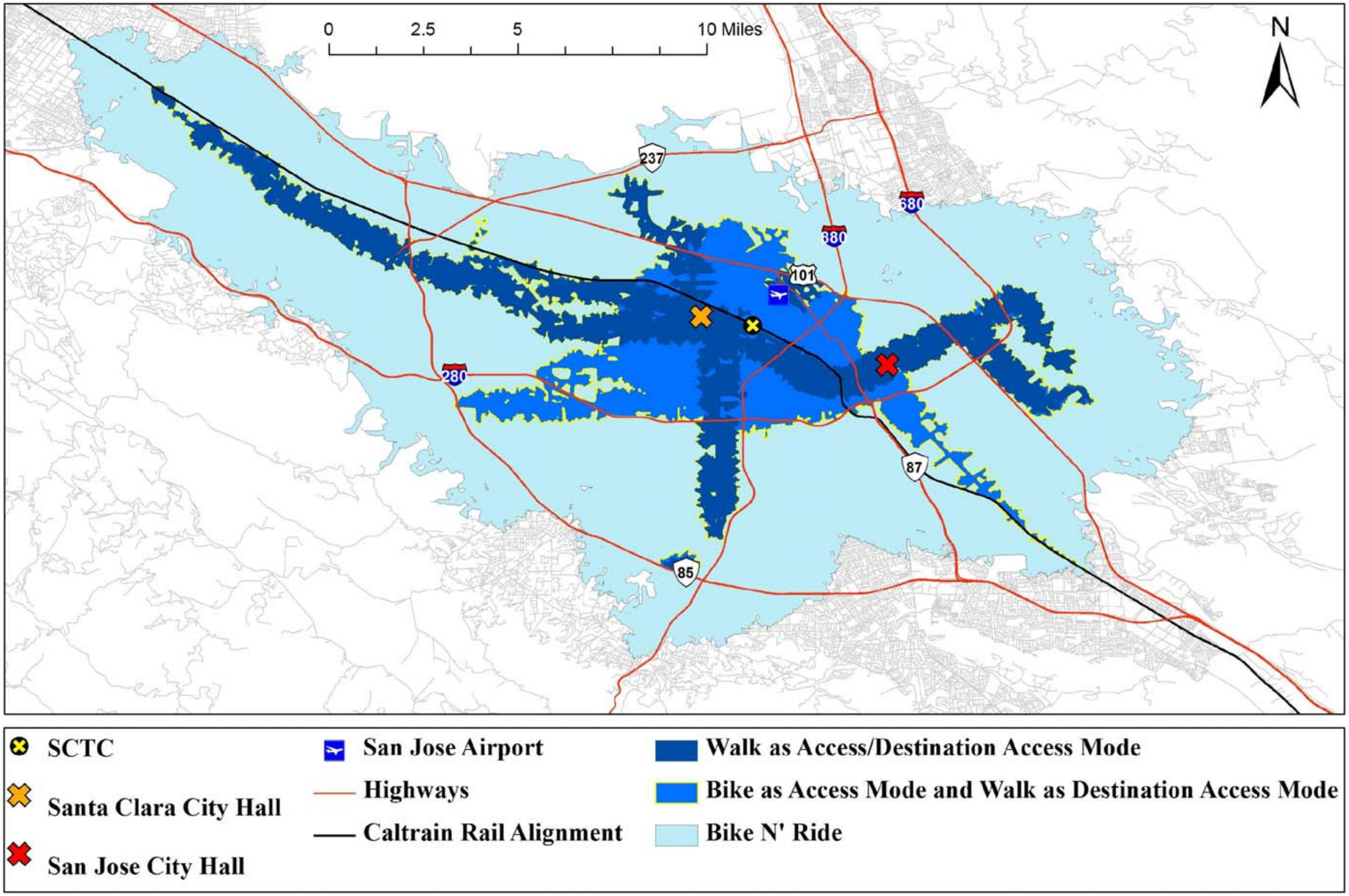

Figure 30: 60-Minute Off-Peak Bus Service Area for Different Access/Destination Access Modes

Figure 29 and Figure 30 demonstrate clearly three findings. First, the area within approximately a 3-mile radius around the SCTC is included in the service area for calculations that use bicycling as the access mode. This is because TBSAT includes the area that a traveler can reach from his trip origin *without* taking the bus as a part of the displayed bus service area (as discussed in section 3.2.1**,** the definition of time-based bus service area). Since, in Run #8 and Run #9, the traveler from the SCTC is assumed to bicycle from the SCTC for up to 15 minutes, the area within the 15-minute bicycling range from the SCTC becomes a large addition to the 60-minute bus service area.

Second, when the access mode changes from walking to bicycling (compare Run #7 and Run #8), several new service area strips stretch out from the SCTC. This is due to the increased number of accessible stops. Once the access mode changes from walking to bicycling, the mobility of the traveler significantly increases. Therefore, within the same 15-minutes access time, the bicyclist may travel farther than the traveler who walks, and so may access many more bus stops and bus routes.

Third, the lightest colored areas in each map indicate the 60-minute bus service area of the SCTC when the traveler uses the Bike n' Ride mode. In addition to the advantage of gaining more choices in boarding bus stops, this traveler bicycles to a destination after leaving the bus. In the same allotted time as the walking traveler, this bicyclist may cover more distance and so has many more choices of final destinations from his disembarkation point. Consequently, the Bike n' Ride traveler has a much larger bus service area than the traveler who walks only (Run #7) or the traveler who bicycles only *to* the bus stop but walks to final destination (Run #8).

5.3.2 Findings of Scenario 3

Table 17 and Table 18 summarize the quick facts of Run #7, Run#8, and Run #9:

Table 17: Scenario 3 Quick Facts (a)

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#6	60	2.05	15	2.05	15	0.5
#7	60	13.68	15	2.05	15	0.5
#8	60	13.68	15	13.68	15	0.5

Table 18: Scenario 3 Quick Facts (b)

TBSAT Run	# of Accessible Stops	# of Accessible Routes	# of Reachable Stops		Service Area Relative Ratio		Service Area Percentage Change	
			(Peak)	(Off-Peak)	(Peak)	(Off-Peak)	(Peak)	(Off-Peak)
#7	17	5	280	250	100.00%	100.00%	Benchmark	Benchmark
#8	566	11	737	533	208.1%	178.4%	+108.1%	+78.4%
#9	566	11	737	533	775.6%	740.1%	+675.6%	+640.1%

Comparing the quick facts in both tables leads to four findings:

(1) Bicycling significantly increases the number of accessible stops:

Due to the mobility of bicycling, shown in Run #8 and Run #9, 566 bus stops are accessible from the SCTC within 15 minutes, while only 17 bus stops are accessible for a traveler walking to a bus stop.

(2) Bicycling significantly increases the number of accessible routes:

The number of accessible routes for the bicyclist (Run#8 and Run#9) from the SCTC increases from 5 routes to 11 routes. This includes all bus routes that are inputted into the TBSAT database in this application as mentioned in the beginning of this chapter (and described in Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION). In fact, from the 566 accessible stops (for Run #8 and Run #9), the traveler should have 23 accessible routes available from the SCTC. However, as mentioned in Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION concerning data preparation, due to the limited amount of research time, this application contains only 11 bus routes in the database. Provided more programming resources to include additional precise routing and path information, some future version of TBSAT will be able to calculate an actual time-based bus service area with bicycling as the access mode that is larger than the result shown in this scenario.

(3) Bicycling mode generates additional reachable stops:

Switching the access mode from walking (Run #7) to bicycling (Run #8 and Run #9) increases the number of accessible routes (from 5 to 11). In turn, the number of reachable stops drastically increases from 280 to 737 during the peak service period and from 250 to 533 during the off-peak service period (see Table 18).

(4) Bicycling significantly increases the service area:

Table 18 shows that, when bicycling is the access mode, a traveler during the peak period is able to reach an area more than twice the size as that when walking is the access mode. Even during the off-peak period, a traveler still gains about 78% more reachable area if he chooses bicycling to bus stops instead of walking.

Moreover, the service area, when using the Bike n' Ride mode, is 7 times larger than the service area that assumes walking as the access/destination access mode. This finding is strong evidence to support the benefits of traveling with the bicycle on the bus.

5.3.3 Planning Implications

From both the visualized results and the statistics it is clear that bicycling to a bus stop is a very effective way to extend the reach of the bus rider. Under the same 60-minute travel-time budget, the peak bus service area of the SCTC doubles when the access mode switches from walking to bicycling. When using the Bike n' Ride mode, the service area increases even more. Never before the use of TBSAT could the benefit of bicycling be shown in terms of the increment of the bus service area in both mapped and numerical form. The results of Scenario 3 are a persuasive instrument for promoting bicycling as a viable alternative access mode as well as destination access mode.

To promote bicycling as an access mode, bicycle storage devices must be available at bus stops so that bus riders can lock their bicycles at the boarding stops. Through travel pattern analyses it is possible to locate bus stops with high boarding volume. Bicycle storage devices, such as racks or hangars, can be installed at such bus stops. For example, VTA has a program that is making efforts to provide at least one bicycle rack at every transit center, Park-and-Ride lot, and light rail station.[31]

In addition, to promote the Bike n' Ride behavior, additional bicycle storage devices must be installed on each bus. For example, VTA buses used on the bus routes that are considered to have higher Bike n' Ride potential are usually equipped with two types of bicycle storage devices. One is the seat that can be converted into bicycle-storage space. Some buses are equipped with an external bicycle rack that allows storing bicycles without reducing passenger space.

Considering the results of Scenario 3 that visually and statistically support the benefits of using bicycling as a viable alternative mode to access the boarding bus stops as well as final destinations after disembarkation, the installation of these bicyclist-friendly measures may be prioritized as an important way to encourage ridership as well as to enhance the bus service area.

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[31] Santa Clara Valley Transportation Authority, *Board Memorandum* (Valley Transportation Authority, September 19, 2007). < http://www.vta.org/inside/boards/packets/2007/11_nov/24.pdf > [27 April 2008]

5.4 Scenario 4: Bad Traffic is a Drag! Varied Traffic Conditions

As presented in section 4.3.3, adverse traffic conditions increase the time that a traveler must spend waiting for the desired bus. In TBSAT, the influence of this wait-time due to traffic conditions is represented as the waiting time/headway ratio, as discussed in sections 4.3.3 and appendix section E.3.4. Scenario 4 visualizes the influence that different traffic conditions contribute to the time-based service area. However, in the real world, the increase in traffic not only increases the passenger waiting time, it also increases the actual bus travel-time. Thus, TBSAT most likely underestimates the impact that adverse traffic conditions have on the time-based bus service area. Nevertheless, this scenario demonstrates TBSAT's capability to estimate the change in time-based bus service area due to a change in the traffic conditions.

Table 19: Scenario 4 Factor Settings

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#10	60	2.05	15	2.05	15	0.5 (LOS A)
#11	60	2.05	15	2.05	15	0.8175 (LOS E)

Run #10 uses the benchmark settings, which assumes the traffic condition on the road maintains the Level of Service A (LOS A), or a free-flow of vehicular traffic . Conversely, Run #11 generates the 60-minute bus service area of the SCTC when the traffic conditions degrade to Level of Service E (LOS E), or an unstable flowing vehicular traffic.

5.4.1 60-Minute Bus Service Area of the SCTC under LOS A/LOS E

Figure 31 and Figure 32 illustrate the 60-minute bus service area of the SCTC according to the settings of Run #10 and Run #11 (summarized in Table 19).

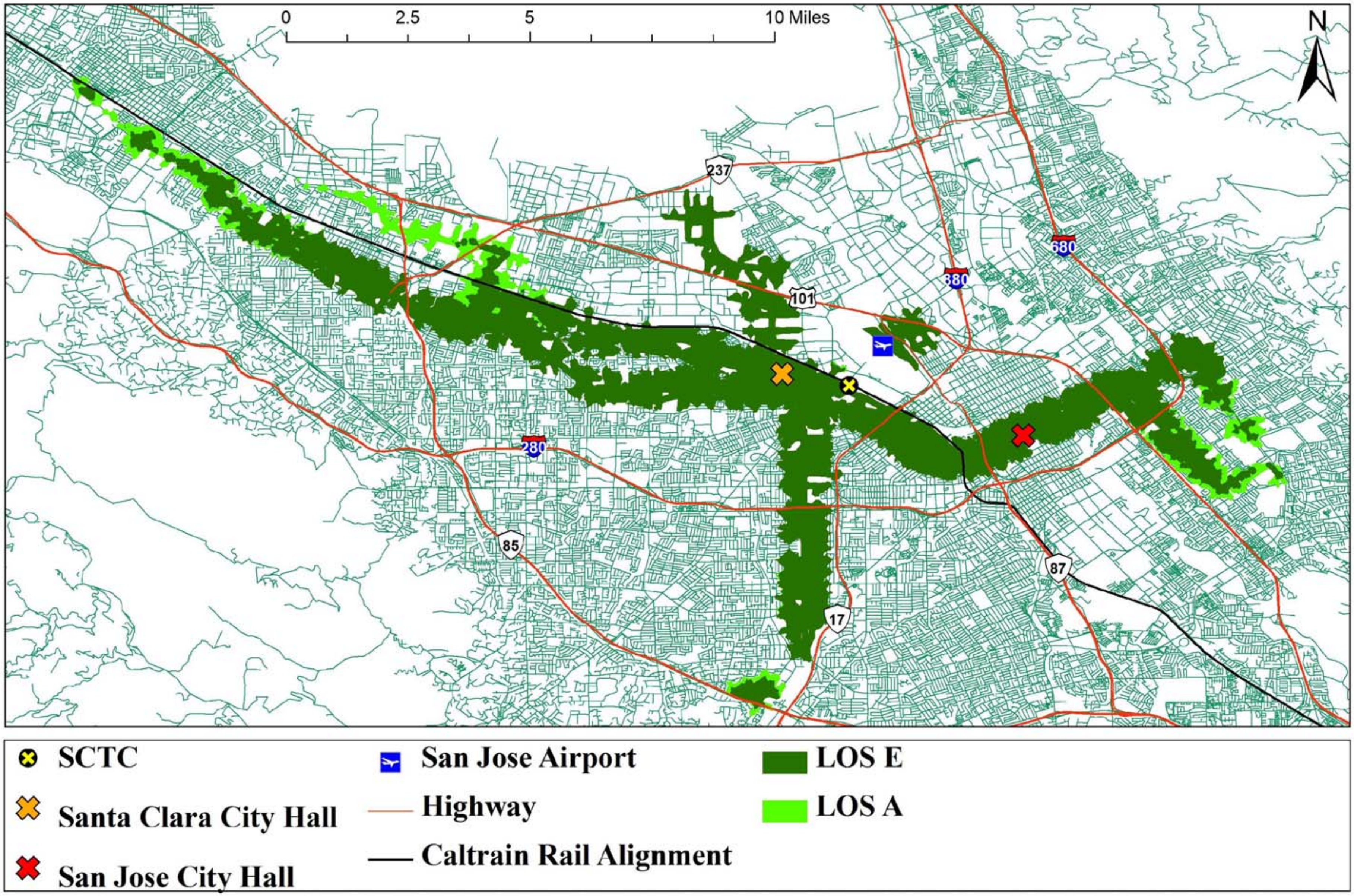

Figure 31: 60-Minute Peak Bus Service Area under LOS A/LOS E

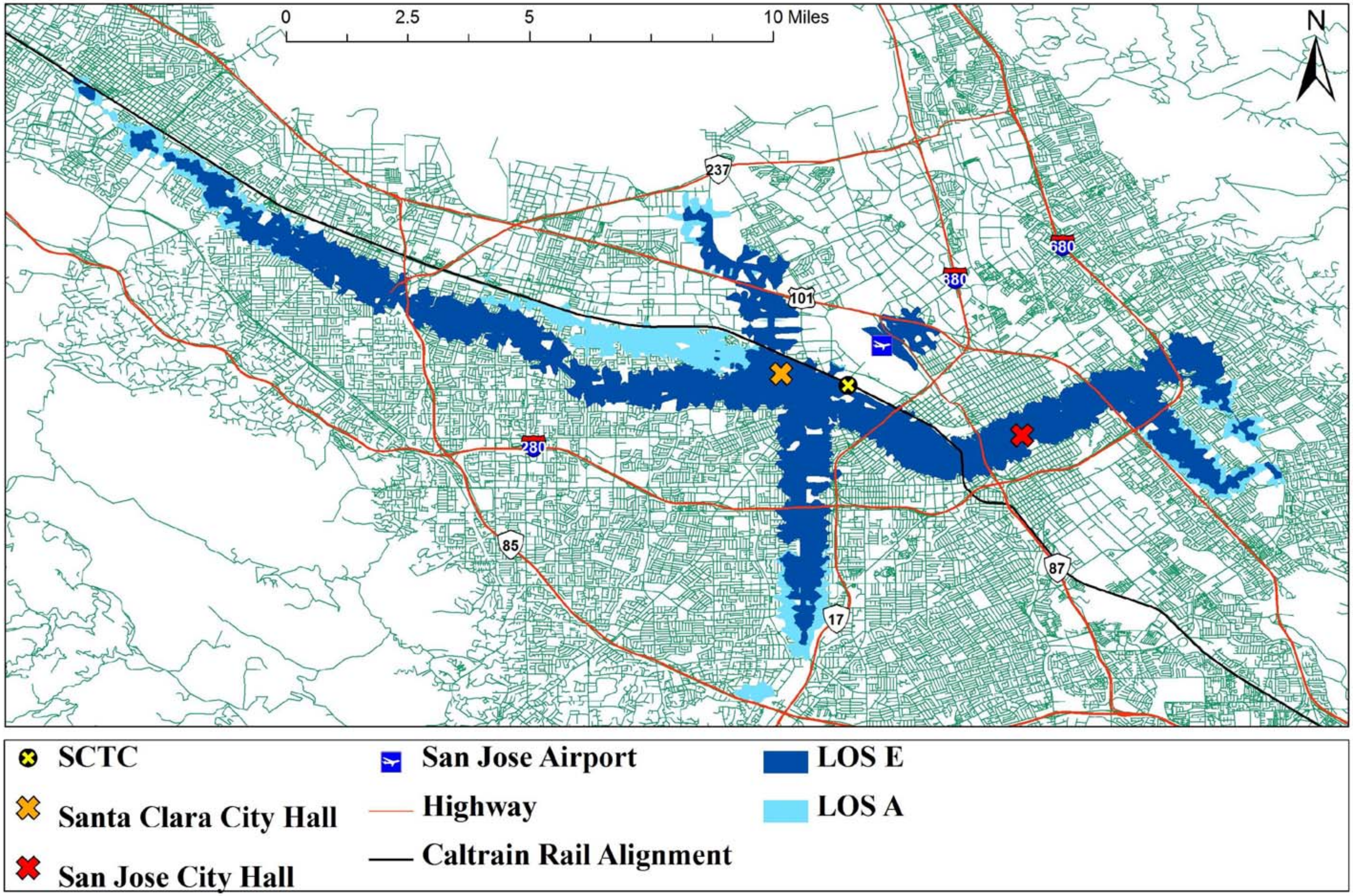

Figure 32: 60-Minute Off-Peak Bus service Area under LOS A/LOS E

In Figure 31 and Figure 32**,** the 60-minute bus service area under LOS E (Run #11) is shown in darker colors. Note that the service area under LOS A (Run #10) actually includes both the darker area and the lighter area.

The impact of degraded traffic conditions on the SCTC 60-minute service area is predictable. As shown in Figure 31, compared to the free-flow traffic conditions (LOS A) case, the congested traffic conditions (LOS E) service area is smaller. Some areas far from the SCTC become unreachable within the 60-minute limit due to the increased traveler waiting time.

Similar to the results during the peak service period, when the traffic conditions degrade from LOS A to LOS E (see Figure 32), the light blue area becomes unreachable from the SCTC within the 60-minute limit, leaving only the smaller dark blue regions as the service area of the SCTC.

5.4.2 Findings of Scenario 4

Table 20 and Table 21 summarize the quick facts of Run #10 and Run 11:

Table 20: Scenario 4 Quick Facts (a)

TBSAT Run	Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
#10	60	2.05	15	2.05	15	0.5 (LOS A)
#11	60	2.05	15	2.05	15	0.8175 (LOS E)

Table 21: Scenario 4 Quick Facts (b)

TBSAT Run	# of Accessible Stops	# of Accessible Routes	# of Reachable Stops		Service Area Relative Ratio		Service Area Percentage Change	
			(Peak)	(Off-Peak)	(Peak)	(Off-Peak)	(Peak)	(Off-Peak)
#10	17	5	280	250	100.00%	100.00%	Benchmark	Benchmark
#11	17	5	252	200	88.8%	80.7%	-11.2%	-19.3%

The data in the quick facts tables and the confirmation of the visualized data in the maps make results of Scenario 4 clear.

(1) Increased traffic does not alter the number of accessible stops or accessible routes:

Since various traffic conditions only affect the amount of time the bus waits in traffic, this scenario confirms that traffic condition changes do not affect a traveler's behavior when accessing boarding stops. The number of accessible stops and accessible routes remain unchanged through two runs.

(2) Increased traffic results in fewer reachable stops:

As traffic congestion increases from LOS A to LOS E, a traveler may still reach the same number of accessible stops and the same number of accessible routes. However, the number of reachable stops (at the destination) decreases because of the time spent waiting in traffic while on the bus. Thus, during the peak period, 28 bus stops that the traveler can reach, under LOS A conditions, become unreachable under LOS E (see Table 21). During the off-peak period, the number of reachable stops decreases from 250 to 200 as traffic degrades from LOS E to LOS A.

(3) Increased traffic congestion results in decreased service area:

As traffic congestion increases from a state of LOS A to LOS E, the 60-minute, peak service period bus service area of the SCTC shrinks by approximately 11% (down to 89%). The off-peak bus service area, under the same conditions, decreases by 19% (down to 81%).

5.4.3 Planning Implications

As described earlier, since degraded traffic conditions increases only the passenger waiting time, not the actual bus travel-time, TBSAT underestimates the impact on the time-based bus service area. Despite this caveat, Scenario 4 demonstrates how changes in traffic conditions affect the *reach* of bus riders.

In highly urbanized areas, traffic congestion often delays the arrival of scheduled buses and increases bus travel-time. The results of Scenario 4 demonstrate this visually and statistically. The maps illustrate the decrease in size of the time-based bus service area due to increased traffic congestion. Such a decrease in area makes the bus service system less competitive. Maintaining standard operating speed without being influenced by traffic congestion becomes a highly desirable solution, increasing the competitiveness of a bus service system. If transportation agencies exercise special measures, such as applying bus-dedicated lanes or allowing bus speeding to maintain the bus speed at LOS A while the overall traffic condition is LOS E, the bus service area eliminate the loss of this 10% to 20% coverage.

5.5 Scenario 5: Collect More Potential Riders! Potential Rider Estimate through Joint Work between TBSAT and Social Statistics

Scenario 5 does not compare the differences in time-based bus service area of the SCTC under different conditions. Instead, it demonstrates how the time-based bus service area maps can be analyzed in conjunction with other planning data to generate new types of transportation planning-related information.

Two questions are asked and answered in Scenario 5:

1. What proportion of land in each census tract in Santa Clara County is served by the 60-minute bus service area of the SCTC?

In large scale planning processes, the bus availability of a geographic region is often estimated by measuring how much this region is served by the service area of the bus system. Similarly, the extent to which the current bus service system covers each census tract of Santa Clara County, can be revealed by creating a map that overlays the 60-minute bus service area of the SCTC, as generated by TBSAT, onto each census tract. For example, if a census tract is mostly covered (served) by the 60-minute bus service area of the SCTC, then this census tract could be considered as highly bus accessible to the SCTC. Answering this question demonstrates TBSAT's ability to identify location-to-location bus accessibility information, in this case, census tracts-to-SCTC.

2. How many residents in each census tract of Santa Clara County are *not* served by the SCTC 60-minute bus service area?

Another important indicator that measures the success of a bus service system is the population covered (served) by the service area of the bus system. Previous service area measurement methods only told planners the total coverage of the bus system. This can assist planners in estimating the population served under such coverage. However, TBSAT generates both location and time specific service area maps, by incorporating the time-based bus service area map and the population information. With the results, planners can estimate how many people in a geographic area can actually gain access to a specific location under specific conditions.

The results may also be used to answer the question: *how many people in each census tract are beyond the reach of the SCTC 60-minute bus service area?* For instance, say a certain census tract contains many people who live outside the SCTC 60-minute bus service area. TBSAT allows planners to see this pattern. Bus service to that census tract could be expanded, which could significantly increase the ridership of the bus system and efficiently promote the auto-independent travel behavior.

5.5.1 What proportion of land does each census tract in Santa Clara County is served by the 60-minute bus service area of the SCTC? What percentage of each Santa Clara County census tract is served by the 60-minute bus service area of the SCTC?

ArcGIS provides the functions to answer this question. First, an overlay of the 60-minute bus service area of the SCTC is placed on the Santa Clara County census tract map. The *Intersect* function in ArcGIS identifies the areas covered by both the census map and the service area map layers. The intersection indicates the physical area of each tract that is serviced by the SCTC 60-minute service area. This is called the **serviced area**. Dividing the size of the serviced area by the census tract's total area provides the percentage of the tract's area that is serviced.

For Scenario 5, the 60-minute bus service area of the SCTC is generated using the benchmark settings used in the previous four scenarios (see Table 22).

Table 22: Setting for 60-Minute Bus Service Area from the SCTC

Total Travel Time Limit (minutes)	Access Speed (mph)	Acceptable Access Time (AAT) (minutes)	Destination Access Speed (mph)	Acceptable Destination Access Time (ADAT) (minutes)	Waiting Time / Headway Ratio
30	2.05	15	2.05	15	0.5

The census tract map for Santa Clara County is included in the 2006 second edition TIGER/Line files[32] for Santa Clara County. This is the same set of files used to construct the existing path map. The census tract information is imported similarly (as explained in Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION). However, the existing map is converted from the Santa Clara TIGER/Line file's road network information, while the census tract map used in Scenario 5 is imported from the census tract information from this file.

Once both the 60-minute bus service area of the SCTC and the Santa Clara County census tract map layers are resident in ArcGIS, the ArcGIS *Intersect* function is applied to generate a layer that contains a number of polygons. Each polygon represents the serviced area of each census tract. These are the areas in each tract that are covered by the 60-minute service area of the SCTC. At the same time these polygons are created, the area of each of these polygons is also calculated. Using the ArcGIS *Calculate Areas* function, the area of each census

[32] TIGER/Line (Topologically Integrated Geographic Encoding and Referencing) files contain various types geographic information including the street coordinates of US territories. It is prepared by the geography division of US Census Bureau.
<http://www.census.gov/geo/www/tiger/tiger2006se/tgr2006se.html> [May, 02, 2008]

tract is obtained. The percentage serviced area may now be calculated for each tract. The calculated percentages are then used to generate a map that visualizes the percentage of the serviced area in each census tract of Santa Clara County.

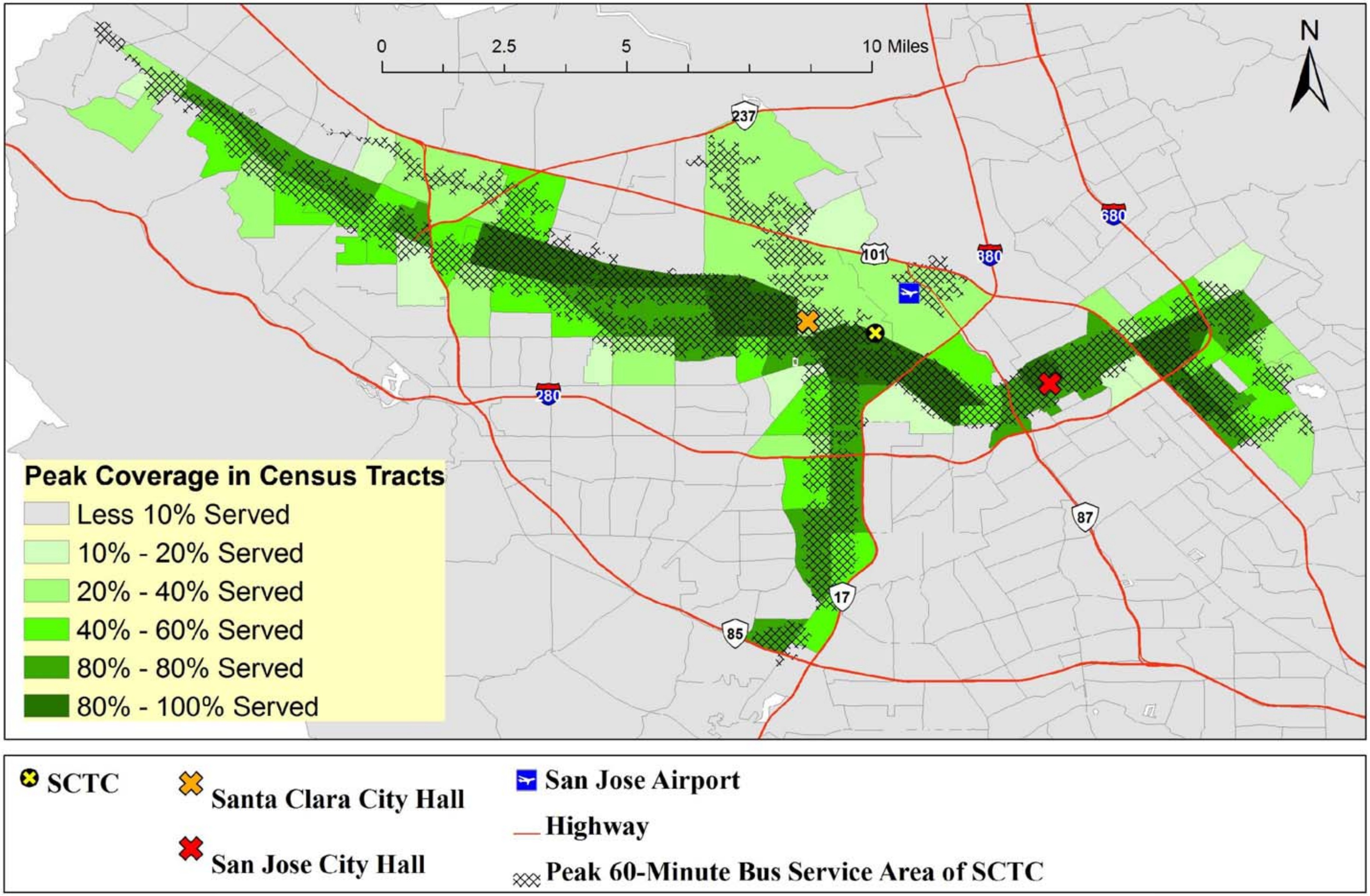

Figure 33: Census Tract Percentage Served by 60-Minute Peak Bus Service Area of SCTC

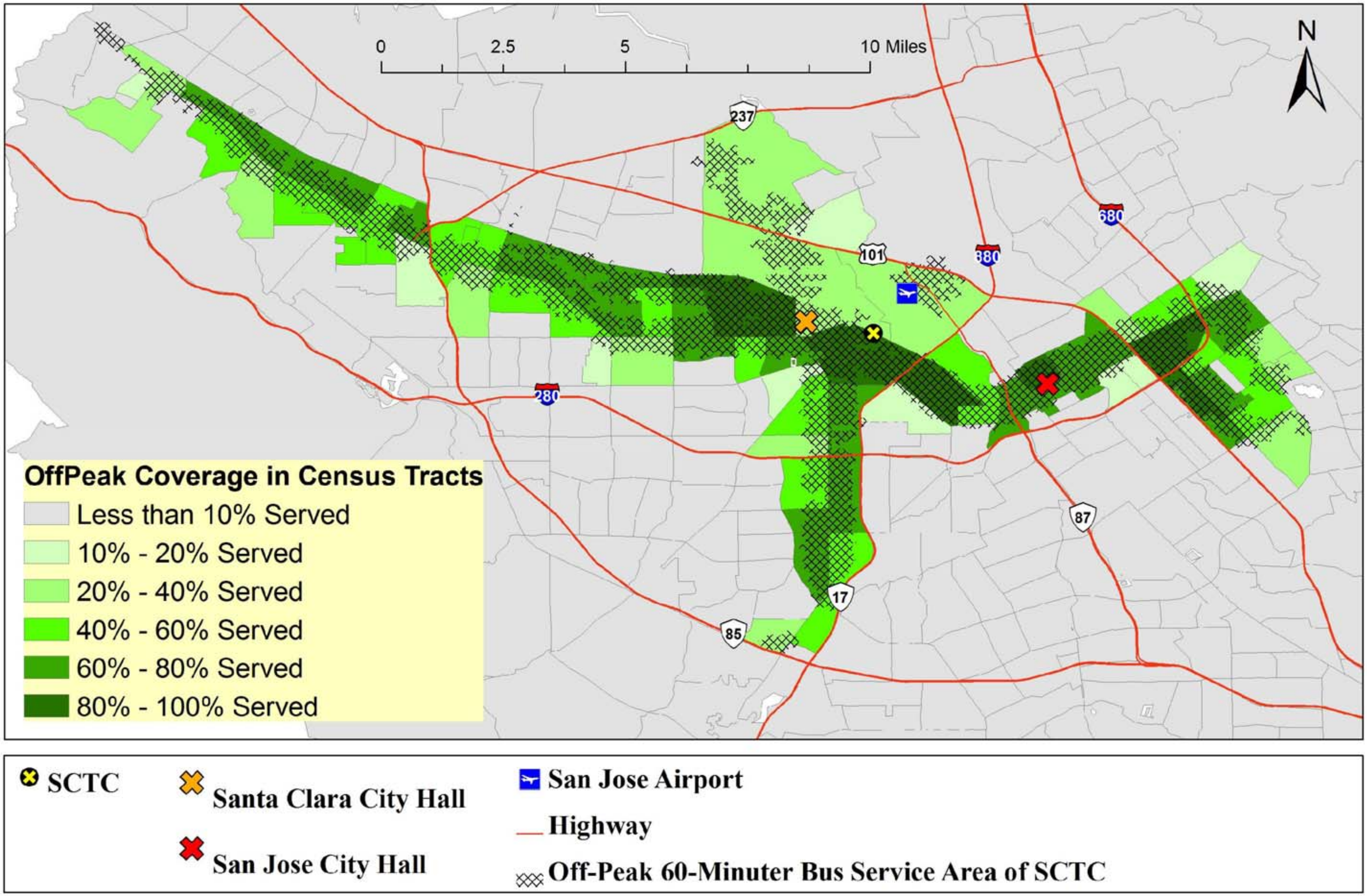

Figure 34: Census Tract Percentage Served by 60-Minute Off-Peak Bus Service Area of SCTC

In Figure 33 and Figure 34, the cross-hatched shape is the 60-minute bus service area for the SCTC (for peak and off-peak periods, respectively). The census tract area color reflects the area of that tract covered by the cross-hatched area. The percentages show how well a census tract is covered by the 60-minute bus service area of the SCTC; in other words, how well a census tract connects to the SCTC. For example, a census tract shown in deepest green indicates that at least 80% of the area within that tract can be reached from the SCTC within one hour. Thus, a deepest green census tract is a highly bus accessible area from the SCTC. Conversely, a grey tract indicates low or no bus accessibility from SCTC to that census tract. Table 23 briefly summarizes the results in Figure 33 and Figure 34:

Table 23: Census Tract Count by Percentage Covered by 60-Minute Bus Service Area of the SCTC

Percentage Covered By 60-Minute Bus Service Area of the SCTC	Less than 10%	10% - 20%	20% - 40%	40% - 60%	60% - 80%	80%+	Total
Peak Census Tract Count	252	10	15	20	27	17	341
Peak Census Tract Percentage Count	73.90%	2.93%	4.40%	5.87%	7.92%	4.99%	100.00%
Off-Peak Census Tract Count	257	9	13	21	28	13	341
Off-Peak Census Tract Percentage Count	75.37%	2.64%	3.81%	6.16%	8.21%	3.81%	100.00%

5.5.2 How many residents in each Santa Clara County census tract are *not* served by the SCTC one-hour bus service area?

Assuming the residents of each census tract are equally distributed within that the census tract, and using the percentage of serviced area computed in section 5.5.1, an estimate of the population *not* within the serviced area of each census tract may be calculated. The result indicates the approximate number of people in each census tract who cannot travel from the SCTC to their homes within one-hour. Such people may have low motivation to travel to/from the SCTC by bus because the travel-time cost of doing so would be greater than the tolerable one hour.

The population within the serviced area in each census tract can be calculated using the formula displayed in Equation 13**:**

$$\text{Population within a Serviced Area of a Census tract} = \left(\text{Population in the Census Tract} \times \frac{\text{Area of the Serviced Area in the Census Tract}}{\text{Area of the Census Tract}} \right)$$

Equation 13: Total Population Covered by the 60-Minute Bus Service Area of the SCTC

Census 2000 tract-level population values were used for this research.[33] Once these values are applied to Equation 13 to identify the population served, they are then applied to Equation 14 to identify the population not covered in each census tract.

$$\text{Population NOT within the Serviced Area of a Census tract} = \text{Population in the Census Tract} - \text{Population within the Serviced Area of a Census tract}$$

Equation 14: Population the SCTC not Served by the SCTC 60-Minute Bus Service Area

The resulting maps, showing the numbers of residents not covered by the 60-minute bus service area of the SCTC in each census tract of Santa Clara County, are displayed in Figure 35 and Figure 36.

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[33] US Census Bureau, *US Census 2000 Decimal Census Dataset*, (2000). <http://factfinder.census.gov/servlet/DTGeoSearchByListServlet?ds_name=DEC_2000_SF1_U&_lang=en&_ts=223867835901> [February, 05, 2008]

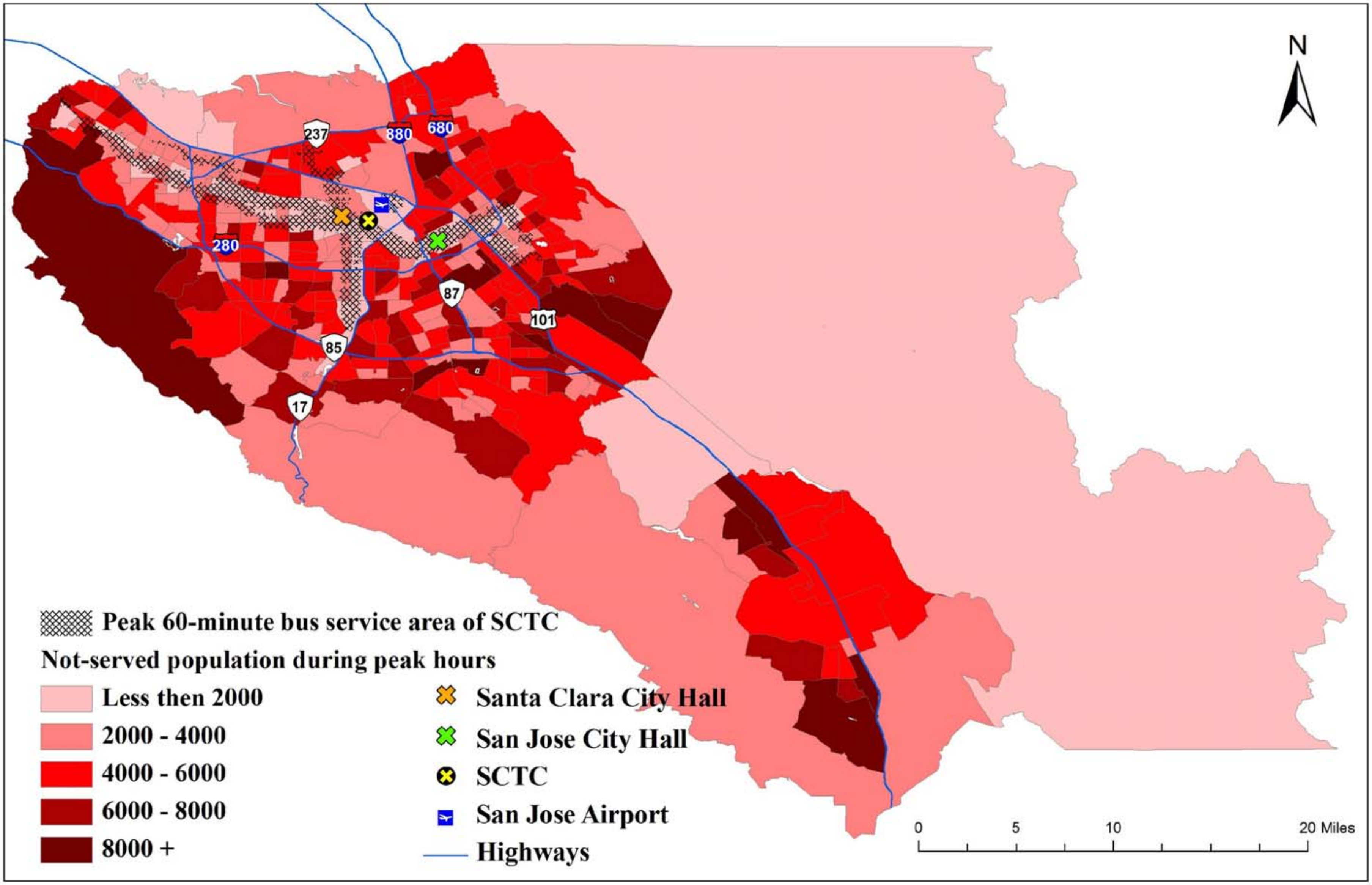

Figure 35: Census Tract Population Not Served by 60-Minute Peak Bus Service Area of SCTC

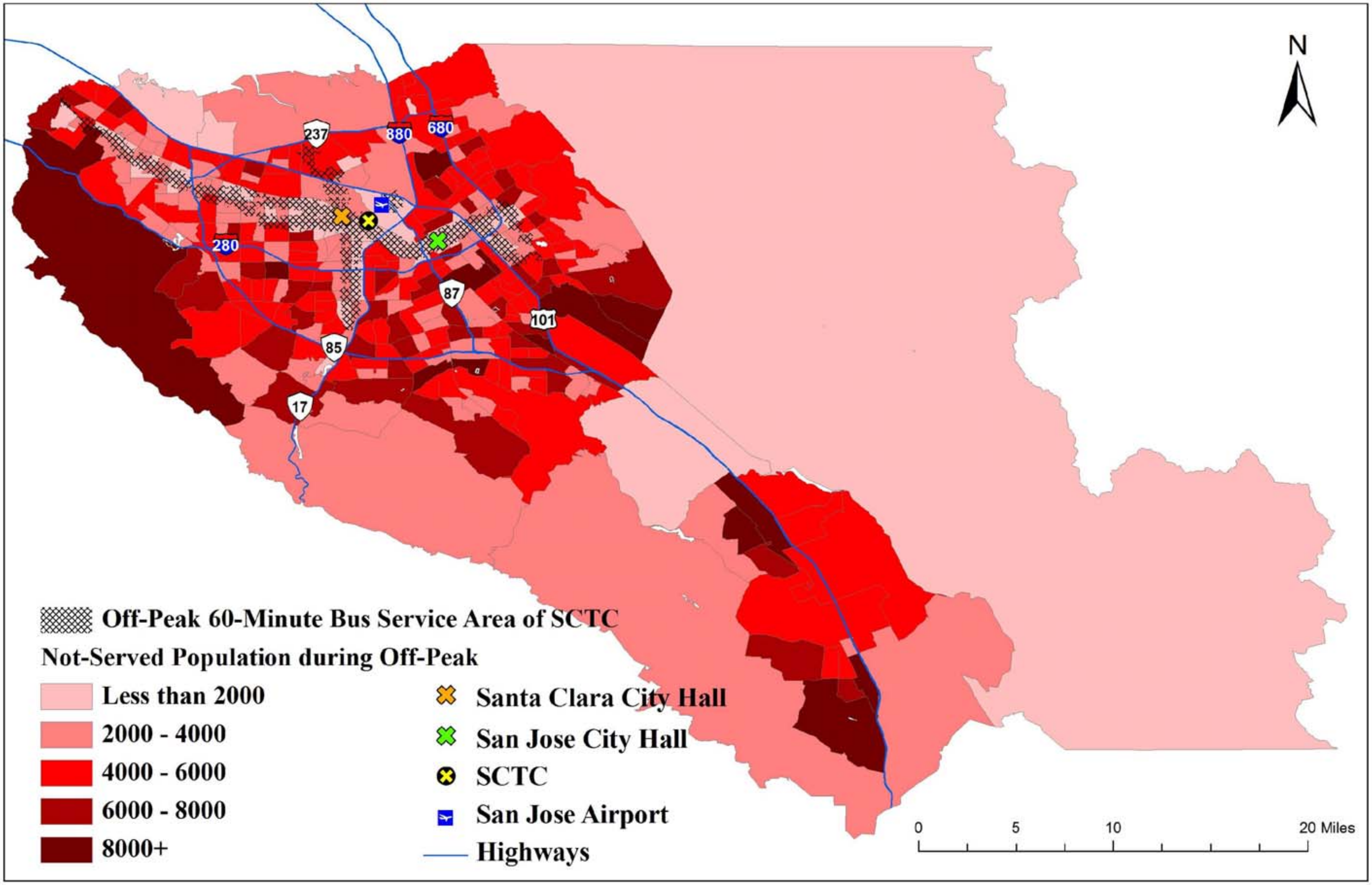

Figure 36: Census Tract Population Not Served by 60-Minute Off-Peak Bus Service Area of SCTC

The results displayed in the two figures indicate that there are still thousands of people in many census tracts who cannot travel between the SCTC and their homes within 60 minutes by bus.

Table 24: Estimated Population in Santa Clara County Not Served by the SCTC's 60-Minute Bus Service Area

Total Population in Santa Clara County	Estimated Population Not Served by the SCTC		Estimated Population % Not Served by the SCTC	
	(Peak)	(Off-Peak)	(Peak)	(Off-Peak)
1,682,585	1,438,921	1,454,218	85.52%	86.43%

Table 24 gives a brief summary estimating the number of Santa Clara County residents served by the SCTC 60-minute bus service area. The current bus service provides coverage for approximately 15% of the population in Santa Clara County, meaning that a majority of the county's residents cannot gain access to the SCTC within a one-hour timeframe.

The process of answering question 2, demonstrates that the time-based service area information generated by TBSAT can be successfully combined with population statistics to produce useful visual and statistical estimates to describe bus service quality for specific geographic area(s). However, these are only estimates. In the real world, populations in a census tract are not guaranteed to be distributed equally across the census tract. As a result, estimating the served/un-served population by using tract level data may create significant error.

For example, consider a census tract whose population is concentrated within a single neighborhood. The existing bus service entirely covers this neighborhood while not covering the other portions of the census tract. The population of this tract is, in fact, totally served. Under such a condition, TBSAT and the calculations described above underestimate the served population in this census tract. Higher resolution data is required to create a more accurate picture. For this problem, street-block level data is more appropriate.

5.5.3 Planning Implications

As the results of Scenario 5 show, the current VTA bus service allows only a limited number of areas and a limited number of residents access to the SCTC within one hour, even though the SCTC is already an emphasized transit hub, which VTA closely monitors to improve bus service quality. The displayed inefficiency of the SCTC may actually reflect that bus service in the South Bay Area as a whole, is less desirable at both the local level and the regional level.

As a local transit hub, the SCTC is designed as a transfer node between many bus routes. A bus transfer node should be a location that is bus-accessible to most of the area it serves. In the SCTC case, the SCTC should be able to collect and distribute passengers from and to most of the areas in Santa Clara County in a timely manner. However, the current bus service can barely allow the SCTC to function as such a transit hub. As a result, the lack of functionality of the SCTC makes the SCTC less competitive than other transit hubs in Santa Clara County, such as the San Jose Diridon Caltrain/ACE/Amtrak station.

Diridon Station receives an equal amount of bus service, compared to the SCTC. However, Diridon Station is also well connected to regional transit. Furthermore, the Diridon station is closer to the area/location that generates the county's highest transit demand: downtown San Jose.

The HP Arena, the largest professional stadium in Santa Clara County, is host to numerous sports and entertainment events. It is within walkable range of Diridon Station. By contrast, the SCTC is less likely to generate such high transit demand. Santa Clara University is the only large facility likely to generate local transit need around the SCTC. Thus, to maintain its status as a functional transit hub, the SCTC must optimize its bus accessibility and transfer options so that riders do not resort to other transit hubs.

As a regional transit hub, the SCTC is a transfer node between regional mass transit (Caltrain at present, BART in the future) and local public transit services (bus). Without a bus service that can quickly collect and distribute its passengers, the SCTC is less desirable as a favored transfer node. Furthermore, without a regional transfer node that can quickly collect and distribute passengers, Santa Clara County is less able to transport incoming and outgoing commuters from and to other counties using its public transportation system. Such conditions make public transportation less desirable as a county-to-county commuting mode.

5.6 Chapter 5 Summary

The five scenarios described in this chapter demonstrate that TBSAT is capable of correctly generating a variety of time-based bus service area maps for the SCTC, according to a variety of conditions.

The time-based bus service area concept is able to represent the SCTC bus accessibility within specified travel-time budgets and under varied conditions. Traditional service area measurement methods are not able to present such information in a visual format. Furthermore, Scenario 5 demonstrates that the time-based bus service area concept can provide even more information when combined with other types of information.

The following section summarizes the important findings in this chapter, particularly those of the five scenarios:

Chapter-wise

(1) Due to limited research time, the TBSAT database in this application only covers 11 bus routes that are available approximately within a 3-mile radius of the SCTC (see introduction of Chapter 5).

(2) The time-based service area shrinks as the passenger disembarks at stops farther away from the SCTC (see section 5.1.1).

(3) Some areas that can be reached from the SCTC during the peak service period are not reachable during the off-peak period (see section 5.1.1).

Scenario 1: How Early Should You Get Up? Varied Travel Time Budget

(1) The size of the peak service area increases by about 400% when the travel-time budget increases from 30 minutes to 60 minutes and about 443% when the travel-time budget increases from 30 minutes to 90 minutes (see section).

(2) The off-peak bus service area increases by about 440% when the travel-time budget increases from 30 minutes to 60 minutes and about 564% when the travel-time budget increases from 30 minutes to 90 minutes (see section 5.1.3).

(3) The reachable area from each reachable stop is capped by the acceptable access range (see section 5.1.3).

(4) It is important for bus service operators to provide corresponding service frequency to specific areas according to the area's characteristics (see section 5.1.4).

(5) The bus service should provide reasonable accessibility under a reasonable travel-time budget (see section 5.1.4).

Scenario 2: Be Athletic! Varied Acceptable Access Time

(1) The number of accessible stops increases as the AAT/ADAT increases. As the AAT/ADAT varies from 10, 15, and 20 minutes, the number of accessible stops increases to 12, 17, and 24, respectively (see section 5.2.1).

(2) As AAT/ADAT increases no additional accessible routes are generated. Such a result may be due to the special characteristics of the SCTC (see section 5.2.1).

(3) A decrease in a traveler's willingness to walk to a bus stop from 15 minutes to 10 minutes, translates to approximately a 34% loss of the bus service area during the peak period and a 35% loss during the off-peak period (see section 5.2.1).

(4) A traveler who is willing to walk longer than average (from 15 minutes to 20 minutes) gains approximately 27% more reachable area during the peak period, and approximately 26% more reachable area during the off-peak.

(5) Improving the walkability of an area may be a practical way to encourage the willingness to walk, thereby increasing the time-based bus service area (see section 5.2.2).

Scenario 3: Get on the Bicycle! Varied Access/Destination Access Mode

(1) Park n' Ride, where a traveler parks his bicycle at the boarding bus stop and then uses the bus, doubles the 60-minute bus service area from the SCTC, as compared to using walking as the access/destination access mode (see section 5.3.2).

(2) Bike n' Ride is the most efficient way to increase the time-based bus service area. This mode boosts the 60-minute bus service area from the SCTC to seven times that of the area when walking is the access/destination access mode (see section 5.3.2).

Scenario 4: Bad Traffic is a Drag! Varied Traffic Conditions

(1) When using TBSAT, the influence of waiting time due to traffic conditions is only represented as the waiting time/headway ratio (see section 5.4).

(2) During the peak service period, the 60-minute service area of the SCTC shrinks approximately 11% when traffic conditions degrade from LOS A to LOS E (see section 5.4.2).

(3) During the off-peak period, the 60-minute service area of the SCTC shrinks approximately 19% when traffic conditions degrade from LOS A to LOS E (see section 5.4.2).

(4) Maintaining the bus operating speed independent of traffic conditions is one solution to increase the competitiveness of a bus service system (see section 5.4.3).

Scenario 5: Collect More Potential Riders! Potential Rider Estimate through Joint Work between TBSAT and Social Statistics

(1) More than 70% of the census tracts in Santa Clara County are poorly connected to the SCTC (less than 10% area covered by the 60-minute bus service area of the SCTC.)(see section 5.5.1).

(2) An estimated 85% of the population in Santa Clara County is unable to access SCTC within one hour (see section 5.5.2).

(3) It is essential to improve the bus service at the SCTC to allow the SCTC maintain its status as a regional transit hub (see section 5.5.3).

The next chapter concludes this research by summarizing the accomplished goals, discussing the possible other applications of TBSAT, and listing the improvements that can be made to the TBSAT in the future.

Chapter 6 : CONCLUSION

This conclusion is composed of two sections. The first section focuses on the improvements that can be made to improve TBSAT. The second examines how well TBSAT achieves the stated research goals, through a review the applicability of TBSAT and the results that are generated by TBSAT.

6.1 Future TBSAT Improvements

During TBSAT's development, many ideas for future improvements and enhancements emerged. The TBSAT developed for this research is a prototype to demonstrate proof of concept. In order to simplify the calculation, this TBSAT makes many assumptions when estimating the time-based bus service area. For example, this TBSAT does not include route transfer behavior. Allowing the flexibility of including more factors or by using more precise raw data as input may significantly improve TBSAT output precision. In addition, improving the TBSAT algorithm coding, will result in improved operation efficiency (and reduced calculation time).

The following four sections discuss the improvements that may be implemented to improve precision, improve usability, and make the tool execute more efficiently. The first section describes increasing TBSAT output precision by refining the precision level of the inputs. The second section focuses on increasing TBSAT output precision by including more factors in the internal calculations. The third section describes ideas for making a more user-friendly interface. Implementing these changes will greatly decrease the learning time for an operator of the tool. Finally, the fourth section discusses improving TBSAT execution efficiency by recoding certain underlying calculations or by using other underlying (GIS and database) applications. This will also improve the tool's portability, allowing executing on a number of different computer platforms.

6.1.1 Improve Output Precision by Providing More Precise Input

In the demonstration runs in Chapter 5, inputs, including the existing path map and the bus route timetable, are simplified (due to a limited data preparation time for this research). Increasing the precision of these two types of information can produce more precise output.

(1) Existing Path Map

During data preparation for the SCTC application (described in Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION) the generated existing path map was generated using the 2006 second edition TIGER/Line files. However, this type of file includes only the alignment of the vehicular road network. It does not include all passable paths for other modes.

For example, when a person chooses to walk to the bus stop, the shortest route may be a shortcut that runs between buildings or a path across a park. Such pedestrian-only paths significantly increase the walkable area from a trip origin to the reachable bus stops. This allows a person to access the same bus stops in less time than walking along the sidewalks of the vehicular roads. This also allows access to more bus stops or bus routes. Ultimately, this translates to an increase in the size of the reachable area.

Conversely, some paths that are shown in a TIGER/Line file are not actually passable via all modes. For example, most highways should not be considered as passable, since such routes do not allow or accommodate pedestrians.

To improve the TBSAT output precision, system maintainers could prepare special sets of existing path maps designed for different modes. For example, a pedestrian-walkable path map could be used when the access mode of a specific TBSAT use is walking.

(2) Bus Route Timetable

For the SCTC application, time points along a bus route were calculated using interpolation between each bus stop published on a VTA bus route schedule (not all bus stops on a bus route are clearly recorded on a published schedule). However, interpolated results do not exactly conform to real conditions. In some cases, the interpolated arrival time at an unpublished bus stop may be slightly different from the real-world arrival time for that route. At some point in the future, should VTA provide more precise data, it is possible that TBSAT could take advantage of that, producing higher precision output.

6.1.2 Improve Output Precision by Including More Factors

TBSAT calculates the time-based bus service area by estimating the duration of the major actions that occur during a bus trip. The time estimate of some actions can be calculated with greater precision if more factors are included. Furthermore, some actions/behaviors that are not included in TBSAT (but are actually involved in a bus trip in the real world) may also affect the precision of TBSAT output. The following discussion focuses on four types of improvements that can improve the TBSAT output precision by including more factors.

(1) Access Time

In TBSAT, the access time from the trip origin to the boarding bus stop is calculated only according to the traveler's assumed access speed and the distance between the trip origin and this boarding bus stop. However, in reality, a person does not maintain the same speed when accessing the bus stop. The access speed fluctuates due to various factors, such as signal timing at major streets that the traveler must cross and the changing gradient of the routes to the bus stops.

Furthermore, depending on the access mode that a traveler uses to reach the boarding stop, traffic conditions can affect the access time. For example, when the access mode to bus service is walking, the pedestrian may have to spend more time crossing at a non-signal controlled crosswalk during higher vehicular traffic volume on the streets. This results in increased access time. Therefore, the walking time to the same bus stops would be longer when the traffic conditions are degraded. It is possible to increase access time estimate precision by including such factors as traffic conditions during specific times in the day and by considering other physical conditions that affect access speed.

(2) Boarding/Disembarking Time

A time factor that is not calculated separately in TBSAT is the time the bus spends loading and un-loading passengers. If traffic conditions allow the bus to arrive at a stop on-time, the loading and unloading action is negligible. However, when the traffic conditions delay the bus, the sum of the time spent loading and unloading at each stop will have a greater impact on the bus travel-time from the trip origin to the desired disembarkable stop.

(3) Bus Travel-Time

In this version of TBSAT, it is assumed that the bus always arrives at the bus stop according to the timetable. However, during heavy congestion, buses often fail to reach scheduled bus stops on time. Thus, the bus travel-time between the boarding stop and the disembarking stop is actually heavily influenced by traffic conditions. It is very difficult to estimate how traffic conditions will impact the bus travel-time because traffic conditions may vary greatly from place to place. Nevertheless, if the impacts of traffic conditions can be estimated and included in the calculation of bus travel-time, it would greatly improve TBSAT’s capability of estimating the bus travel-time.

(4) Route Transfer Behavior

The most important bus-taking behavior that TBSAT does not include is route transfer. That is, the traveler must take a single bus from point of origin to the destination (see section 3.1). Allowing route transferring would allow travelers access to the bus routes that are not available at the trip origin. By using the list of reachable stops as the list of accessible stops in the next loop, it is technically possible to include route transfer behavior in the TBSAT.

In the future, if the calculation mechanism of TBSAT is to be improved, including the route transfer into the calculation must be the highest priority. The second priority would be the calculation of the bus travel-time. The third priority would be the improvement of the access time calculation. The fourth priority would be providing a higher precision existing path map. However, providing such a map may significantly improve the precision of the calculations of access time and the reachable areas after disembarking. Finally, the tasks of preparing a timetable that requires no interpolation to the time points at minor bus stops and one that involves the calculation of boarding/disembarking time should be performed after the other four improvements have been implemented.

6.1.3 Develop a More User-Friendly Interface

One of the most important challenges that this version of TBSAT faces is the friendliness of its interface. TBSAT is currently developed as a tool that requires its users to possess at least some ArcGIS and Access 2007 programming and operating knowledge. The tool must be run as a task broken down into the execution of several successive, separate modules (phases). The advantage of this structure is that it allows future programmers to improve TBSAT module by module without having to revise the whole program. However, without an integrated interface, TBSAT users must jump between the two modules, use different tools to complete each phase, and sometimes manually input values. Future programmers should be able to separate the user interface from the main program, leaving a simple, easy to understand interface visible to the user. The interface would capture all the user's input variables and transfer them to the calculating portion of the tool. All the ArcGIS and Access processes could run, seamlessly, behind this interface.

Furthermore, running TBSAT over the internet is also possible after the implementation of a proper interface. User data could be input from a remote client machine. Then, both the ArcGIS component and the database component of TBSAT could run the main program/database on another server. Should TBSAT become a tool available to the public, such an internet interface would be essential.

6.1.4 More Efficient Database and Module Coding

TBSAT was developed on top of the two applications of ArcGIS and Microsoft Access. Software modules were written to work with each of these. Design and coding of the ArcGIS component and the database component of TBSAT be should reviewed and rewritten to improve TBSAT's overall efficiency.

(1) ArcGIS Component

In the current version of TBSAT, Phase 1 and Phase 3 require a user to explicitly use tools in the TBSAT toolbox to complete certain processes before obtaining the time-based bus service area map. A design review of these phases may allow a programmer to integrate these multiple processes into one single process to improve the efficiency.

At this time, TBSAT does not include a tool to allow the TBSAT data maintainer to quickly or automatically prepare the existing path map or the bus stop location data. In the future, such tools could be added to ease the burden of preparing of this underlying data.

(2) Database Component

The database component of TBSAT is somewhat friendlier to general users as well as TBSAT data maintainers, since the underlying application (Microsoft Access) is more visually organized. The strength of building the database component on Access is that the structure of the database is more understandable. The programming of an Access database can be easily revised (compared to other database programs). As well, the Access database is designed to easily migrate to other database programs as necessary.

Access is friendly and its processing power is sufficient to handle calculations under 100,000 SRD plans (possible trip plans that can occur from the trip origin). However, Access is inferior in calculation efficiency compared to other professional databases when the number of SRD plans exceeds 1 million. Faster and more efficient database choices include SQL Server, Apache DB, or Oracle Database.

For the calculation of SRD plans in a high-density city that is well-served by multiple, powerful bus services, and when route transferring is allowed, it is possible for TBSAT to easily generate more that 1 million different choices for a traveler. Under such conditions, a more powerful computer and database component must be used.

6.2 Conclusion

As stated in Chapter 1, the primary goal of this research was to provide an easy-to-use tool for people to create time-based bus service area maps that reveal the bus service area of a designated location within a given travel-time budget. TBSAT must allow general users to quickly identify the time-based bus service area of the desired location based on that user's pre-determined conditions. TBSAT achieves this goal, as demonstrated by the scenarios in Chapter 5. Depending on the complexity of the street network of the analyzed area and the bus service information, TBSAT may take from 5 minutes to 20 minutes to generate the time-based bus service area maps according to user's inputs. However, for most users, providing the manual inputs, including inputting the acceptable access distance (see appendix section E.2.1) and the range of the accessible area from trip origin (see appendix section E.4.3), would be a significant inconvenience. Both of these actions require users to open the property dialog boxes and manually input specific values into specific places.

For TBSAT system administrators/maintainers, TBSAT must allow update and maintenance of the TBSAT database that is easy enough so that the bus service information in the TBSAT can be frequently synchronized with the latest real-world bus service. As described in appendix section E.2.1 and E.3.2, the bus service information, including bus stop locations, bus route information, and bus route headway information, must be prepared in specific formats before being inputted into the ArcGIS component or the database components of TBSAT. For an experienced TBSAT system maintainer updating of the bus service information should not take too much time since the metadata of each type of information is fairly simple.

The second goal of this research was to examine the applicability of TBSAT to a real-world situation. The scenarios, as applied to the SCTC in Chapter 5**,** prove that TBSAT is capable of generating time-based bus service area maps, using real data, according to the traveler's pre-designated conditions. TBSAT is capable of reflecting the change in the time-based bus service area of the selected location according to changes in the traveler's total travel-time budget, the traveler's access behavior, the bus headway (frequency), or traffic conditions.

In addition, in Chapter 5, Scenario 5 proves that it is possible to generate new types of planning-related information by integrating the time-based bus service area map with other types of information. The maps and the other resulting information generated under different conditions could be very useful during the decision making process. For example, the results that TBSAT generates in Scenario 6 allow planners to see if the current bus service does sufficiently serve the SCTC. Such an output may provide essential additional information when planning service improvements. As another example, with proper input, TBSAT could generate both the time-based bus service maps of the current bus service as well as the maps after proposed service changes. Such outputs could allow planners to compare visually the change in bus accessibility before and after proposed service changes.

Although TBSAT is not completely user-friendly or full-featured today, this research has achieved its goal of proving that the time-based bus service area, which is a new type of bus accessibility information that can help planners to generate implications, can be successfully visualized by a programmed application (TBSAT).

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Appendix A: TBSAT USER'S QUICK MANUAL

This manual is designed for users who expect to be familiar with the operation of TBSAT within the least amount of time. This manual provides a step-by-step instruction to users who want to identify the time-based service area of a user's interested location under the following conditions:

1. *The bus service information in user's TBSAT, including the routing, the timetable, and the bus headway (frequency), is already updated and conforms to the current available bus service in the analysis area.*
2. *The street network map in users' TBSAT is already updated and conforms to the current street network in the analysis area.*
3. *No need to modify the calculation of any factor/variables*

System Requirements: ESRI ArcMap 9.2 or later and Microsoft Access 2007 or later

Install TBSAT

The entire TBSAT folder must be copied from the DVD-ROM and pasted to the root directory (C:\) of the computer. It is strongly recommended that users not place the TBSAT folder in other directories.

Preparing Predetermined Factors

To quickly generate the time-based bus service area map for a particular location, several types of information must be prepared by the users before using TBSAT:

1. The trip origin (Location of interest)

Users must be able to identify the approximate location of the trip origin on the map or at least know the address of the trip origin. For example, if the purpose of a TBSAT run is to identify the 1 hour bus service area from your home, the trip origin will be your home.

2. Total Travel Time

The maximum travel time budget people can afford. If 30 minutes is used as the total travel time, the generated map will be the 30-minute bus service area map for the location of user's choice.

3. Access Speed (Optional)

The assumed speed that people travel to bus stops in order to board the bus. If in this TBSAT run the mode people accessing bus stops is assumed to be walking, users may not need to prepare their own access speed since TBSAT suggests 2.05 mph as the default access speed based on extensive research. Otherwise, if in this run a mode other than walking is assumed as the access mode, biking for example, please define the speed of biking before applying TBSAT.

4. Acceptable Access Time (Optional)

The maximum time budget people are assumed to be willing to spend accessing toward bus stops. For example, if in this run the presumed access mode is walking and people are assumed to be willing to walk no more than 15 minutes, the acceptable access time in this run is 15 minutes. TBSAT uses 15 minutes as the default acceptable access time.

5. Destination Access Speed (Optional)

Similar to the access speed, the destination access speed, which is the speed people use to reach to their final destination after disembarking the bus, must be specified. The TBSAT default destination access speed is 2.05 mph, which is the speed of walking. If a mode other than walking is assumed, biking for example, please define the speed of biking as the destination access speed in this run.

6. Acceptable Destination Access Time (Optional)

Similar to the acceptable access time, acceptable destination access speed represent the maximum time people are willing to spend in traveling to their final destination after disembarking. For example, if in this run the user assumes people cannot afford more than 20 minutes of walking after disembarking the bus, this value should be 20 minutes. The default acceptable destination access time is 15 minutes.

7. Waiting Time/ Headway Ratio (Optional)

The ratio of the assumed bus-waiting time to the scheduled frequency of the bus route. TBSAT assumes that people always need to wait for half of the bus frequency at the bus stop before the desired bus arrives. The waiting time/headway ratio in such case is 0.5. However, this ratio could be changed according to the traffic conditions of user’s scenario. For example, when the traffic condition of the user’s scenario is level of service C, TBSAT suggests using 0.675 as the waiting time/headway ratio. Users may accept this 0.5 value or choose other ratios later during the operation.

After all seven types of information are readied; users may proceed to the following 11 steps and obtain the time-based bus service area:

Table 25: 11 Steps to Obtain the Time-Based Bus Service Area Using TBSAT

1	Open TBSAT.mxd
2	Clear Outputs of Last TBSAT Run
3	Specify Trip Origin
4	Specify Acceptable Access Distance
5	Generate List of Accessible Stops
6	Open TBSATDB.accdb
7	Generate List of Reachable Stops
8	Load Reachable Stops
9	Load Trip Origin
10	Specify Acceptable Destination Access Distance
11	Generate Time-Based Bus Service Area

Step 1: Open TBSAT.mxd

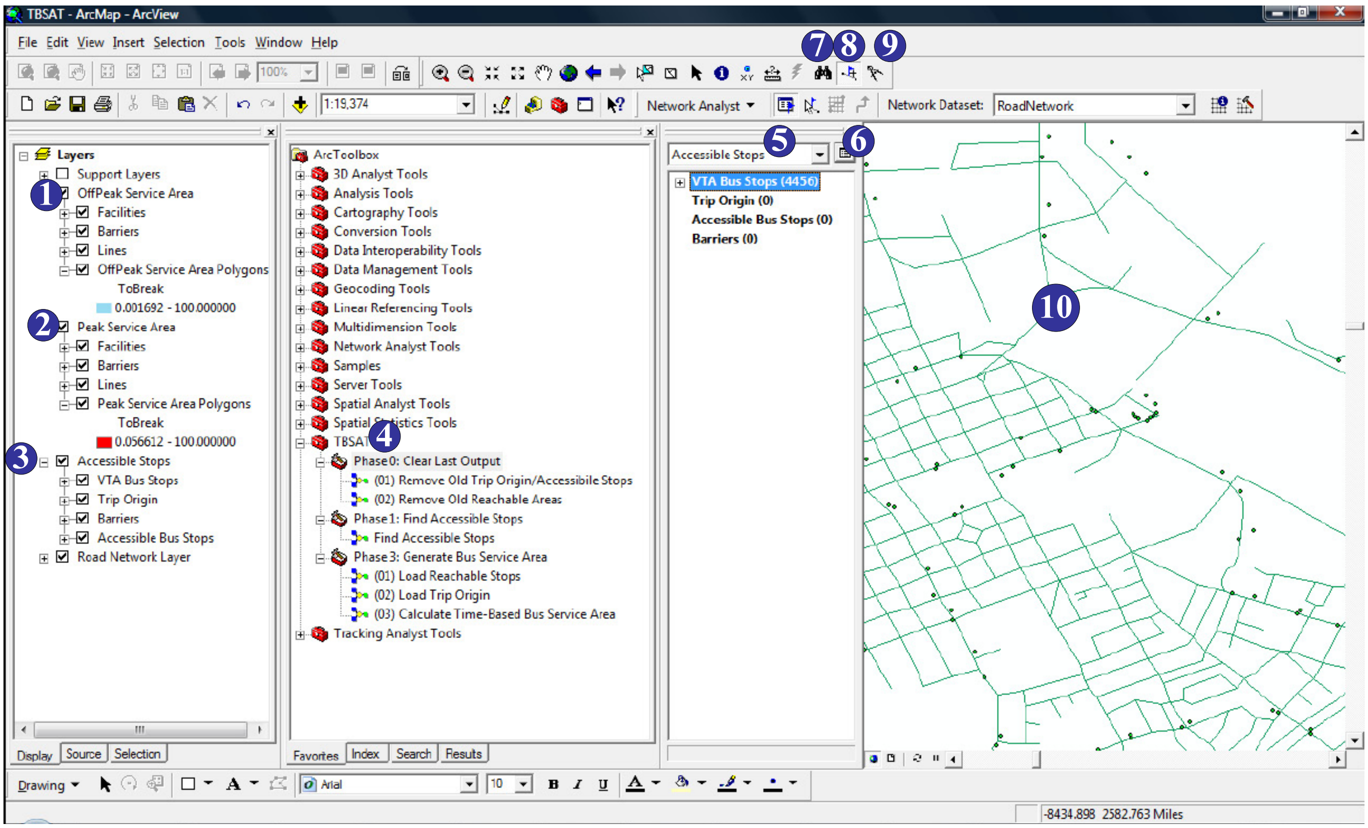

Figure 37: Open TBSAT.mxd

As shown in Figure 37, as user opens TBSAT.mxd, a standard ArcGIS interface will be opened along with the TBSAT tools that will assist the users to generate the time-based bus service area of the place of interest. The essential items listed in the figure are described below:

❶ Off-peak Service Area Layer

The off-peak time-based bus service area of users' chosen location under user's pre-determined condition will be calculated, generated, and then placed in the *Off-Peak Service Area Polygon layer*. This layer initially contains the off-peak service area polygon generated from the last run. Users will be guided to these contents and generate the correct off-peak service area polygon.

❷ Peak Service Area Layer

The peak time-based bus service area of users' chosen location under users' pre-determined condition will be calculated, generated, and placed in the *Peak Service Area Polygon layer*. Similar to the off-peak service area layer, this layer initially contains the peak service area polygon generated from the last run. Users will be guided to these contents and generate the correct peak service area polygon.

3 Accessible Stops Layer

The layer that will assist users to locate the bus stops which are accessible to the location of interest.

4 TBSAT Toolbox

The TBSAT toolbox contains six tools that can assist users generating the time-based bus service area of the place of interest. Users will be guided to use these tools in the following steps.

5 Network Analysis Layer List

This drop-box shows the network analysis layer that TBSAT users are currently working on. TBSAT contains three network analysis layers: *Accessible Stops*, *Peak Service Area*, and *OffPeak Service Area*. In some steps, users will be instructed to switch between three layers.

6 Network Analysis Layer Property Box

When selected, ArcGIS will bring up the property window of the current working network analysis layer, which is the layer shown in the network analysis layer list box. Each network analysis layer has unique settings in this property window. Users will be instructed to change some values in the property window of the three layers mentioned above in different steps.

7 Address Finder

This tool allows users to specify the location of the trip origin on the map by inputting the address of the trip origin. This tool will only function correctly when the "Accessible Stops" appears in the *Network Analysis Layer List* box.

8 Add Location Tool

Unlike the address finder, which locates the trip origin by referring to the address of the trip origin, this tool allows users to directly specify the location of the trip origin on the map without knowing the address of the trip origin. This tool will only function correctly when the "Accessible Stops" appears in the *Network Analysis Layer List* box.

9 Acceptable Access Distance Calculator

A pop-up calculator that can assist users converting the *Acceptable Access Time* and the *Access Speed* into the *Acceptable Access Distance*. The calculated *Acceptable Access Distance* must be manually input into the specific places following the instruction to allow TBSAT functioning properly.

10 Map Window

The window shows the geographic region of interest. Users may be instructed to shift the view to the trip origin during the operation. After the time-based bus service area is generated, users can visually see the results in this window.

Step 2: Clear Outputs of Last TBSAT Run

Before a new TBSAT run can be executed, the outputs of the last TBSAT run that remain in TBSAT.mxd must be removed. The Phase 0: Clear Last Output toolset in the TBSAT toolbox contains two tools that can assist users with this. By double-clicking the (01) Remove Old Trip Origin/Accessibile Stops tool and then clicking "OK", the old trip origin and the list of accessible stops of the last TBSAT run will be removed. Then, by double-clicking the (02) Remove Old Reachable Areas tool and then clicking "OK", the time-based bus service area generated in last run will be deleted.

Step 3: Specify Trip Origin

The location of the trip origin must be designated by the users. TBSAT allows users to accomplish this in one of the two following methods:

1. Use Add Location Tool

Before adding the trip origin, please make sure that the "*Accessible Stops*" appears in the *Network Analysis Layer List* box and highlight the *Trip Origin* layer by left-clicking on it before adding the trip origin as shown in the following Figure 38. If in the map window users can self-navigate to the approximate area of the trip origin, users can add the trip location simply by left-clicking the button and then left-clicking on the location of the trip origin on the map.

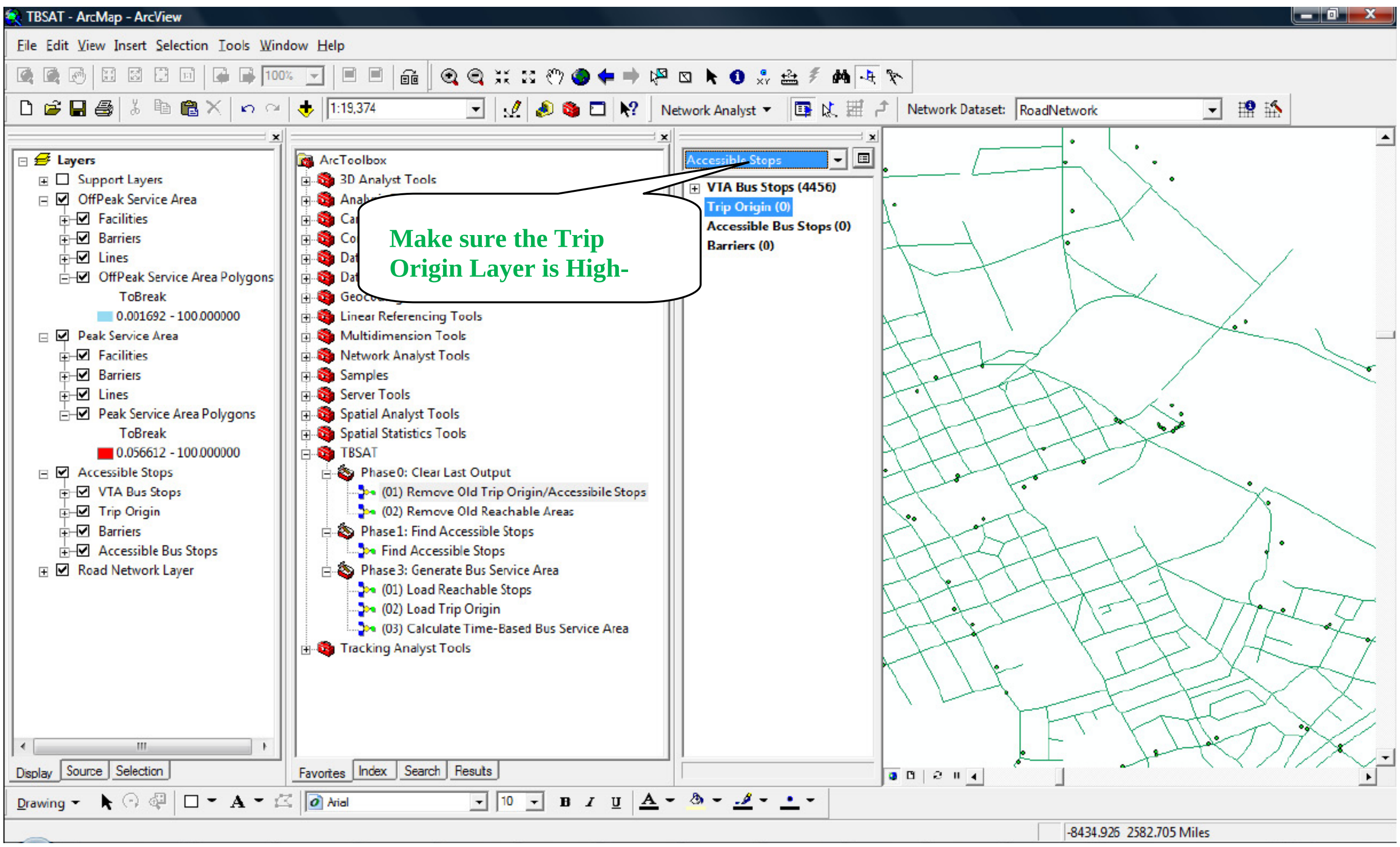

Figure 38: Highlight the Trip Origin Layer before Adding the Trip Origin

2. Use Address Finder

The second way to add the trip origin is to use the binocular shape  *Address Finder*. After inputting the address of the desired trip origin in the pop-up address finder window as shown in Figure 39, TBSAT users can right-click on the location founded in the bottom of the "Find" widow and then click on the "*Add as Network location*" to add the desired trip origin into TBSAT. Similar to adding the trip origin using the add location tool, please make sure that the "*Accessible Stops*" appears in the *Network Analysis Layer List* box and highlight the *Trip Origin* layer by left-clicking on it before adding the trip origin.

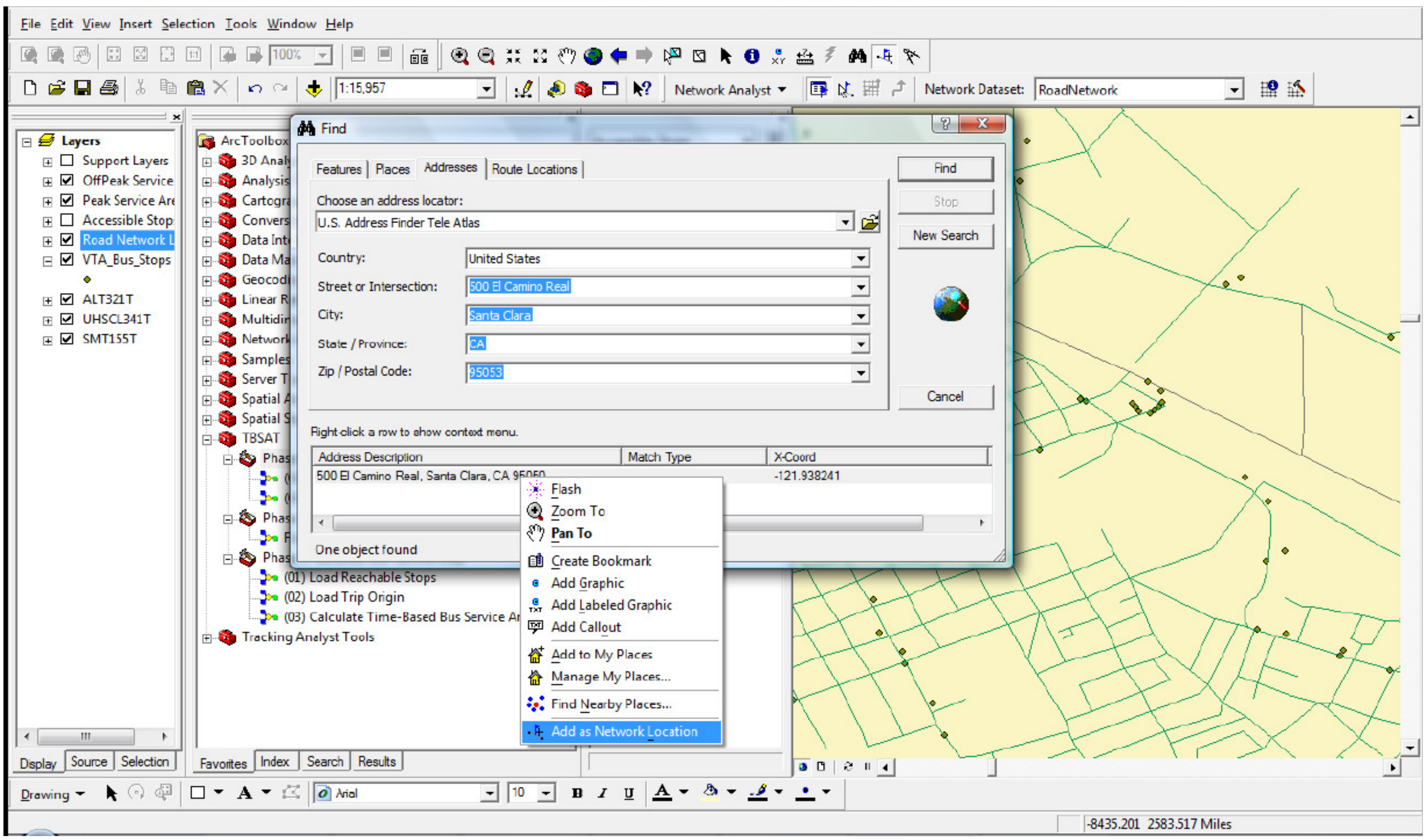

Figure 39: Add Trip Origin Using Address Finder

Once the location of the trip origin is specified, the trip origin will be shown as a square in the map window, as shown in the following Figure 40.

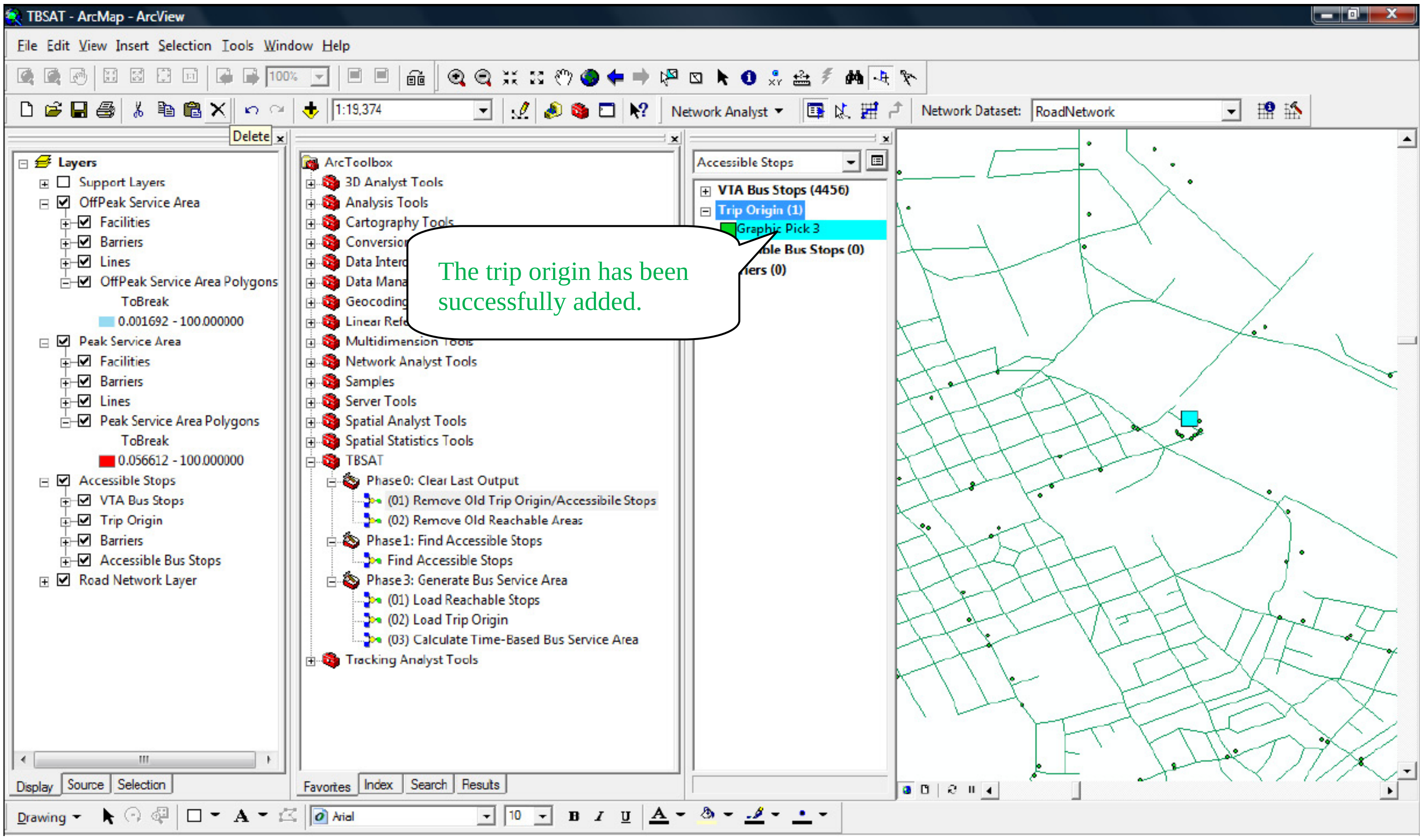

Figure 40: Adding the Trip Origin Successfully

Step 4: Specify Acceptable Access Distance

In this step, users are required to input the acceptable access distance into TBSAT. Acceptable access distance represents the maximum distance people are willing to travel from the trip origin to the bus stops. The value of the acceptable access distance is determined by users' pre-determined *Access Speed* and *Acceptable Access Time*. Users have to multiply the access speed with the acceptable access time to gain the acceptable access distance. TBSAT provides the *Acceptable Access Distance Calculator* to assist users with this. By clicking the compass icon, the acceptable access distance calculator will pop-up. Once the user's desired access speed and acceptable access time are entered, by clicking the "*Calculate*" button the acceptable access distance will be automatically calculated and shown in the bottom box of the calculator as shown in the following Figure 41.

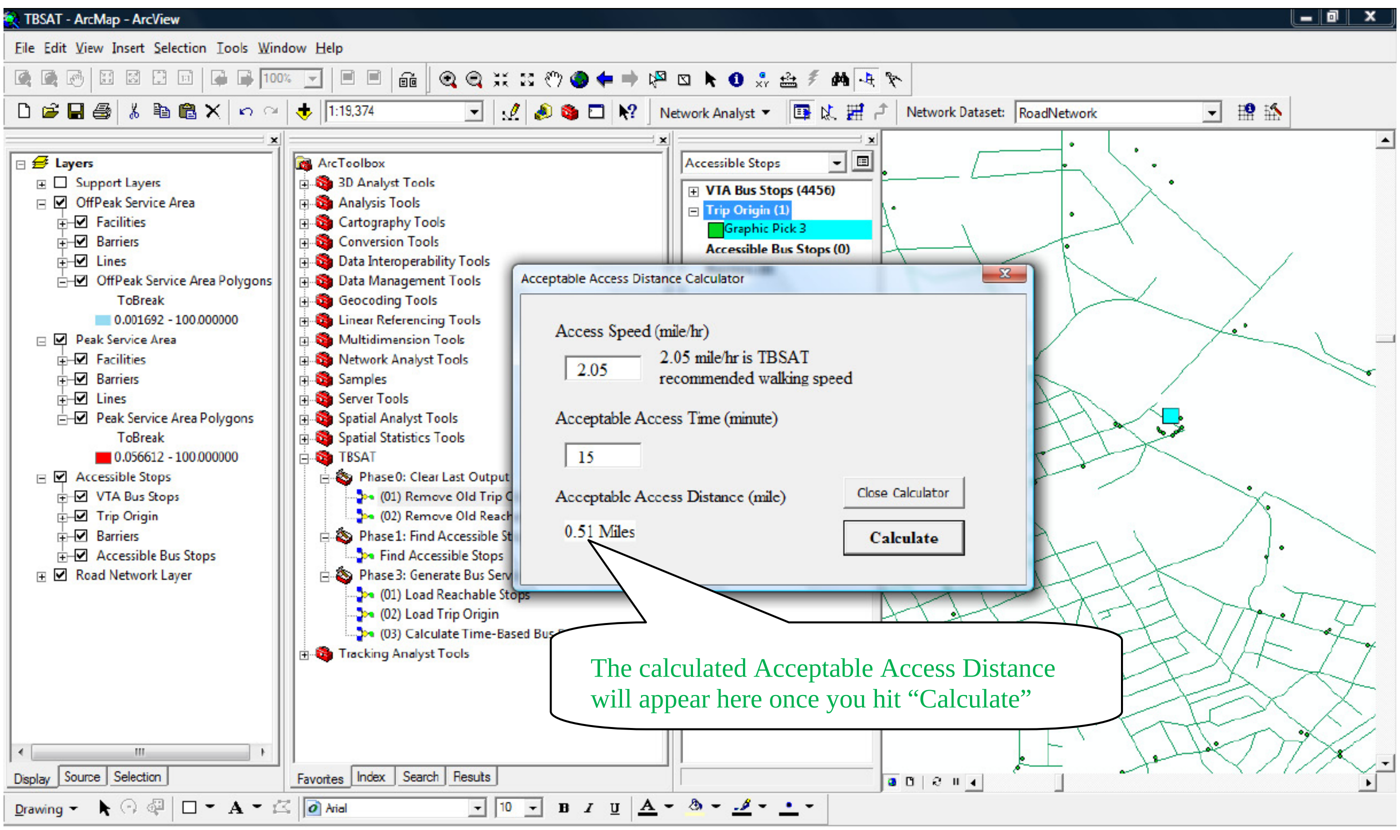

Figure 41: Acceptable Access Distance Calculator

Then, the converted acceptable access distance must be manually entered into the *default cutoff* field of the *Accessible Stops Layer* as shown in Figure 42. To do this, users have to open the *Network Analysis Layer Property Box* of *Accessible Stops Layer* by clicking the property button  when "Accessible Stops" appears in the *Network Analysis Layer List* box. Then, as shown in Figure 42, in the property window, users have to switch to the "Analysis Setting" tab and type-in value of the acceptable access distance into the "*Default Cutoff*" box. After the input is complete, users can hit the "OK" button and close the property window.

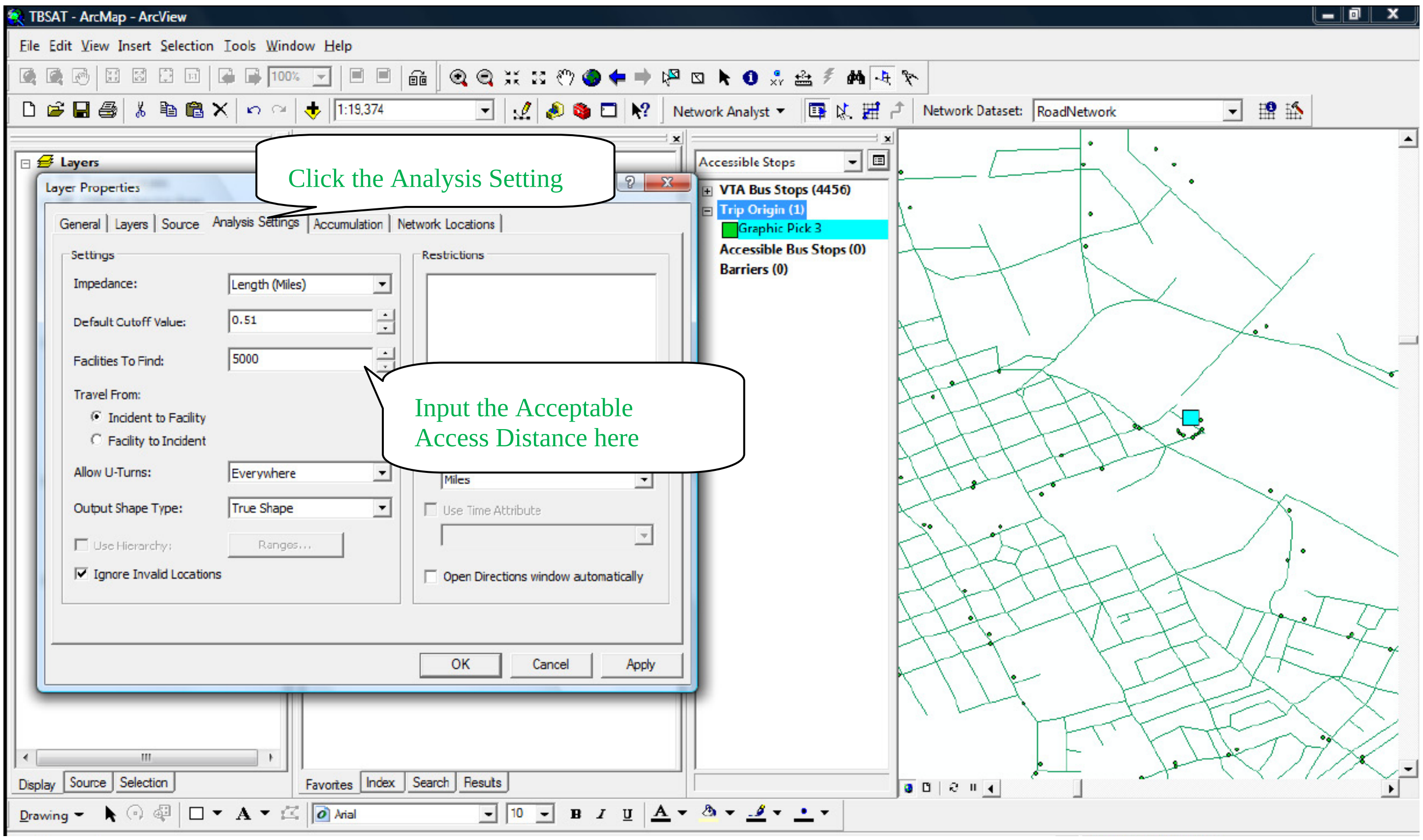

Figure 42: Input Acceptable Access Distance

The six actions involved in this step are listed in Table 26:

Table 26: Procedure to Complete Step 4

Step 4 Procedure	
1	Obtain Acceptable Access Distance using Acceptable Access Distance Calculator
2	Select "Accessible Stops" in the Network Analysis Layer List Box
3	Click the property button
4	In the pop-up property window, switch to "Analysis Setting" tab
5	Enter the obtained Acceptable Access Distance in the Default Cutoff box
6	Click "OK" to close the property window

Step 5: Generate List of Accessible Stops

By double-clicking the Find Accessible Stops tool in the Phase 1: Find Accessible Stops toolset, the list of accessible bus stops will be generated as the input for the subsequent step. After running this step, users may save TBSAT.mxd and close TBSAT.mxd.

Step 6: Open TBSATDB.accdb

In this step users will move to the database component of TBSAT. When opening the TBSATDB.accdb file, the factor setting form will be displayed.

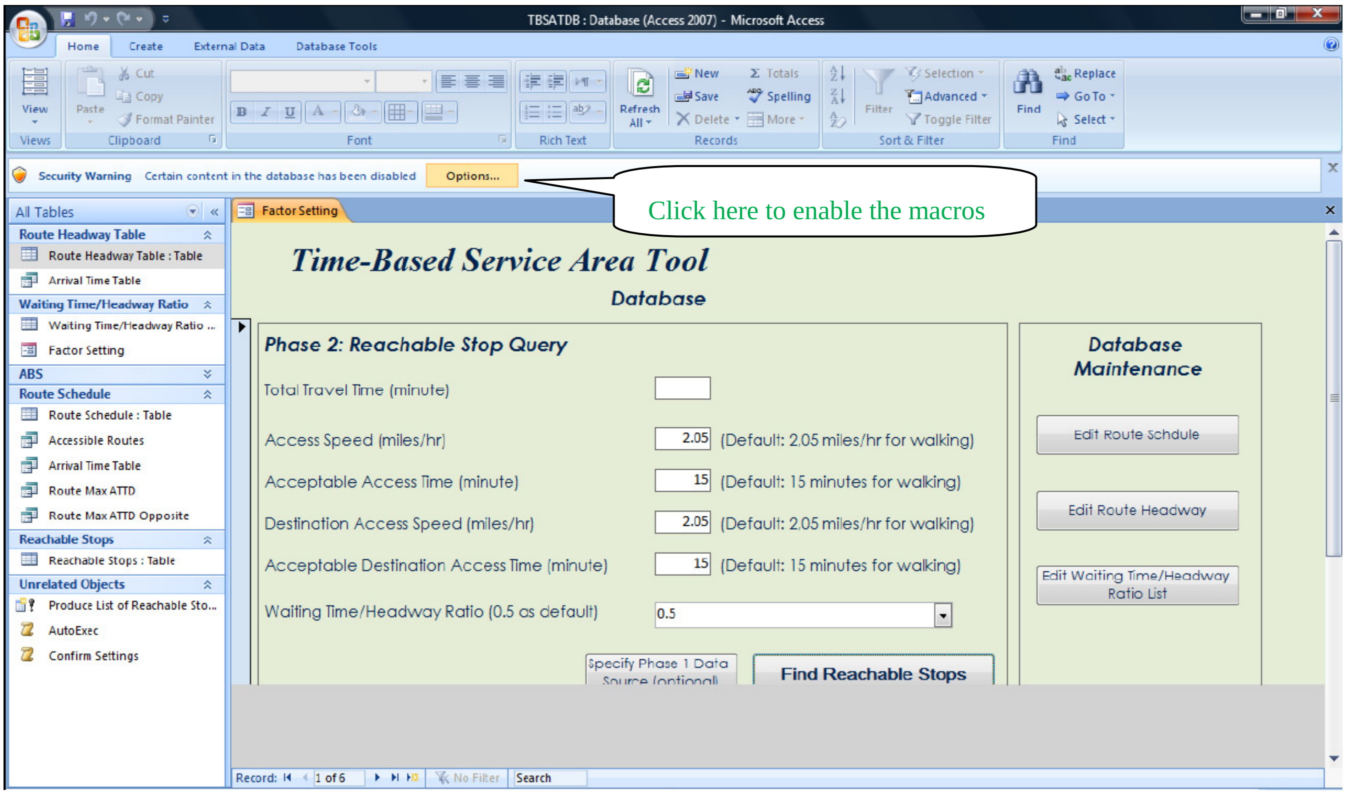

Figure 43: Enable Macros in TBSATDB.accdb

As shown in Figure 43, to make the database work properly, users must first enable the functioning of macros by clicking the "*Options*" button and choosing "Enable this content".

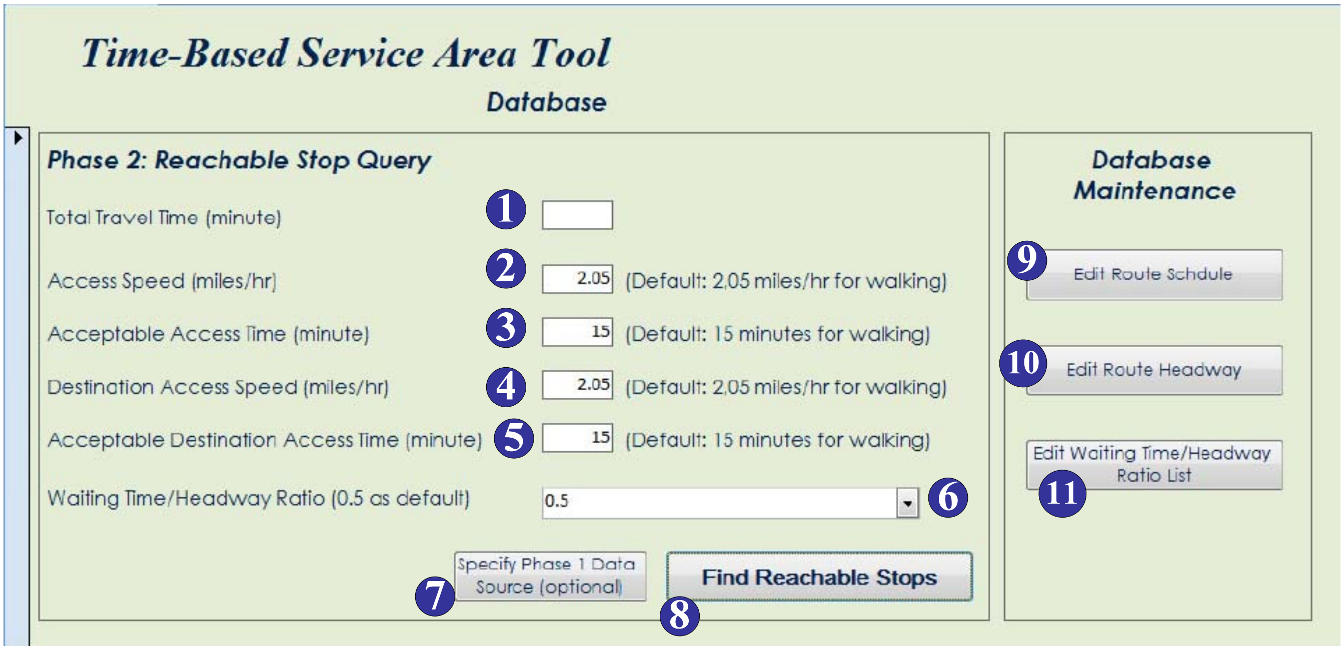

Figure 44: The Factor Setting Form in TBSAT.accdb

❶ Total Travel Time

Users must input the total travel time into this box.

❷ Access Speed

Users must input the access speed into this box.

❸ Acceptable Access Time

Users must input the acceptable access time into this box. The value in this box must conform to the acceptable access time entered in step 4.

❹ Destination Access Speed

Users must input the destination access speed into this box.

❺ Acceptable Destination Access Time

Users must input the acceptable destination access time into this box.

❻ Waiting Time/Headway Ratio

As described above, TBSAT assumes that bus riders always need to wait for half of the bus frequency at the bus stop before their desired bus arrives. Thus, the default waiting time/headway ratio is 0.5 here. However, TBSAT users may choose a different ratio according to users' pre-determined traffic condition by opening the drop-down list here. Furthermore, if none of the values in this list conforms to users' pre-determined condition, users may manually input the desired waiting time/headway ratio into this box.

7 Specify Phase 1 Data Source

This function is for advanced users who do not place the entire TBSAT in C:\TBSAT but in another location. The result of step 5, which is the list of accessible stops named ABS.dbf, is saved in C:\TBSAT\AccessibleStops\ABS.dbf by default. However, if the entire TBSAT is not placed in C:\TBSAT, the location of ABS.dbf will change. The "*Specify Phase 1 Data Source*" function is for users to specify the correct location of ABS.dbf when users are placing TBSAT in a directory other than C:\TBSAT.

8 Find Reachable Stops

After inputting all six factors in the factor setting form, by clicking this button TBSATDB will execute a series of processes and generate the list of reachable stops for phase 3 of TBSAT operation.

9 Edit Route Schedule

This is designed for TBSAT system/database maintainers. This button will open the *Route Schedule* table in TBSATDB.accdb and allow maintainers to update the bus route schedule.

10 Edit Route Headway

This is designed for TBSAT system/database maintainers. This button will open the *Route Headway* table in TBSATDB.accdb and allow maintainers to update the route headway information for each bus route.

11 Edit Waiting Time/Headway Ratio List

This is designed for TBSAT system/database maintainers.

This button will open the *Waiting Time/Headway Ratio* table in TBSATDB.accdb and allow maintainers to update the list of the suggested waiting time/headway ratios.

Step 7: Generate List of Reachable Stops

After opening the TBSATDB.accdb, users simply have to enter the value for the six factors from item 1 to 6 and click the "*Find Reachable Stops*" button. After a series of confirmations (clicking "OK" or "Yes" for all pop-up windows), users will be prompted to save a file titled *reachable stops.xls*. Please navigate to C:\TBSAT and replace the old *reachable stops.xls* in the C:\TBSAT folder. After reachable stops.xls is successfully saved, users may close the database and proceed to next step.

Step 8: Load Reachable Stops

After opening the TBSAT.mxd that saved in step 5, double-click on the (01) Load Reachable Stops tool so that TBSAT can load the reachable stops.xls generated in step 7 into ArcGIS.

Step 9: Load Trip Origin

In order to correctly display the time-based bus service area, in this step users have to load the location of the trip origin to both the *Peak Service Area* layer and the *OffPeak Service Area* layer. To do this, simply double-click on the (02) Load Trip Origin tool and then TBSAT will automatically load the location of the trip origin to both layers.

Step 10: Specify Acceptable Destination Access Distance

Similar to step 4, the *Destination Access Speed* and the *Acceptable Destination Access Time* must be converted into the *Acceptable Destination Access Distance* using the *Acceptable Access Distance Calculator* as shown in Figure 45.

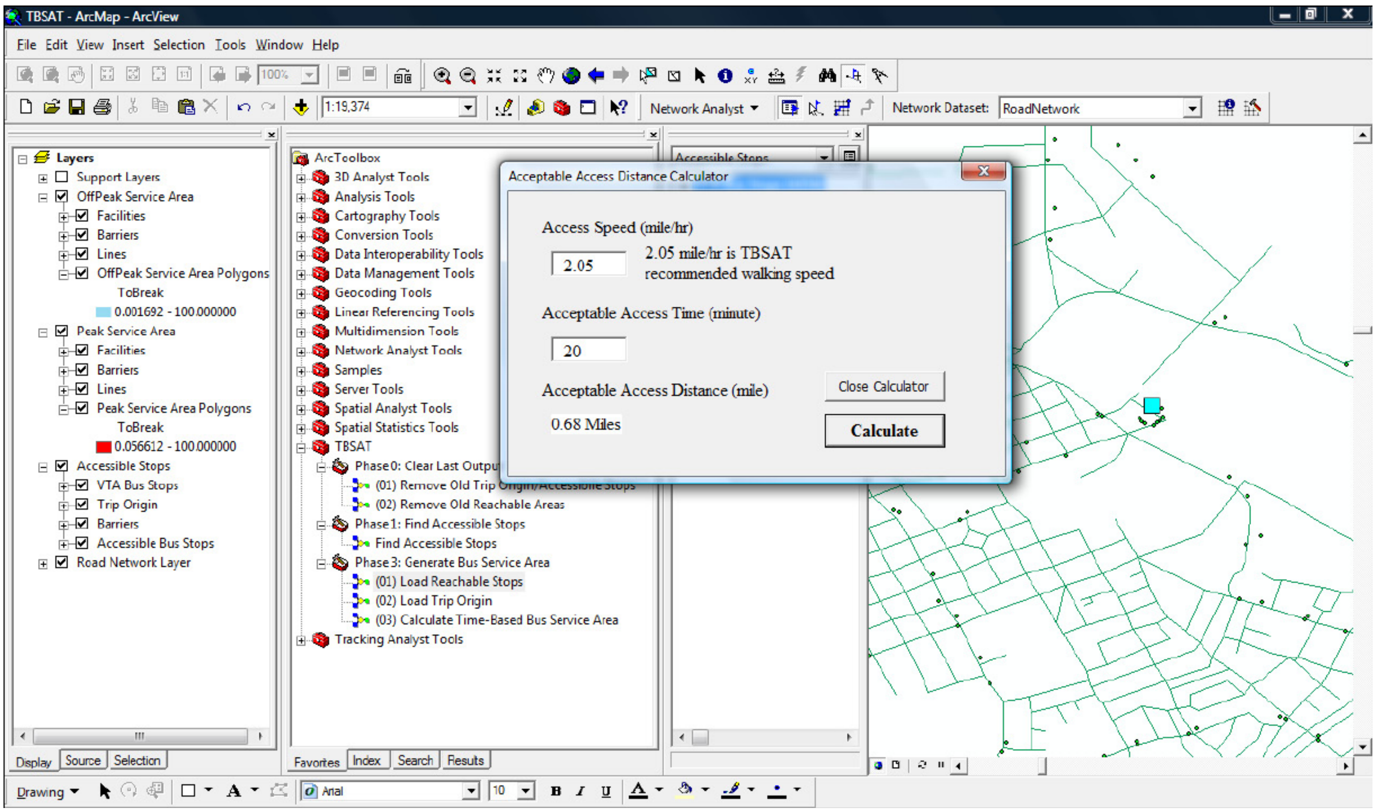

Figure 45: Obtain Acceptable Destination Access Distance using Acceptable Access Distance calculator

In Figure 45, the destination access speed is 2.05 mph and the acceptable destination access time is 20 minutes. As a result, the acceptable destination access distance of 0.68 miles is obtained after clicking the "*Calculate*" button. This obtained value must be input into the *Peak Service Area layer* and the *OffPeak Service Area layer*.

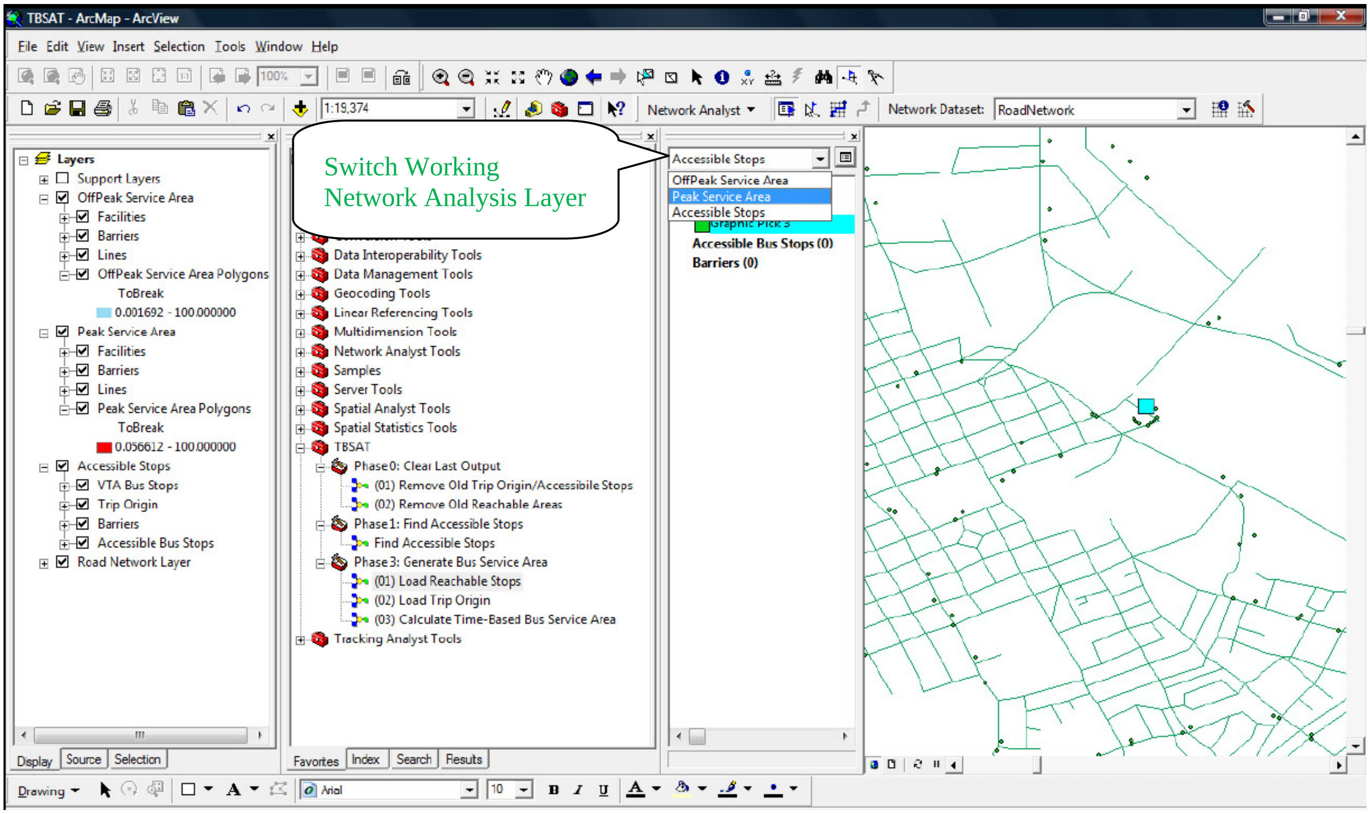

Figure 46: Switch Working Network Analysis Layer to Peak Service Area Layer

First, users have to switch the current working network analysis from "*Accessible Stops*" to "*Peak Service Area*" by choosing the Peak Service Area Layer in the *Network Analysis Layer List* as shown in Figure 46.

Second, as shown in Figure 47, by selecting the property button  when "*Peak Service Area*" appears in the *Network Analysis Layer List box*, the property window of the Peak Service Area will appear.

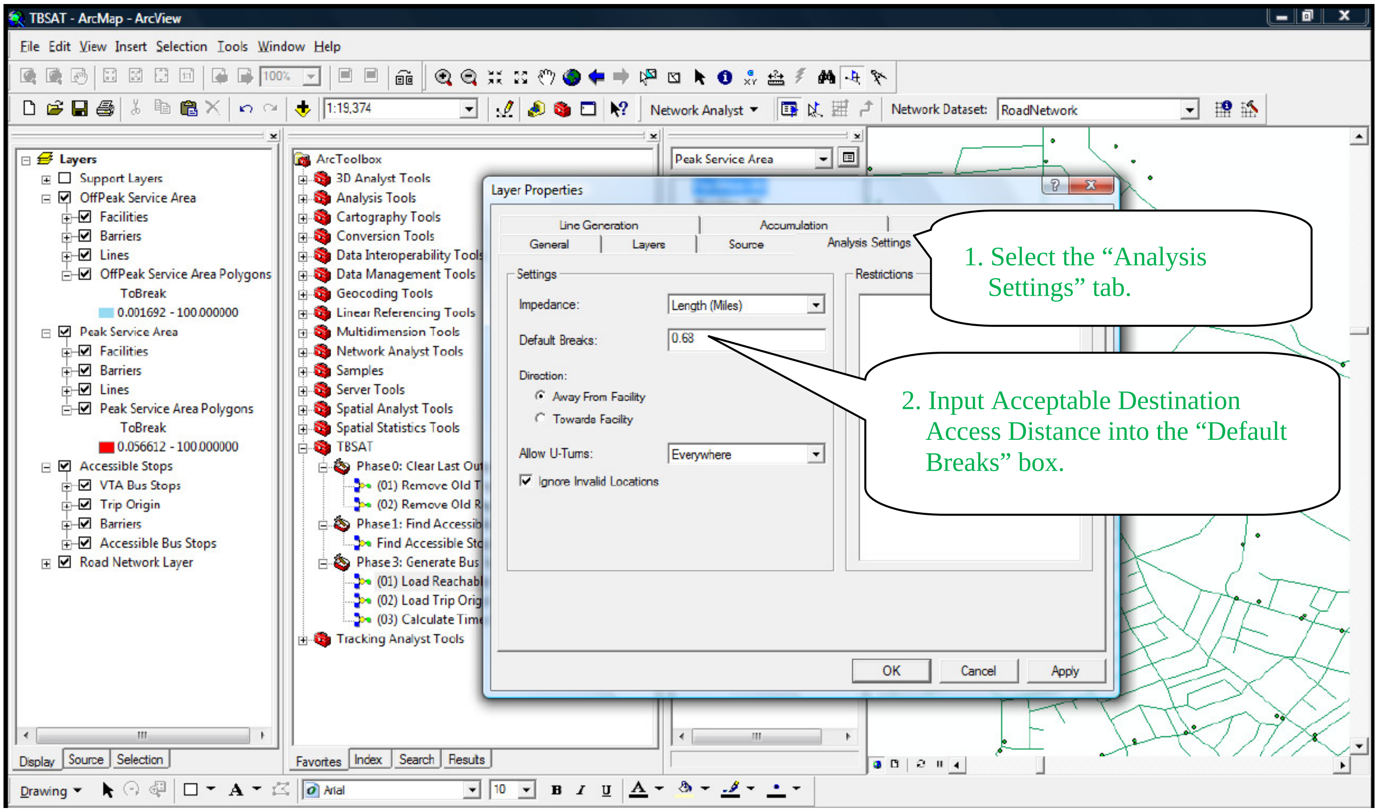

Figure 47: Input Acceptable Destination Access Distance into Default Breaks Box

By selecting the "*Analysis Setting*" tab in the pop-up window, users will see the input box for "*Default Breaks*" .The converted acceptable destination access distance should be entered here. Then, click "OK" to close the property window.

Now users have to repeat the action of switching network analysis layer, opening property window, and inputting the acceptable destination access distance as the default breaks. The only difference is this time users must switch the current working network analysis from "*Accessible Stops*" to "*OffPeak Service Area*" instead of the "*Peak Service Area*" layer.

Step 11: Generate Time-Based Bus Service Area

The last step of a TBSAT run is to double-click the (03) Calculate Time-Based Bus Service Area tool after steps 1 to 10 are successfully and correctly completed.

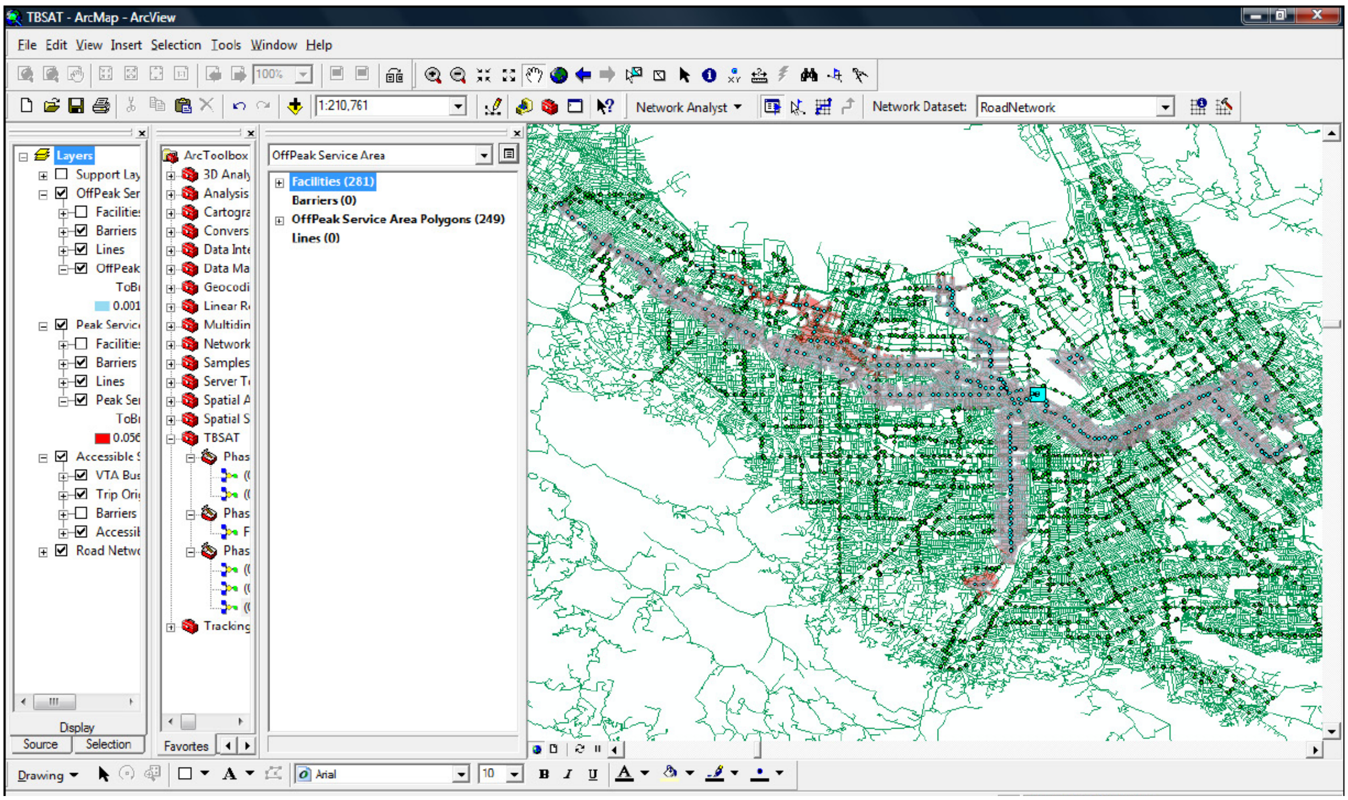

Figure 48: Generated Time-Base Bus Service Areas

As shown in Figure 48, the generated time-based bus service area will appear in the map window. The light blue area is the **off-peak** time-based bus service area of the selected location in the users' pre-determined travel time limit and the light red area is the **peak** time-based bus service area. Both service area polygons are saved as "*TBSA_Peak*" and "*TBSA_Offpeak*" respectively in the personal geodatabase file named *TBSAT_Merged_Service Area*.

Appendix B: DEFAULT ACCESS SPEED

In section 4.1.5, the default access speed is suggested to be 2.05 mph. Such recommendation comes from the research of the following review of three types of studies: Design guidelines for planning purpose, survey results, and medical studies on physical capability of men.

Walking Speed Suggestions from Design Guidelines

Design guidelines for planning usually suggest walking speeds as a reference for planners/engineers who are responsible to the design of walking environment. A suggested design walking speed that is frequently referenced in transportation engineering comes from U.S. Federal Highway Administration's (FHWA) Manual on Uniform Traffic Control Devices (MUTCD). 4 ft/s (2.73 mph) is suggested by MUTCD as the regular design pedestrian walking speed.[34] However, the lowest suggested walking speed in the latest 2007 provisional update of MUTCD suggests is much lower: 3 ft/s (2.05 mph). [35] The purpose to this change is due to the walking behavior change in recent years.

Peter Calthorpe, on the other hand, suggests a design walking speed of 2.27 mph when designing a transit-oriented environment. This rough value includes many external factors which obstacle pedestrian movements such as traffic, hill gradient, and rivers.[36] Frank Tenser indicates a design walking speed of 4km/hr (2.49 mph) in his study of designing access to health care facilities.[37] James L. Pline suggests using a speed between 0.91m/sec (2.05 mph) and 0.99m/sec (2.26 mph) as the design walking speed.[38] Focusing on traffic-interrupted pedestrian walking behavior, J.S. Milazzo's study suggests a walking speed of 4 ft/sec (2.73 mph),[39] which is the same value of the 2004 MUTCD suggestion.

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[34] Federal Highway Administration, "Manual on uniform traffic control devices," (November 2004), 4C-6. <http://mutcd.fhwa.dot.gov/pdfs/2003r1/Ch4.pdf > [May 5, 2008]

[35] Federal Highway Administration, "2007 notice of proposed amendments for the manual on uniform traffic control devices," (2007), 322. <http://mutcd.fhwa.dot.gov/resources/proposed_amend/npa_text.pdf> [May 5, 2008]

[36] Peter Calthorpe, *The next American metropolis: ecology, community, and the american dream.* (New York: Princeton Architectural Press,1993).

[37] Frank Tanser, Brice Gijsbertsen, and Kobus Herbst, "Modeling and understanding primary health care accessibility and utilization in rural south africa: An exploration using a geographical information system," *Social Science & Medicine* 63, no. 3 (2006).

[38] James L Pline, *Traffic engineering handbook,* 4th ed. (Englewood Cliffs, N.J: Prentice-Hall, 1992).

[39] J.S Milazzo II, M. Rouphail, J.E. Hummer, and D.P. Allen, "Quality of service for interrupted-flow pedestrian facilities in highway capacity manual 2000," *Transportation Research Record* 1678 (1999).

Walking Speed Suggestions from Survey Analysis

Previous surveys maybe the largest source which provides suggestions on pedestrian walking speed because walking speed estimate itself is an empirical value which can be only identified by survey or observation. Numerous surveys that cover different factors involved in human's walking behavior were conducted in the past. From the results of those surveys we could expect some reasonable values to help us deciding the default walking speed in TBSAT.

In the survey conducted by A. Coffin, which focuses on the difference on walking speed between general adults and elderly, the mean walking speeds in gender-specific observations are 1.24 m/sec (2.77 mph) for woman and 1.29 m/sec (2.89 mph) for men. The 15th percentile walking speeds for the elderly in various conditions which are founded in this survey fall between 1 m/sec to 1.2 m/sec (2.24 to 2.68 mph). As a result, A. Coffin suggests a design walking speed of 1.0 m/sec (2.24 mph).[40]

Another study conducted by Xiong Hui focuses on the transportation engineering aspect of pedestrian walking behavior. By observing detail pedestrian movement including walking speed, step frequency, and step size on the street this study has deep discussion regarding to walking. In this study the mean walking speed of all observations is 1.22 m/sec (2.73 mph)[41].

Mohammed S. Tarawneh's study takes various factors such as age, gender, into consideration during obtaining empirical walking speed. Tarawneh's research took place in Jordan and the final observed average walking speed is 1.34 m/s (3 mph) and a design standard of 1.11m/s (2.49 mph), which is the 15th percentile speed of the entire study, is suggested[42].

In 2006 Jeannette Montufar announced a study which particularly observes the difference in pedestrian walking speed when walking along the street and walking across the street. This study identifies that the 15th percentile normal walking speed (speed when pedestrian walking along the street) for young people and elderly are 1.1 m/sec (2.46 mph) and 0.88 m/sec (1.97 mph) respectively. On the other hand, the 15th percentile crossing speed for young people and elderly are 1.33 m/sec (2.98 mph) and 1.08 m/sec (2.42 mph) respectively. This research also compares the research results with the design speed of 2004 U.S. MUTCD standard and the proposed 2006 MUTCD standard. The conclusion of this report indicates a design speed of 3.0 ft/sec (2.05 mph) will be able to accommodate more than half

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[40] A. Coffin and J. Morrall, "Walking speeds of elderly pedestrians at crosswalks," *Transportation Research Record* 1487 (1995).

[41] Xiong Hui, Lv Jian, Jiang Xiaobei, and Li Zhenshan, "Pedestrian walking speed, step size & step frequency from the perspective of gender and age: A case study in beijing, China," in *86th Transportation Research Board Annual Meeting. Congress Held in Washington D.C. January 2007*.

[42] Amr Mohammed, Amer Shalaby, and Eric J Miller, "An empirical analysis of transit network evolution: case study of the mississauga, Ontario bus network," in *85th Transportation Research Board Annual Meeting, Congress Held in Washington, D.C January 2006*.

of the elderly pedestrians when they are walking along the street or crossing the streets.

Table 27: Walking Speed vs. Crossing Speed

Unit: mph	15th Percentile Normal Walking Speed	15th Percentile Crossing Walking Speed
Young People	2.46	2.98
Elderly	1.97	2.42
Old MUTCD Standard: 2.73 mph		
New MUTCD Standard: 2.05 mph		

Reproduction: Chao-Lun Cheng

Source: The Normal Walking Speed of Pedestrians and How Fast They Walk When Crossing the Street.[43]

Another field study conducted by Richard L. Knoblauch suggests a series of design standards regarding to pedestrian walking speed. After observing 7,123 pedestrians, two design walking speed values are proposed, one for younger pedestrian and one for elderly pedestrian. Knoblauch's study breaks people into younger people and elderly people by age of 65. By observing the walking speed of these two groups under different conditions including gender, day of week, weather condition, wind, temperature, and street classification Knoblauch's study has a result of concluding the mean walking speed of younger people as 1.25 m/sec (2.8 mph) and the mean walking speed for elderly people as 0.97 m/sec (2.17 mph). For design purpose the walking speed for younger people can be 1.22 m/sec (2.73 mph) and 0.91 m/sec (2.04 mph) for elderly people. The observation of Knoblauch's study took place at four different urban areas (Richmond, Virginia; Washington, D.C.; Baltimore, Maryland; and Buffalo, New York).

[43] Jeannette Montufar, Jorge Arango, Michelle Porter, and Satoru Nakagawa, "The normal walking speed of pedestrians and how fast they walk when crossing the street," in *86th Transportation Research Board Annual Meeting Congress Held in Washington D.C.*, 2007.

Walking Speed Suggestions from Medical Research

Another important resource which describes about people's walking behavior is medical studies, which specifically measure people's ordinary walking behavior in detail in order to compare the physical fitness between patients and healthy people.

Table 28: Suggestions on Design Walking Speed

Suggested Walking Speed mph	Source TYPE	Source	Note
Crossing Speed Suggestions			
2.04	Survey	Richard L. Knoblauch	Elderly Crossing Speed
2.05	Governmental Manual	Manual on Uniform Traffic Control Devices (Proposed Renewal)	Crossing Speed
2.05 - 2.26	Design Guideline	James L Pline	Crossing Speed
2.05	Survey	Jeannette Montufar	Suggested Crossing Speed
2.24	Survey	A. Coffin	Suggested Crossing Speed
2.73	Governmental Manual	Manual on Uniform Traffic Control Devices	Crossing Speed
2.73	Survey	Richard L. Knoblauch	Youth Crossing Speed
Normal Walking Speed Suggestions			
1.97	Survey	Jeannette Montufar	Elderly Normal Walking Speed
2.49	Design Guideline	Frank Tanser	Normal Walking Speed
2.27	Design Guideline	Peter Calthorpe	Normal Walking Speed
2.35	Medical Research	Adam Graf	Normal Walking Speed
2.46	Survey	Jeannette Montufar	Youth Normal Walking Speed
2.49	Survey	Tarawneh	Normal Walking Speed
2.49	Medical Research	Marius Henriksen	Normal Walking Speed
2.57	Medical Research	Rezaul Begg	Normal Walking Speed
2.73	Survey	Xiong Hui	Normal Walking Speed
2.8	Medical Research	G.A. Lichtwark	Normal Walking Speed

In Adam Graf's study, a healthy, comfortable "gait" speed of 1.05 m/sec (2.35 mph) is suggested.[44] On the other hand, a study conducted by Marius Henriksen suggests another standardized walking speed of 4 km/hr (2.49 mph) by performing a gait data analysis.[45] In another medical walking data collection/analysis, Rezaul Begg produced another walking speed suggestion, which is 1.15 m/sec (2.57 mph) for young people and 0.88 m/sec (1.97 mph) for the elderly.[46] In one of Coen H. van Gool's study which compares the walking behavior of obese people and the general public, an average walking speed of the general public of 1.16 m/sec (2.59 mph) can be found. Finally, G.A. Lichtwark's study, which analyze people's health condition in when walking and running, has a 2.8 mph result regarding to the average walking speed of human.

By referencing various types of previous studies we can find the walking speed suggestion ranges from 1.97 mph to 2.8 mph. For design purpose we expect the default walking speed can be applied for 85% of the population. Both the proposal of the latest version of MUTCD and Jeannette Montufar's suggest a design walking speed of 2.05 mph to include most of the population. As a result, TBSAT suggests 2.05 mph as the default access speed V_a when walking is to be the mean of accessing to boarding bus stop.

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[44] Adam Graf et al, "The effect of walking speed on lower-extremity joint powers among elderly adults who exhibit low physical performance," *Archives of Physical Medicine and Rehabilitation* 86, no. 11 (2005).

[45] Marius Henriksen et al, "Increased joint loads during walking – a consequence of pain relief in knee osteoarthritis," *The Knee* 13, no. 6 (2006).

[46] Rezaul Begg, et al, "Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls. " *Gait & Posture* 25, no. 2 (2007).

Appendix C: DEFAULT ACCEPTABLE ACCESS TIME

In this research, acceptable access time is identified as one of the important factors that constrain the number of bus stops which can be directly accessed from the trip origin.

Since walking appears to be the major mode people use to access bus, TBSAT suggests an acceptable walking time as the default acceptable access time that appears in the TBSAT input interface.

The following discussion collects suggestions for both maximum walking time and maximum walking distance because distance can be converted into walking time by using walking speed.

Table 29: Suggestions on Acceptable Walking Time

Suggested Acceptable Walking Time	Source	Note
0.19 - 0.25 mile	Ammons	
0.25 mile	Sun	
0.25 mile	Murray	
0.25 mile	Weinstein	25th percentile walkable distance
0.3 mile	Mazza	
0.328 mile	Weinstein	The research result of 9.6 minutes is converted into 0.328 mile according to walking speed 2.05 mph
0.38 mile	Calthorpe	
0.5 mile	Weinstein	50th percentile walkable distance
0.5 mile	Zimring	
0.5 mile	Cottrell	
0.5 mile	Pikora	If Trip Purpose is to access Public Transportation
0.512 mle	Sorensen	The research result of 15 minutes is converted into 0.512 mile according to walking speed 2.05 mph

David N. Ammons proposes a maximum walkable distance between 300 to 400 meters (0.19 mile to 0.25 mile).[47] In Sun Sheng Han's research regarding to the neighborhood design, 400 meters (0.25 mile) is proposed as the maximum walking distance.[48] Alan T Murray's research regarding to the public transportation access also takes 400 meters (0.25 mile) as the comfortable walking distance to general public.[49] L. Mazza, on the other hand, defined the maximum walkable distance as 500 meter (0.3 mile) by observing the environment of four British cities (Bologna, Edinburgh, Florence and Leicester.)[50]

In André Sorensen's study, three distances are suggested as the walkable range. A distance within 5 minutes walking is the preferred distance for excellent marketability. A 10-minute walking distance is essential to both business and the ridership. At last, a walking distance within 15 minutes is recognized as the comfortable distance for transit users.[51] If we use our suggested walking speed of 2.05 mph to convert 15 minutes into length, we can find out that a 15-minute walking is approximately to be 0.5 mile long.

A study by Asha Weinstein focuses on the pedestrian walking pattern by analyzing NHTS (National Household Travel Survey) and gives statistics-based information regarding to the walkable distance. In NHTS data, the average walking time for people who walk to transit station is 9.6 minutes, which can be converted into 0.33 mile by using our default walking speed of 2.05 mph.[52] In Peter Calthorpe's study, the maximum walking distance is suggested to be 2000 feet (0.38 mile). According to Calthorpe's assumption of walking speed, which is 2.27 mph, the 2000 feet distance can be converted into 10 minute of walking.[53]

In another study of pedestrian walking pattern of Marc Schlossberg which is based on field surveys, a 50th percentile walkable distance of appromixate 0.5 mile is found and the 25th percentile walkable distance is 0.25 mile.[54] In Craig Zimring's study discussing

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[47] David N. Ammons, *Municipal Benchmarks: Assessing local performance and establishing community standards*, 2th ed. (Thousand Oaks: Sage Publications, Inc, 2001).

[48] Sun Sheng Han, "Global city making in Singapore: A real estate perspective," *Progress in Planning* 64, no. 2 (2005).

[49] Alan T. Murray, et al, "Public transportation access," *Transportation Research Part D: Transport and Environment* 3, no. 5 (1998).

[50] L. Mazza and Y. Rydin, "Urban sustainability: Discourses, networks and policy tools," *Progress in Planning* 47, no. 1 (1997).

[51] André Sorensen, "Land readjustment and metropolitan growth: An examination of suburban land development and urban sprawl in the Tokyo metropolitan area," *Progress in Planning* 53, no. 4 (2000).

[52] Asha Weinstein and Paul Schimek, "Extent and correlates of walking in the USA: An analysis of the NHTS," *Transportation Research Part D: Transport and Environment* 12, no. 8, (December 2007).

[53] Peter Calthorpe, *The next american metropolis: ecology, community, and the american dream* (New York: Princeton Architectural Press, 1993).

[54] Marc Schlossberg, et al, "How far, by which route, and why? A spatial analysis of pedestrian preference," in *86th Transportation Research Board Annual Meeting* (Washington D.C.: Transportation Research Board, 2007).

about the relationship between site planning and human's physical activity a similar suggestion regarding to the maximum walking distance, which is within 0.25 mile and 0.5 mile, is proposed.[55] In Wayne D. Cottrell's study which focuses on relating bus transportation with land use development, it is also suggested that 0.5 mile could be the maximum walkable distance.

Finally, a valuable pedestrian walking pattern survey conducted by T J Pikora analyses the distance from the trip generation point of transit riders to their boarding station. Traditional travel behavior surveys asks test-takers about the distance they have walked, which could be lack of precision due test-takers' sense in distance. Pikora's survey asks the location of the trip generation point and the boarding station of test-takers and then accurately measure the walking distance those test-takers actually walked through GIS techniques. An important finding from Pikora's study is that people are willing to walk longer than they usually want to if the purpose of the walking is to take public transportation. The result of Pikora's study indicates that people usually walk for less than 400 meters (0.25 mile). However, people are willing to walk for 800 meters (0.5mile), which is twice longer than they usually can tolerate if the purpose of the trip is to walk to public transportation station.[56]

By reviewing all the obtained suggestions regarding to acceptable walkable distance, TBSAT takes 0.5 mile as its default acceptable access distance and this distance can be converted into an acceptable access time of **14.63 minutes** according to the TBSAT suggested access speed (2.05 mph). Although 14.63 minutes (0.5 mile) is higher than some of the suggestions above, it still can be considered as proper if we believe that, if the purpose of walking is to access public transportation, people are willing to walk longer than they usually are. To simplify the computation, the default acceptable access time (AAT) in TBSAT will be **15 minutes**.

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[55] Craig Zimring et al, "Influences of building design and site design on physical activity: research and intervention opportunities," *American Journal of Preventive Medicine* 28, no. 2 (2005), 188.

[56] T J Pikora, B Giles-Corti, and R Donovan, "How far will People walk to facilities in their local neighbourhoods," in *Australia: Walking the 21st Century Congress Held in Perth, Western Australia:* Department of Planning and Infrastructure, Government of Western Australia, 2001), 26.

Appendix D: DATA PREPARATION FOR THE SCTC APPLICATION

In Chapter 5, five scenarios describe the bus accessibility of the SCTC under different conditions through the application of TBSAT. Before running TBSAT according to the settings in five scenarios, two types of information are required to be prepared and input into the TBSAT components.

The first required information is the existing path map of Santa Clara County. As discussed in section 4.1.3 and section 4.5.2, the existing path map allows TBSAT to find accessible bus stops around the SCTC as well as to generate service area along the existing paths from each bus stop that can be reached within the travel time limit from the SCTC.

The second required information is the bus service information including the location of the bus stops, the route schedule (timetable) of the routes available around the SCTC, and the headway (frequency) during peak and off-peak of the routes available around the SCTC. Due to the limited amount of time, in this application, only the route information of 11 VTA bus routes has been input into the TBSAT database. These eleven input bus routes are route 10, route 22, route 23, route 32, route 58, route 60, route 68, route 81, route 304, route 328 and route 522. They are estimated accessible from the SCTC within approximately 3 miles. Figure 49 indicates the location of the bus stops on these 11 bus routes.

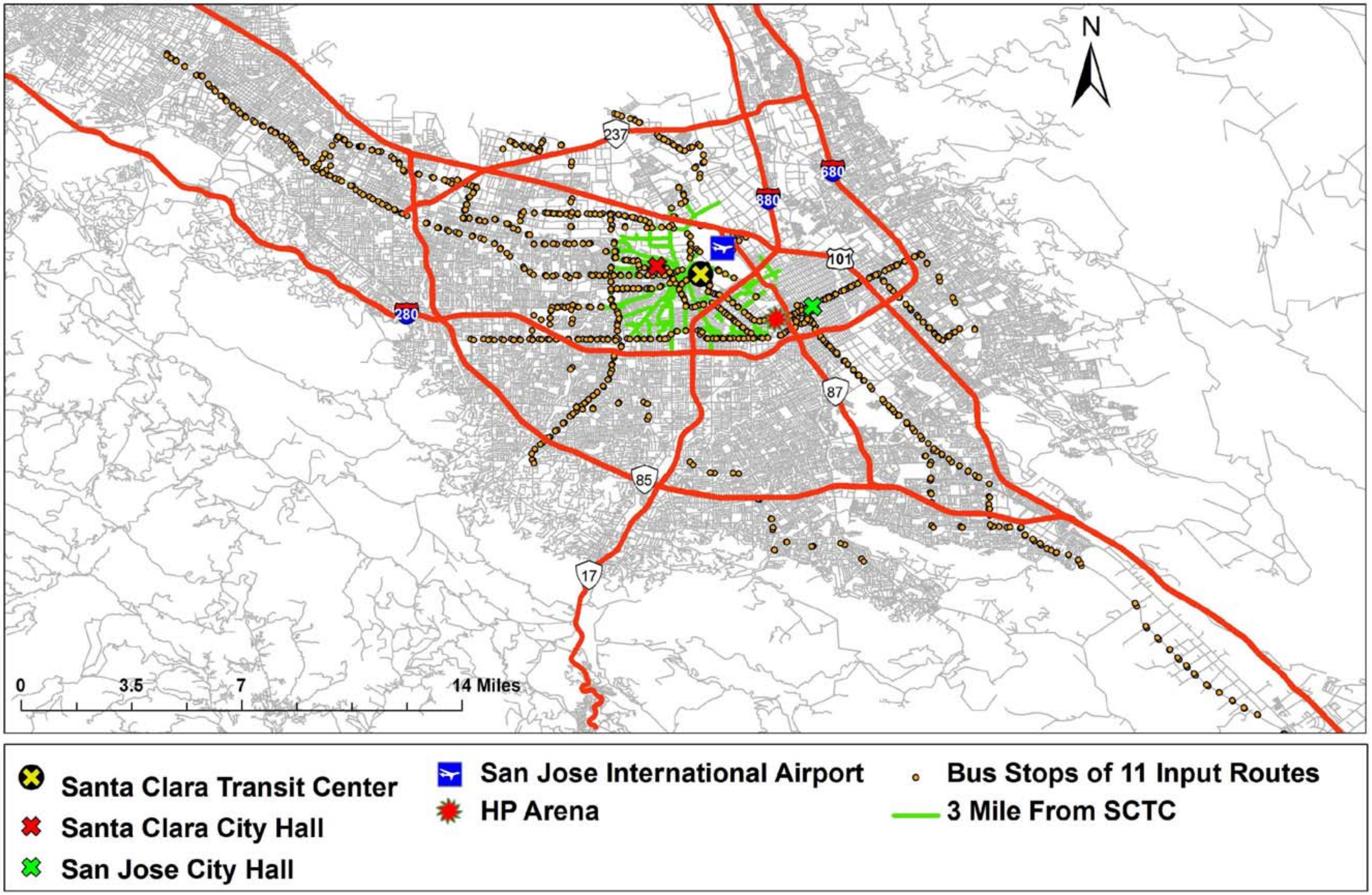

Figure 49: Prepare Existing Path Map and 11 Bus Routes

Since it is assumed that there is no difference in the bus service condition and the existing paths through all five scenarios, the bus service information and the existing path map could be prepared only once and then be used in all five scenarios.

1. Existing Path Map

As discussed in section 4.1.3, to access any bus stops from trip origin, travelers must move along existing paths. Also, in section 4.5.2 it is discussed that TBSAT calculates the reachable areas from reachable bus stops along existing paths. For the five scenarios in Chapter 6, we choose to use the 2006 second edition TIGER/Line files[57]of Santa Clara County, which records the existing street network, as the existing path map. How the existing path map participates the generation of time-based service area is discussed in section 4.1.3 and section 4.5.2.

As discussed in appendix section E.2.1, the existing path map must be prepared as a *network dataset* and input in to TBSAT. However, the street layouts provided by the TIGER/Line files are coded in a unique TGR file format. To convert a TGR format street layout file into a shapefile, which can be converted again into a network dataset later by ArcGIS, we choose to use a program *TGR2SHP*[58]. After TGR format street layout is converted into the shapefile format, we use the *Create Network Dataset* function in ArcCatalog[59] to convert the shapefile formatted street layout into network dataset. The converted existing path map in network dataset format appears in the grey network shown in Figure 49.

2. Bus Stop Location

The location of bus stops determines how travelers can access the bus service and the destination they can reach. For the five scenarios in chapter 6, the bus stop location is obtained from Valley Transportation Authority (VTA), which is the major bus service operator in Santa Clara County as well as around the SCTC.

However, as mentioned in section 4.1.2, the location of bus stop must be input into the TBSAT database component in the format of a dot feature class. Nevertheless, the raw data obtained from VTA specifies the location of bus stops in longitude and latitude. Thus, to convert the raw bus stop location into dot feature class, we have to use the *add X-Y data* function in ArcGIS to add the bus stops into their corresponding geographic location into an ArcGIS layer. Then, this layer can be saved as a dot feature class so that the location of bus stops in this dot feature

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[57] TIGER/Line (Topologically Integrated Geographic Encoding and Referencing) files contain various types geographic information including the street coordinates of US territories. It is prepared by the geography division of US Census Bureau.
<http://www.census.gov/geo/www/tiger/tiger2006se/tgr2006se.html>[May 5, 2008]

[58] TGR2SHP is a program that transforms the data in TIGER/line file format into *shapefile* format, which is the more commonly used format for GIS programs.
<http://tnatlas.geog.utk.edu/freeware/TGR2SHPWhitepaper.pdf>[May 5, 2008]

[59] ArcCatalog is one of ArcGIS family programs that specializes in managing ArcGIS related files. It is also capable to transform standard *shapefiles* into network datasets, which is the only format that the network analysis function in ArcGIS accepts.

class can be loaded into the facilities layer of the ASNAL as discussed in appendix section E.2.1 by TBSAT system maintainers.

3. Route Schedule (Timetable)

As discussed in section 4.3.1, TBSAT requires the bus route schedule to be input in the Absolute Travel Time Differential (ATTD) format.

Table 30: Example of ATTD Format Bus Route Schedule

Route	STOP	ATTD	Direction	Route	STOP	ATTD	Direction
304	505310	0	W	304	237416	0	E
304	495307	1.8	W	304	237415	0.8	E
304	475303	3.6	W	304	237413	1.6	E
304	465302	5.4	W	304	247408	2.4	E
304	465502	7.2	W	304	247406	3.2	E
304	465510	9	W	304	247410	4	E
304	465605	10.6	W	304	257403	4.8	E
304	465701	12.2	W	304	267404	5.6	E
304	455802	13.8	W	304	267406	6.4	E
304	465801	15.4	W	304	267405	7.2	E

As shown in Table 30, the ATTD format route schedule contains four types of information: the route name, the stop name, the ATTD at stop, and the direction of that route. As discussed in section 4.3.1, the first stop of each direction of a bus route must have its ATTD as zero.

To converted standard VTA route schedule into a complete ATTD format route schedule that can be maintained in the TBSAT database, there are several task to complete:

1. Convert timetable into ATTD format

Each direction of any VTA bus route records its schedule as the timetable below:

Table 31: Standard VTA Route Schedule

Route 304 Westbound Schedule								
TRSA STN	SNEL STN	MTRY SENT	MTRY CURT	1ST CLRA	SCOT SPAC	SCOT BOWR	ARQS LAWR	SNVL T.C.
5:28A	5:37A	5:45A	5:51A	6:02A	6:18A	6:22A	6:26A	6:35A
6:00A	**6:09A**	**6:17A**	**6:23A**	**6:34A**	**6:50A**	**6:54A**	**6:58A**	**7:07A**
6:25A	6:34A	6:42A	6:48A	7:00A	7:17A	7:22A	7:26A	7:35A
6:53A	7:03A	7:12A	7:19A	7:31A	7:49A	7:54A	7:59A	8:08A
7:25A	7:35A	7:44A	7:52A	8:05A	8:21A	8:27A	8:32A	8:41A

To transform the standard route schedule into the ATTD format schedule, first we pick only one row from Table 31. Then, since the ATTD at the first stop is always zero, thus, the ATTD at each later stop would be the difference between the time points at that stop and the first stop. For example, if we convert the standard schedule into ATTD format of route 304 in Table 31 based on the second row, the ATTD of route 304 at first stops is zero (6:00A), the ATTD at second stop is 9 minutes (6:09A), and so on. In such case, the ATTD of the last stop of westbound route 304 should be 67 minutes (7:07A).

2. Replace the stop names with the unique stop IDs

If we compare the standard VTA schedule (Table 31) and the transformed ATTD format schedule (Table 30), it is apparent that in the standard VTA schedule the bus stops are recognized by their names. However, in the ATTD format schedule, bus stops are recognized by their STOP IDs. TBSAT requires the name of each bus stop to be recorded consistently in both the dot feature class that indicates the location of bus stops (See appendix section E.2.1) and in the ATTD format schedule (See appendix section E.3.2). VTA recognizes each bus stop by their unique seven-digit ID. Thus, in this application, the name of the bus stops will be recorded in such seven-digit number. Such information is obtained from VTA officials.

A part of the raw data which obtained from VTA officials matches the name of each bus stop to their corresponding seven-digit ID:

Table 32: Corresponding Table between STOP ID and Stop Name

Index	STOP	STPNAM	ST_DIR
822	237412	EVELYN & MARSHALL	W
847	247305	EVELYN & DEODAR	W
2302	237407	EVELYN & FRANCES	W
5514	247401	FAIR OAKS & ARQUES	S

As we can see in Table 32, with such raw data we can easily replace the name in the schedule with their corresponding STOP ID.

3. Interpolate unavailable time point at minor stops

The last task in preparing the ATTD format VTA bus schedule is to interpolate the ATTD at the bus stops that are not recorded in the standard VTA schedule. In the example of standard VTA bus schedule shown in Table 31 we could find that the schedule only indicating the time points at nine major stops instead of the time points at all bus stops along route 304. However, to estimate the bus travel time between the boarding stop and the disembarking stop, TBSAT will need the exact ATTD time points at both stops. As a result, in the preparation of ATTD format route schedule, this research performs an interpolation to estimate the ATTD time points at the stops between two major stops.

Table 33: Interpolation of ATTD at Minor Bus Stops

STOP	Sequence	ATTD
256601	1	**0**
256702	2	
256704	3	
266701	4	
266807	5	
266804	6	
266808	7	
266805	8	
276803	9	
286804	10	
286806	11	
296804	12	
296802	13	
296901	14	**13**
296904	15	
296905	16	
306901	17	
306902	18	
306903	19	
316904	20	
316912	21	
316915	22	
326915	23	
326910	24	**22**

STOP	Sequence	ATTD
256601	1	**0**
256702	2	1
256704	3	2
266701	4	3
266807	5	4
266804	6	5
266808	7	6
266805	8	7
276803	9	8
286804	10	9
286806	11	10
296804	12	11
296802	13	12
296901	14	**13**
296904	15	13.9
296905	16	14.8
306901	17	15.7
306902	18	16.6
306903	19	17.5
316904	20	18.4
316912	21	19.3
316915	22	20.2
326915	23	21.1
326910	24	**22**

As shown in the left side of Table 33, in this schedule only three major stops have their time points specified in the standard schedule and can be converted into ATTD minutes. However, the stops between two major stops do not have their time point specified in the standard schedule. Thus, we assume that, the bus travel time between any back-to-back bus stop pair between two major stops should be equal. According to this assumption we can perform an interpolation to estimate the ATTD at the minor stops as shown in the right side of Table 33.

After completing the three tasks listed above, now we possess the ATTD format route schedule that should be prepared and input into the TBSAT database as discussed in appendix section E.3.2.

4. Peak/Off-peak Headway (Frequency) of Bus Routes

As mentioned in section 4.3.3, TBSAT estimates how long a person might wait for the arrival of his desired bus by referencing how frequent a bus will departure from the first stop of the route. The peak/off-peak headway information of all VTA bus routes is obtained from VTA official. The peak/off-peak headway information is also input into the TBSAT database as discussed in appendix section E.3.2.

With all four types of information are correctly input, now we could proceed to each scenario and identify the time-based bus service area of the SCTC under different conditions by running TBSAT with different settings.

Appendix E: PROGRAMMING TBSAT

This appendix describes the programming structure of TBSAT and how TBSAT generates time-based bus service area maps through the combined application of ESRI's ArcGIS and Microsoft Access (Microsoft's database software). In addition, how raw bus service data is loaded into TBSAT is also explained in detail in this appendix.

TBSAT is a semi-automated application that allows its users to generate time-based bus service area maps which indicate the destinations a traveler can reach from a designated starting point, under a specified travel-time limit. TBSAT consists of three phases that operate using two computer programs, all of which are described in this appendix. This appendix begins with the description of how TBSAT completes the six-step procedure (also described in section 3.3) within the three phases to generate the time-based bus service area. This is followed by a description of how the user programs TBSAT to execute the procedures in each phase and generated necessary outputs for each phase.

Note that the actual coding of the processes that TBSAT executes is not included in this appendix (due to its large volume). The coding of TBSAT tools in ArcGIS and the objects in the TBSAT database are not "packaged" (that is, not assembled into low-level machine language), and so are visible to TBSAT users and programmers. Thus, those who are interested in modifying TBSAT code may open these objects in edit mode and read or modify the code. For further information, please contact the author.

E.1 The Three Phases of TBSAT

TBSAT generates time-based bus service areas for a starting location under the user supplied criteria by following the six-step procedure developed in section 3.3. For the balance of efficiency, ease of maintenance, and ease of use, TBSAT has two components. The components operate on ESRI ArcGIS 9.2 and Microsoft Access 2007, respectively.

Table 34: Procedural Steps in Each TBSAT Phase

Procedural Steps		Phase	TBSAT Component	Operation Platform
Step 1:	Find Accessible Stops	1	ArcGIS Component	ESRI ArcGIS 9.2
Step 2:	Find Accessible Routes	2	Database Component	Microsoft Access 2007
Step 3:	Calculate Remaining Available Time at Disembarkable Stops		Database Component	
Step 4:	Find Reachable Stops		Database Component	
Step 5:	Generate Reachable Areas from Reachable Stops	3	ArcGIS Component	ESRI ArcGIS 9.2
Step 6:	Merge All Reachable Areas into A Full Time-Based Bus Service Area Map		ArcGIS Component	

As shown in Table 34, TBSAT completes all six steps in three phases. Phase 1 operates using the TBSAT ArcGIS component and generates the list of accessible stops as the final output. Phase 2, which uses the TBSAT database component, accomplishes Step 2 through Step 4 to produce the arrival timetable, which specifies the reachable stops and their corresponding remaining available time. Finally, in Phase 3, TBSAT again uses the ArcGIS component (Step 5) to generate the reachable stops and areas around those stops, and, finally, (Step 6) to merge all that information to generate the time-based bus service area map.

In the ArcGIS component of TBSAT, process models[60] are created. These combine multiple operations of ArcGIS into *tools*[61] in the *TBSAT toolbox*.[62] Using the process models, TBSAT completes three of the six steps shown in Figure 12 and Table 34. All three steps involve spatial calculations, which can be done more efficiently in ArcGIS.

[60] In ArcGIS, a process model is the programming code which allows ArcGIS to represent specific attributes of the target object through a series of operations. Each process model is composed of multiple processes. For example, one process model in TBSAT is designed to differentiate accessible stops and non-accessible stop. This model selects accessible stops from all bus stops on the map and then moves these accessible stops to a new layer. Both the action of selecting and the action of moving are defined as processes.

[61] A tool in ArcGIS is a set of processes that allows users to achieve specific tasks in ArcGIS. TBSAT process models are also *tools* because they support TBSAT users by identifying the time-based service area in the ArcGIS environment.

[62] An ArcGIS toolbox contains multiple toolsets composed of tools. Each tool provided in the TBSAT toolbox completes multiple ArcGIS processes, which in turn supports users by completing a part of the task of generating a time-based service area map.

For example, in Step 1 of this six-step procedure, the accessible stops from the trip origin are identified according to the access distance from trip origin to each bus stop on the map. TBSAT provides a tool (process model) in the TBSAT toolbox that automatically completes the operations of measuring the access distance from trip origin to each bus stop on the map and then creates the list of accessible stops in a single process model operation.

In the database component of TBSAT, which is developed based on Microsoft Access 2007, TBSAT completes the steps that require querying different tables. These steps identify accessible routes (Step 2), calculate remaining available time (Step 3), and identify reachable stops (Step 4). For example, to find accessible routes, TBSAT must refer to multiple tables, including route schedules, the list of accessible routes, and the route headway table.

In each of the following sections of this appendix describes, the detailed processes that TBSAT completes in each phase is described. First, its process flowchart is presented. Then, each process involved in each phase is discussed within the context of its sequence within its respective phase. The input data that each process requires and the output that each process generates are also described.

E.2 Phase 1: Find Accessible Stops in ArcGIS

Phase 1 consists of a single step: Step 1. In Phase 1 of a TBSAT run, a general TBSAT user must specify the location of the trip origin, the access speed (V_a), and the acceptable access time (AAT). The final output of Phase 1 is the list of accessible stops, which is one of the required inputs to Phase 2. As can be seen in the following flowchart (Figure 50), certain *factors* must be entered manually. These factors are location of the trip origin, the acceptable access distance, the location of bus stops (system administrator only), and the street layout (system administrator only). Once these factors are input, TBSAT automatically generates the list of accessible stops through the *Find Accessible Stops* tool Find Accessible Stops described in this section.

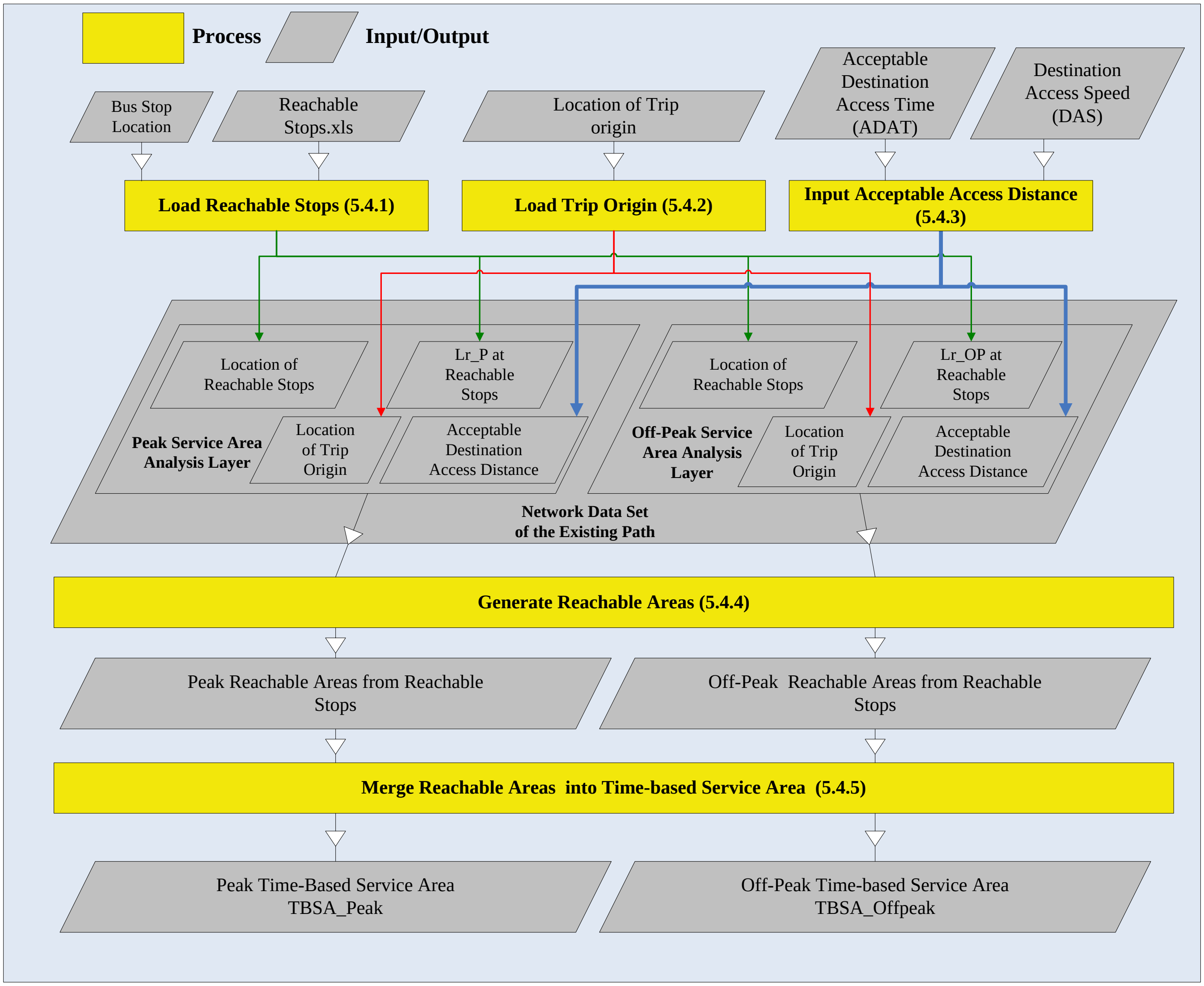


Figure 50: Phase 1 Process Flowchart: Find Accessible Bus Stops

E.2.1 Accessible Stops Network Analysis Layer (ASNAL)

As shown in Figure 50, in TBSAT, the process of finding accessible stops is executed according to the input supplied to the **Accessible Stops Network Analysis Layer (ASNAL)**. The ASNAL is a *closest facility analysis*[63] layer, which is one of the four types of ArcGIS group network analysis layers[64] that must be built on top of the network dataset. In ArcGIS, a network analysis layer stores the information that is required by a network analysis session. A network analysis analysis layer is built on top of a network dataset. In this case, the network dataset specifies the paths available in the region under analysis. Using the available path information that the network dataset provides and the information stored in itself, the network analysis layer helps users perform a specific analysis in TBSAT. For example, as shown in Figure 50, the ASNAL is a network analysis layer that uses the existing path information in the network dataset and other information, such as the location of the trip origin and the location of bus stops, to help TBSAT users identify accessible stops.

A closest facility analysis identifies the accessible "facilities" that can be accessed along an existing path (network dataset), from the specified trip origin, within a specified range. Since the ASNAL is a closest facility analysis layer, it stores the information, including which network dataset is used to access facilities (existing path map), the trip origin, the location of the facilities (bus stops), and the facility-searching range limit (acceptable access distance). These four types of essential information, required to construct a complete ASNAL, are shown in Figure 51. Through the execution of the closest facility analysis based on the ASNAL, TBSAT finds the accessible stops from the trip origin. The following four sections detail these four types of information, which are also the inputs to the process of finding accessible stops, as outlined in the flowchart of Figure 50.

---

[63] Closest facility analysis is one of four types of network analyses that ArcGIS can perform. It finds the facilities that can be accessed from a specific origin within a specific distance along the network.

[64] A group layer contains multiple layers that are required for one GIS process. A group network analysis layer contains multiple layers that are required in one network analysis process.

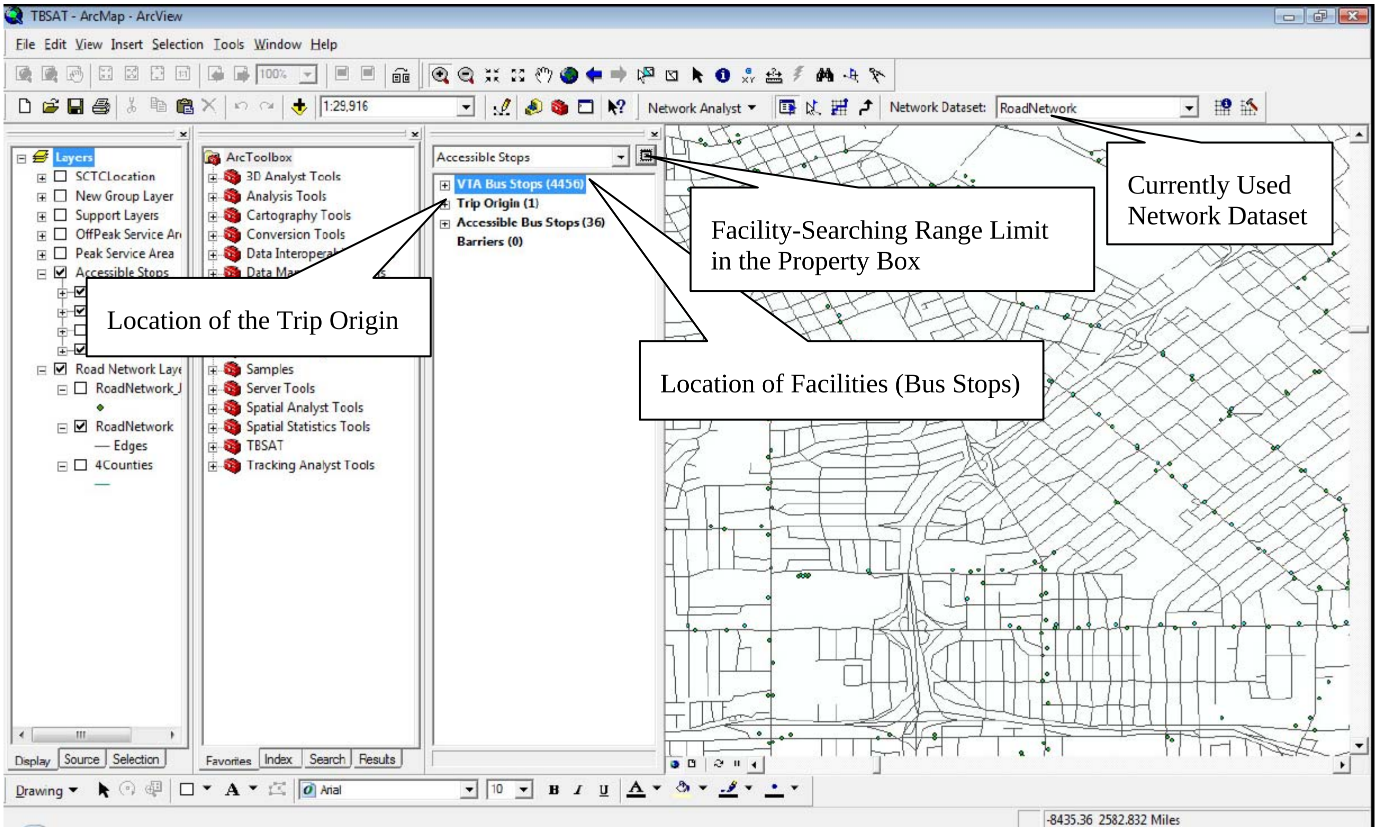


Figure 51: Accessible Stops Network Analysis Layer

1. Existing Path Map (Network Dataset)

In TBSAT, the network dataset is the street map, since people move along streets when approaching accessible stops and accessing their final destination from reachable stops. As shown at the upper-right corner in Figure 51, the network dataset, named "RoadNetwork" (see upper right area of the figure), is the network dataset on top of which the ASNAL is built.

As discussed in section 4.1.3, this existing network map must be prepared in the standard format of network dataset.[65]

2. Location of the Trip Origin

The location of the trip origin must be designated by the TBSAT user, depending on the purpose of the TBSAT run. TBSAT provides two ways to enter the trip origin into the ASNAL after left-clicking on the "*Trip Origin*" layer, shown in the third column in Figure 51. First, the user can enter the trip

[65] To create a network dataset that can be used in the Network Analyst function in ArcGIS, please refer to: <http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Creating_a_network_dataset>.

location by using the Add Location button and then left-clicking on any desired location on the map. The second way to enter the trip origin is to use the binocular shape *Address Finder* tool.

After inputting the address of the desired trip origin, the TBSAT user can execute the *Add as Network Location* function to add the desired trip origin to the ASNAL (for a glossary of terms, see Appendix A: TBSAT USER'S QUICK MANUAL).

3. Location of Bus Stops

As mentioned in section 4.1.2, bus stop locations must be input into the ASNAL as a dot feature class. Bus stop locations may remain unchanged through different TBSAT runs, as long as these runs are applied to the geographical areas that are covered by the same bus service system.

As shown in Figure 52, the location of 4,456 VTA operating bus stops is included in the "VTA Bus Stops" layer, which is a facility layer of the ASNAL.

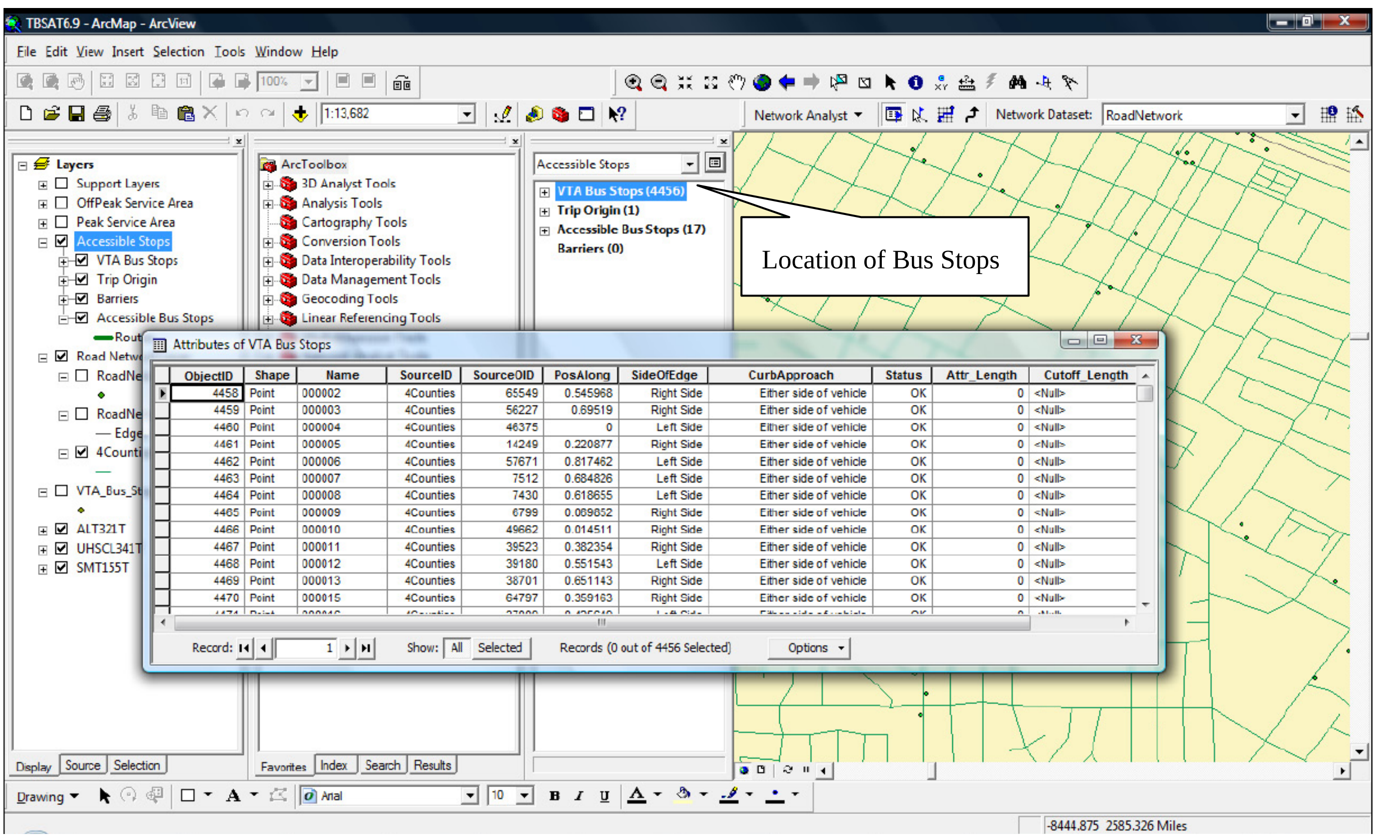
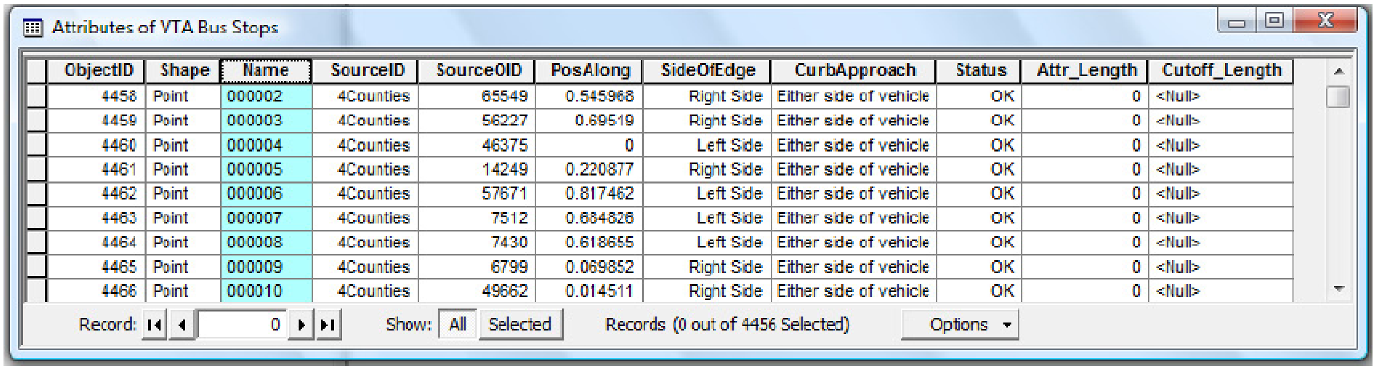


Figure 52: Bus Stop Location Layer in the ASNAL

In general, the typical end-user (who does not maintain the underlying system) does not need to modify the bus stop locations. However, TBSAT system maintainers do need to update underlying data, including bus stop locations, when bus service changes. The following paragraph briefly describes a critical action for loading the bus stop locations into the ASNAL.

Figure 53: Specify the Name of the Bus Stops When Loading Bus Stops



Attributes of VTA Bus Stops

ObjectID	Shape	Name	SourceID	SourceOID	PosAlong	SideOfEdge	CurbApproach	Status	Attr_Length	Cutoff_Length
4458	Point	000002	4Counties	65549	0.545968	Right Side	Either side of vehicle	OK	0	<Null>
4459	Point	000003	4Counties	56227	0.69519	Right Side	Either side of vehicle	OK	0	<Null>
4460	Point	000004	4Counties	46375	0	Left Side	Either side of vehicle	OK	0	<Null>
4461	Point	000005	4Counties	14249	0.220877	Right Side	Either side of vehicle	OK	0	<Null>
4462	Point	000006	4Counties	57671	0.817462	Left Side	Either side of vehicle	OK	0	<Null>
4463	Point	000007	4Counties	7512	0.684826	Left Side	Either side of vehicle	OK	0	<Null>
4464	Point	000008	4Counties	7430	0.618655	Left Side	Either side of vehicle	OK	0	<Null>
4465	Point	000009	4Counties	6799	0.069852	Right Side	Either side of vehicle	OK	0	<Null>
4466	Point	000010	4Counties	49662	0.014511	Right Side	Either side of vehicle	OK	0	<Null>

Record: 0 Show: All Selected Records (0 out of 4456 Selected) Options

As shown in Figure 53, when loading data into the bus stop locations layer of the ASNAL, TBSAT system maintainers can allow all but one field (attribute) to be automatically generated. A unique name must be specified for each bus stop in the *Name* field, according to the raw bus stop information. The names must be consistent with those used in the *Route Schedule* table in the TBSAT database component (see section 5.3.2). For example, in Figure 53, the name of each bus stop is recorded as a seven-digit number according to VTA's official bus stop naming convention. The other fields are automatically generated when the bus stop location data are loaded into this layer.

4. Acceptable Access Distance (Cutoff Value)

As mentioned in section 4.1, ArcGIS can search for facilities within the designated searching range (distance, travel cost, etc.) from the trip origin. In the standard ArcGIS closest facility analysis, such a searching range is defined as the *cutoff*[66] value. Similarly, in TBSAT, the facilities are bus stops and the searching range is the acceptable access distance. As a result, in the ASNAL, the cutoff value is the acceptable access distance. The acceptable access distance must be correctly specified for TBSAT to produce correct results.

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[66] The term *cutoff* value represents the limit to the range that ArcGIS uses to search for facilities around trip origin in a closest facility analysis.

However, as discussed in section 4.1, people usually tend to measure the distance in terms of time, especially when walking is the travel mode. Thus, TBSAT provides its users a pop-up *Acceptable Access Distance Calculator* to convert their desired access speed and their acceptable access time into an acceptable access distance.

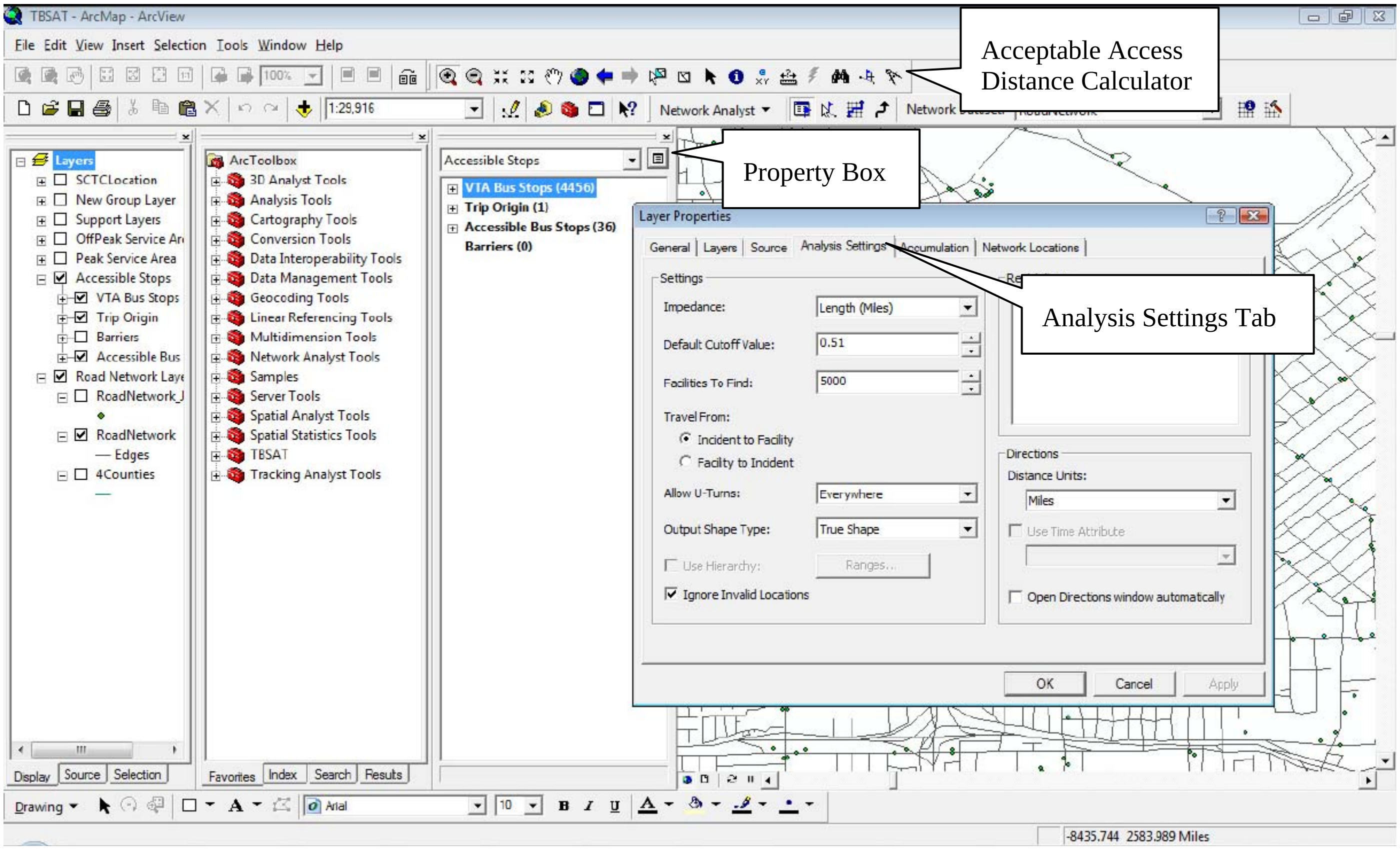


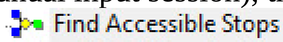
Figure 54: Open Acceptable Access Distance Calculator

As shown in Figure 54, clicking on the compass icon  initiates the acceptable access distance calculator pop-up window. The user enters his desired access speed and acceptable access time as input, and then clicks the calculate button. The acceptable access distance is calculated and shown in the bottom box of the calculator.

The user must enter this calculated acceptable access distance into the default cutoff field of the ASNAL. To enter the default cutoff, the user must open the layer property window of the ASNAL by clicking the *Property* button  in the third column (see Figure 54) and then switch to the *Analysis Setting* tab. The value must be entered here.

Once all four types of information listed above area prepared and input into the ASNAL, TBSAT can then find accessible stops using the information in the ASNAL.

E.2.2 Activate Find Accessible Stops Tool

As shown in Step 1 of the flowchart in Figure 50, once the ASNAL is fully prepared (after the manual input session), the user may double-click on the *Find Accessible Stops* tool 

. This tool can be found in the Phase 1 toolset[67] in the TBSAT Toolbox shown in Figure 55. Executing this tool, TBSAT automatically performs multiple ArcGIS processes, resulting in the generated list of accessible stops for Phase 2.

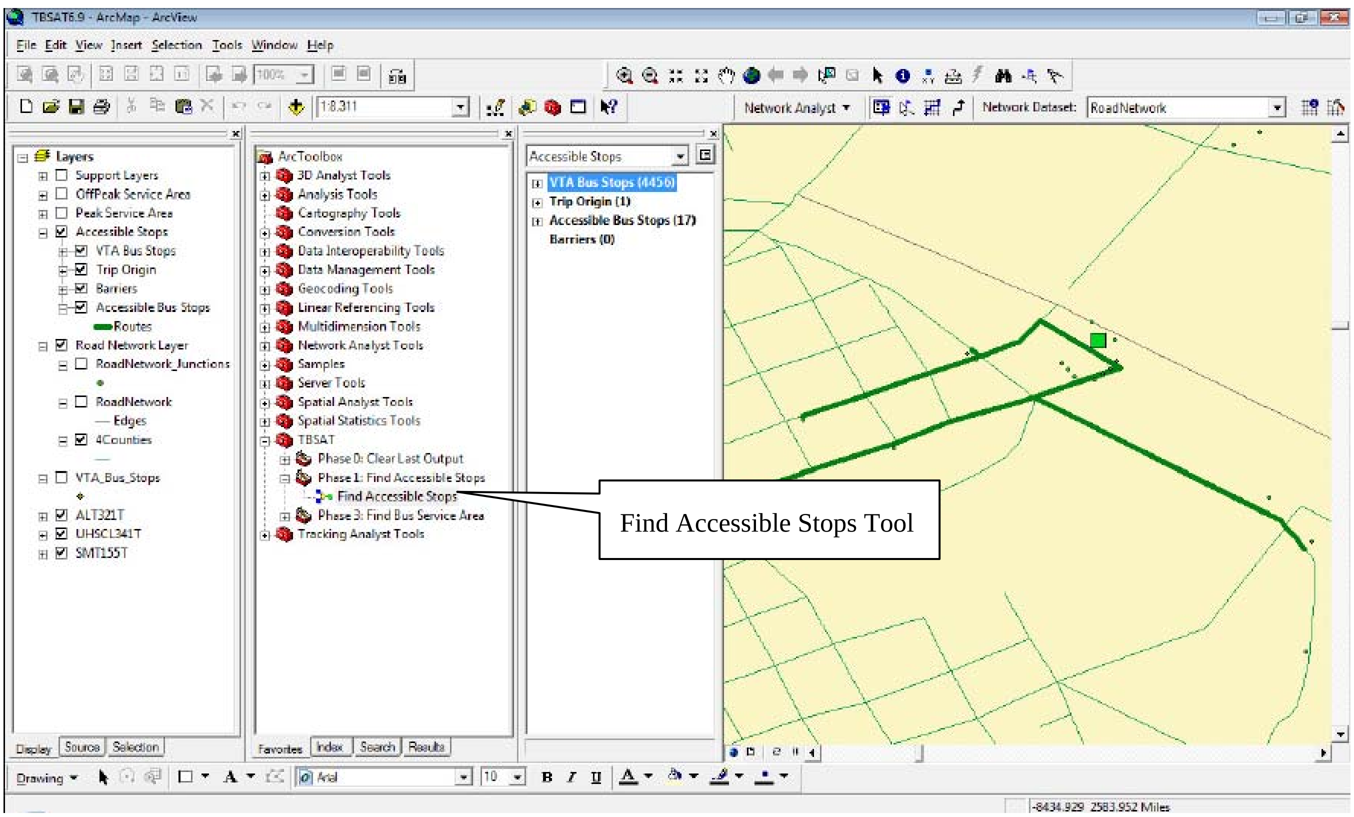


Figure 55: TBSAT Tool: Find Accessible Stops Tool

The *Find Accessible Stops* tool consists of several ArcGIS successive processes. The first process identifies the bus stops that are within the acceptable access distance from the trip origin and the shortest routes the lead to these accessible stops. The output of this process is a *list of routes to accessible stops* similar to that shown in Table 35.

---

[67] A toolset in ArcGIS contains multiple ArcGIS tools that allow the user to perform specific tasks.

Table 35: Example List of Routes to Accessible Stops

Attributes of Accessible Bus Stops

ObjectID	Shape	FacilityID	FacilityRank	Name	Total_Length	IncidentCurbApproach	FacilityCurbApproach	IncidentID
635	Polyline M	6698	1	Graphic Pick 2 - 347010	0.013781	Left side of vehicle	Left side of vehicle	15
636	Polyline M	6699	2	Graphic Pick 2 - 347011	0.018466	Right side of vehicle	Right side of vehicle	15
637	Polyline M	6697	3	Graphic Pick 2 - 347009	0.027799	Left side of vehicle	Left side of vehicle	15
638	Polyline M	6696	4	Graphic Pick 2 - 347008	0.044675	Left side of vehicle	Right side of vehicle	15
639	Polyline M	6695	5	Graphic Pick 2 - 347007	0.054538	Left side of vehicle	Left side of vehicle	15
640	Polyline M	6691	6	Graphic Pick 2 - 347001	0.064482	Left side of vehicle	Left side of vehicle	15
641	Polyline M	6539	7	Graphic Pick 2 - 337011	0.084091	Left side of vehicle	Right side of vehicle	15
642	Polyline M	6543	8	Graphic Pick 2 - 337016	0.088296	Left side of vehicle	Right side of vehicle	15
643	Polyline M	6544	9	Graphic Pick 2 - 337017	0.093034	Left side of vehicle	Right side of vehicle	15
644	Polyline M	6541	10	Graphic Pick 2 - 337014	0.150649	Right side of vehicle	Left side of vehicle	15
645	Polyline M	6542	11	Graphic Pick 2 - 337015	0.159264	Right side of vehicle	Left side of vehicle	15
646	Polyline M	6535	12	Graphic Pick 2 - 337005	0.291863	Left side of vehicle	Left side of vehicle	15
647	Polyline M	6540	13	Graphic Pick 2 - 337013	0.346231	Right side of vehicle	Left side of vehicle	15
648	Polyline M	6692	14	Graphic Pick 2 - 347002	0.41316	Left side of vehicle	Left side of vehicle	15
649	Polyline M	6536	15	Graphic Pick 2 - 337006	0.413871	Left side of vehicle	Left side of vehicle	15
650	Polyline M	6537	16	Graphic Pick 2 - 337007	0.449085	Left side of vehicle	Left side of vehicle	15
651	Polyline M	6685	17	Graphic Pick 2 - 346908	0.480965	Left side of vehicle	Left side of vehicle	15

Record: 1 Show: All Selected Records (0 out of 17 Selected) Options

As shown in Table 35, the list of routes to accessible stops includes the shortest routes from the trip origin to each accessible bus stop and the length of these routes (Total_Length column). Note that the name (Name column) of each route ends with the name of the accessible stop to which each route leads. For example, the first route in Table 35 begins from the trip origin and ends at bus stop 347010. The length of the first route, which is 0.013781 miles, is also the access distance from the trip origin to accessible stop 347010.

E.2.3 Join the Bus Stop Locations and the List of Routes to Accessible Stops

Once the list of *routes to accessible stops* data (which includes the length of each route) has been generated, each route must be matched with the name of its corresponding target facility (bus stop), which is the Name of each accessible stop. From this corresponding of information, TBSAT creates a table containing both the name and access distance for each accessible stop. In ArcGIS terms, the creation of this correspondence is called a *join*.

Attributes of VTA Bus Stops

ObjectID	Shape	Name	SourceID	SourceOID	PosAlong	SideOfEdge	CurbApproach	Status	Attr_Length	Cutoff_Length
6693	Point	347005	4Counties	54385	0.420251	Left Side	Either side of vehicle	OK	0	<Null>
6694	Point	347006	4Counties	54385	0.023755	Left Side	Either side of vehicle	OK	0	<Null>
6695	Point	347007	4Counties	65094	0.631124	Left Side	Either side of vehicle	OK	0	<Null>
6696	Point	347008	4Counties	65094	0.579876	Right Side	Either side of vehicle	OK	0	<Null>
6697	Point	347009	4Counties	65094	0.492184	Left Side	Either side of vehicle	OK	0	<Null>
6698	Point	347010	4Counties	65094	0.419343	Left Side	Either side of vehicle	OK	0	<Null>
6699	Point	347011	4Counties	65094	0.251785	Left Side	Either side of vehicle	OK	0	<Null>
6700	Point	347101	4Counties	3661	0.679841	Right Side	Either side of vehicle	OK	0	<Null>
6701	Point	347102	4Counties	3661	0.813797	Right Side	Either side of vehicle	OK	0	<Null>
6702	Point	347201	4Counties	57606	0.06825	Left Side	Either side of vehicle	OK	0	<Null>

Record: 2241 Show: All Selected Records (1 out of 4456 Selected) Options

Attributes of Accessible Bus Stops

ObjectID	Shape	FacilityID	FacilityRank	Name	Total_Length	IncidentCurbApproach	FacilityCurbApproach	IncidentID
635	Polyline M	6698	1	Graphic Pick 2 - 347010	0.013781	Left side of vehicle	Left side of vehicle	15
636	Polyline M	6699	2	Graphic Pick 2 - 347011	0.018466	Right side of vehicle	Right side of vehicle	15
637	Polyline M	6697	3	Graphic Pick 2 - 347009	0.027799	Left side of vehicle	Left side of vehicle	15
638	Polyline M	6696	4	Graphic Pick 2 - 347008	0.044675	Left side of vehicle	Right side of vehicle	15
639	Polyline M	6695	5	Graphic Pick 2 - 347007	0.054538	Left side of vehicle	Left side of vehicle	15
640	Polyline M	6691	6	Graphic Pick 2 - 347001	0.064482	Left side of vehicle	Left side of vehicle	15
641	Polyline M	6539	7	Graphic Pick 2 - 337011	0.084091	Left side of vehicle	Right side of vehicle	15
642	Polyline M	6543	8	Graphic Pick 2 - 337016	0.088296	Left side of vehicle	Right side of vehicle	15
643	Polyline M	6544	9	Graphic Pick 2 - 337017	0.093034	Left side of vehicle	Right side of vehicle	15
644	Polyline M	6541	10	Graphic Pick 2 - 337014	0.150649	Right side of vehicle	Left side of vehicle	15
645	Polyline M	6542	11	Graphic Pick 2 - 337015	0.159264	Right side of vehicle	Left side of vehicle	15
646	Polyline M	6535	12	Graphic Pick 2 - 337005	0.291863	Left side of vehicle	Left side of vehicle	15
647	Polyline M	6540	13	Graphic Pick 2 - 337013	0.346231	Right side of vehicle	Left side of vehicle	15
648	Polyline M	6692	14	Graphic Pick 2 - 347002	0.41316	Left side of vehicle	Left side of vehicle	15
649	Polyline M	6536	15	Graphic Pick 2 - 337006	0.413871	Left side of vehicle	Left side of vehicle	15
650	Polyline M	6537	16	Graphic Pick 2 - 337007	0.449085	Left side of vehicle	Left side of vehicle	15
651	Polyline M	6685	17	Graphic Pick 2 - 346908	0.480985	Left side of vehicle	Left side of vehicle	15

Record: 1 Show: All Selected Records (1 out of 17 Selected) Options

Figure 56: Join List of Bus stops and List of Routes to Accessible Stops

As shown in Figure 56, in the upper table (the bus stop locations described in appendix section E.2.1), ObjectID 6698 refers to bus stop 347010. In the lower table (the list of routes to accessible stops), FacilityID 6698 refers to the destination of the first route in this list, which is also bus stop 347010. With this information, TBSAT can now *join* the data in the lower table into the upper table by building a one-to-one relationship between each bus stop in the upper table and the corresponding route to the accessible stops in the lower table. By joining the data in this manner, attributes from a route in the lower table are appended to the matching record in the upper table (whose ObjectID is the same as the FacilityID for this route).

For example, in Figure 56, the highlighted route in the lower table will be joined to the highlighted bus stop in the upper table because the ObjectID of this bus stop is the same as the FacilityID of the highlighted route. The joined location of bus stops table is shown in Figure 57.

Attributes of VTA Bus Stops

Facilities.ObjectID	CFRoutes.FacilityID	CFRoutes.Name	CFRoutes.Total_Length	Facilities.Shape	Facilities.Name
6685	6685	Graphic Pick 2 - 346908	0.480985	Point	346908
6537	6537	Graphic Pick 2 - 337007	0.449085	Point	337007
6536	6536	Graphic Pick 2 - 337006	0.413871	Point	337006
6692	6692	Graphic Pick 2 - 347002	0.41316	Point	347002
6540	6540	Graphic Pick 2 - 337013	0.346231	Point	337013
6535	6535	Graphic Pick 2 - 337005	0.291863	Point	337005
6542	6542	Graphic Pick 2 - 337015	0.159264	Point	337015
6541	6541	Graphic Pick 2 - 337014	0.150649	Point	337014
6544	6544	Graphic Pick 2 - 337017	0.093034	Point	337017
6543	6543	Graphic Pick 2 - 337016	0.088296	Point	337016
6539	6539	Graphic Pick 2 - 337011	0.084091	Point	337011
6691	6691	Graphic Pick 2 - 347001	0.064482	Point	347001
6695	6695	Graphic Pick 2 - 347007	0.054538	Point	347007
6696	6696	Graphic Pick 2 - 347008	0.044675	Point	347008
6697	6697	Graphic Pick 2 - 347009	0.027799	Point	347009
6699	6699	Graphic Pick 2 - 347011	0.018466	Point	347011
6698	6698	Graphic Pick 2 - 347010	0.013781	Point	347010
4458	<Null>	<Null>	<Null>	Point	000002
4459	<Null>	<Null>	<Null>	Point	000003
4460	<Null>	<Null>	<Null>	Point	000004
4461	<Null>	<Null>	<Null>	Point	000005
4462	<Null>	<Null>	<Null>	Point	000006
4463	<Null>	<Null>	<Null>	Point	000007
4464	<Null>	<Null>	<Null>	Point	000008
4465	<Null>	<Null>	<Null>	Point	000009
4466	<Null>	<Null>	<Null>	Point	000010

Figure 57: Location of Bus Stops Table Joined by the List of Routes to Accessible Stops

As shown in Figure 57, 17 identified routes to accessible stops that are shown in Figure 56 have been joined to corresponding bus stops from the bus stop locations table. Since only 17 of the 4456 bus stops can be accessed from the designated trip origin through 17 routes, the joined bus stop location table contains only 17 records (bus stops) with a non-null value in their Total_Length fields. For example, in Figure 57, bus stop 347010 (highlighted in blue) has a Total_Length of 0.013781 miles because it can be accessed from the trip origin. On the other hand, bus stop 000006 (outlined in red) has no value in its Total_Length field because it did not match any route to accessible stops. This means that it is not an accessible stop.

E.2.4 Select Bus Stops with Non-Null Access Distance

As discussed in appendix section E.2.3, the joined table of bus stop locations contains only those bus stops that are accessible from the trip origin. This is indicated by the non-null Total_Length value (see Figure 57) in the joined table. Now the user must tell TBSAT to create the final output of Phase 1, the list of accessible stops, from this joined table of bus stop locations.

First, TBSAT selects only the accessible stops from the joined bus stop locations table (that is, the bus stops that have a non-null Total_Length value). See the blue-highlighted entries in Figure 57. Then, it creates a new table containing only the selected bus stops entries. Each entry includes the Total_Length information appended from the join action. Since the Total_Length of a route to its corresponding accessible stops equals to the access distance, the newly-produced table actually contains both the name of the accessible stops and their corresponding access distances (Total_Length). The resulting table is the list of accessible stops.

Attributes of VTA Bus Stops

Facilities.ObjectID	CFRoutes.FacilityID	CFRoutes.Name	CFRoutes.Total_Length	Facilities.Shape	Facilities.Name
6685	6685	Graphic Pick 2 - 346908	0.480985	Point	346908
6537	6537	Graphic Pick 2 - 337007	0.449085	Point	337007
6536	6536	Graphic Pick 2 - 337006	0.413871	Point	337006
6692	6692	Graphic Pick 2 - 347002	0.41316	Point	347002
6540	6540	Graphic Pick 2 - 337013	0.346231	Point	337013
6535	6535	Graphic Pick 2 - 337005	0.291863	Point	337005
6542	6542	Graphic Pick 2 - 337015	0.159264	Point	337015
6541	6541	Graphic Pick 2 - 337014	0.150649	Point	337014
6544	6544	Graphic Pick 2 - 337017	0.093034	Point	337017
6543	6543	Graphic Pick 2 - 337016	0.088296	Point	337016
6539	6539	Graphic Pick 2 - 337011	0.084091	Point	337011
6691	6691	Graphic Pick 2 - 347001	0.064482	Point	347001
6695	6695	Graphic Pick 2 - 347007	0.054538	Point	347007
6696	6696	Graphic Pick 2 - 347008	0.044675	Point	347008
6697	6697	Graphic Pick 2 - 347009	0.027799	Point	347009
6699	6699	Graphic Pick 2 - 347011	0.018466	Point	347011
6698	6698	Graphic Pick 2 - 347010	0.013781	Point	347010
4458	<Null>	<Null>	<Null>	Point	000002
4459	<Null>	<Null>	<Null>	Point	000003
4460	<Null>	<Null>	<Null>	Point	000004
4461	<Null>	<Null>	<Null>	Point	000005
4462	<Null>	<Null>	<Null>	Point	000006
4463	<Null>	<Null>	<Null>	Point	000007
4464	<Null>	<Null>	<Null>	Point	000008
4465	<Null>	<Null>	<Null>	Point	000009

Record: 0 Show: All Selected Records (17 out of 4456 Selected) Options

Figure 58: Select Bus Stops with Non-Null Value in the Total_Length Field

TBSAT selects bus stops that have a non-null Total_Length value by executing a query process. As shown in Figure 58, all accessible stops, which are the bus stops that have a non-null value in their Total_Length field, have been selected (in blue) after the query process. In the next process, these selected bus stops are exported to a separate table as the list of accessible stops.

E.2.5 Export List of Accessible Stops

TBSAT must export the list of accessible stops, the output of Phase 1, into an independent table in a file format that can be imported by Microsoft Access as input to Phase 2.

TBSAT exports the selected bus stops identified in appendix section E.2.4 (the accessible stops) to a single Dbase format file named *ABS.dbf*. The fields of the list of accessible stops in ABS.dbf are the same as those of the joined bus stop table (in Figure 58). Remember, however, ABS.dbf only records the accessible stops, instead of all bus stops. In Phase 2, the TBSAT database component (Access) directly refers to file ABS.dbf for the list of accessible stops. No manual intervention is required by the user.

E.2.6 Remove the Join between the List of Bus Stops and the List of Routes to Accessible Stops

In appendix section E.2.3, the bus stop locations table was joined to the list of routes to accessible stops table in order to produce the list of accessible stops as discussed in appendix section E.2.5. In the final process in Phase 1, TBSAT removes this join, which means to break the one-to-one relationship between these two tables, and returns them to separate tables. The join must be removed since the list of routes to accessible stops may be different for each TBSAT run. Figure 59 illustrates this procedure.

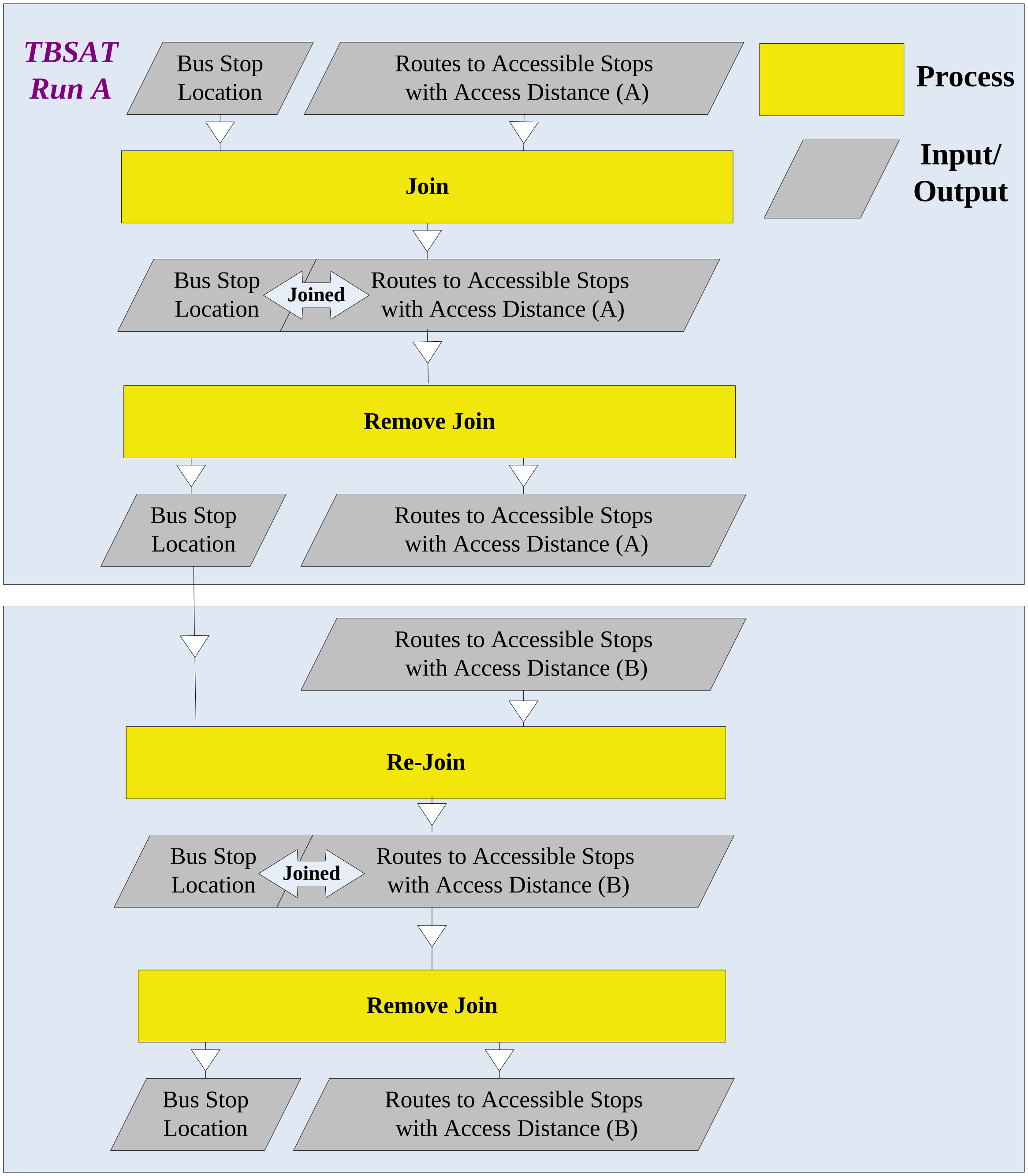


Figure 59: Remove Join for Next TBSAT Run

As shown in Figure 59, in TBSAT Run A, the *bus stop locations table* is first joined to the route to accessible stops table (A), produced in Run A (see discussion in appendix section E.2.3). However, in the next TBSAT run, Run B, the bus stop locations table is supposed to be joined to the *new* route to accessible stops table (B), instead of the old table (A), in order to produce the correct list of accessible stops for Run B. Thus, before the new table (B) can be joined to the bus stop locations table, the old join relationship between the bus stop locations table and the old table (A) must be removed.

The final TBSAT process in Phase 1 removes the join between the bus stop location table and the list of routes to accessible stops so that the newly produced list of routes to accessible stops in the future runs can be successfully joined to the bus stop location table.

E.3 Phase 2: Find Reachable Stops Using Microsoft Access 2007

As shown in Table 34 in appendix section E.1, Phase 2 of TBSAT runs the database component developed on Microsoft Access 2007. Phase 2 completes Steps 2, 3 and 4 of the six-step procedure of TBSAT. Phase 2 runs in two stages: the data preparation stage and the process execution stage. The two stages area represented in the upper and the lower panels of Figure 60.

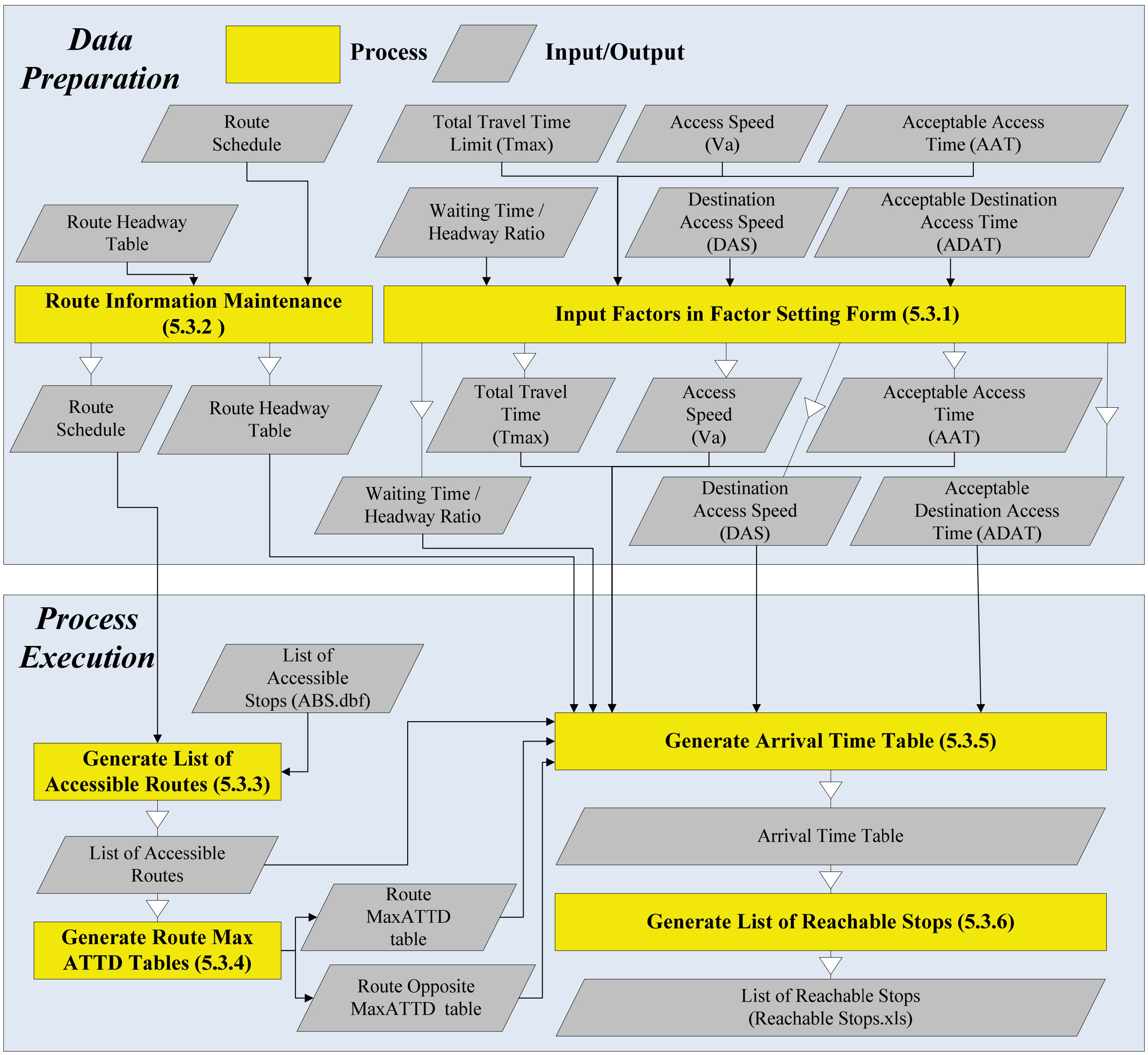


Figure 60: Phase 2 Flowchart

In the data preparation stage, the user must specify the value of certain factors, including total travel time (t_{max}), access speed (V_a), acceptable access time (AAT), destination access speed (DAS), acceptable destination access time (ADAT), and the waiting time/headway ratio. If the current bus route information, which includes the route schedule and the route headway, is different from the bus route information stored in the tables of the database, system maintainers must update the bus route information in the *route schedule table* and the *route headway table* before the user runs TBSAT.

Once factors are correctly specified in the data preparation stage, TBSAT automatically completes the process execution stage of Phase 2. The list of reachable stops is produced along with the maximum remaining available time for each reachable stop. The outputted list of reachable stops is saved in Microsoft EXCEL format, a format recognized by ArcGIS. TBSAT imports this file to ArcGIS in Phase 3.

E.3.1 Input Factors in Factor Setting Form

As shown in the flowchart for Phase 2 (Figure 60), the TBSAT user inputs the value of six factors through the factor setting form, shown in Figure 61.

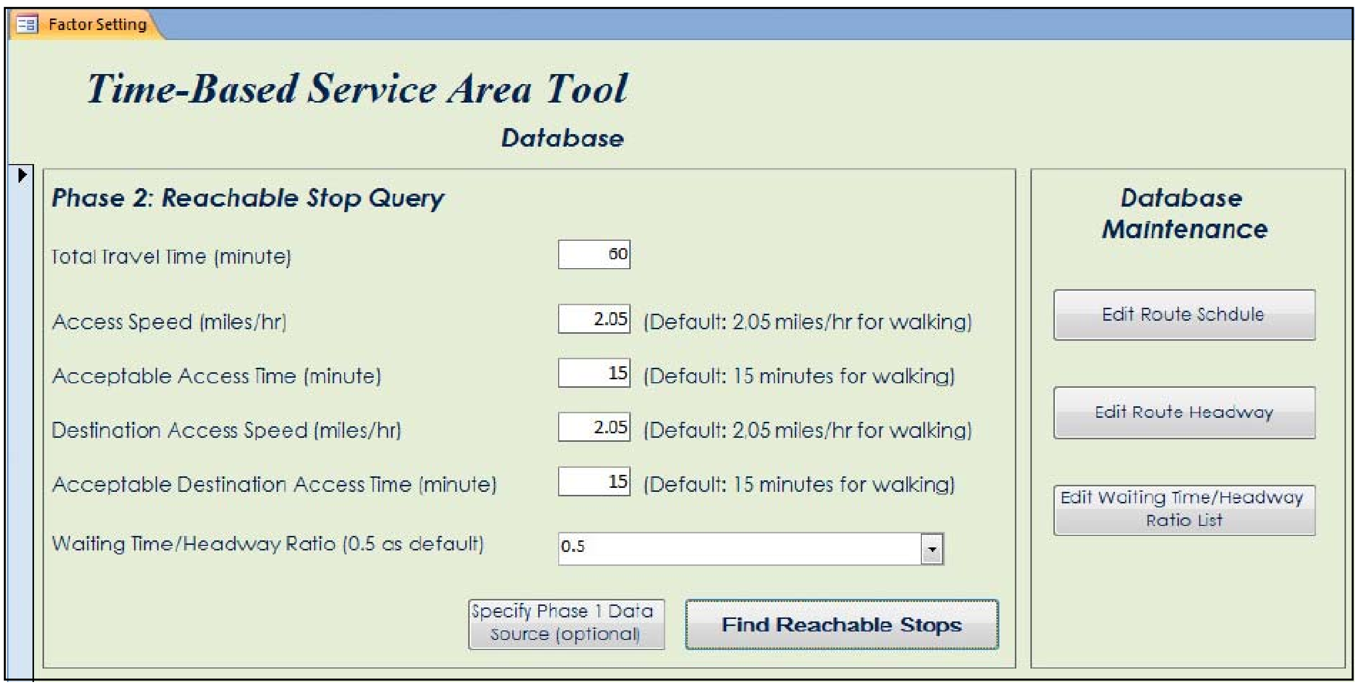


Figure 61: Factor Setting Form in the TBSAT Database

As shown in Figure 61, the factor setting form appears once when TBSAT the user opens the TBSAT database. The five value boxes and a drop-down list on the left section allow the user to specify the value of six different factors:

1. Total Travel Time (t_{max}):

As mentioned in section 4.3.5, total travel time is decided by the user's pre-determined total travel budget of the analysis. There is no suggested value for total travel time.

2. Access Speed (V_a):

According to the research in section 4.1.5, the suggested access speed, which is the suggested walking speed, is 2.05 mph. The user may specify another walking speed, or, if a different access mode is used (such as bicycling), the speed of another mode.

3. Acceptable Access Time (AAT):

Following the research result in section 4.1.7, the suggested acceptable access time for walking is 15 minutes. The user may specify another time here.

4. Destination Access Speed (DAS):

This is the speed the traveler uses to access his final destination after disembarking from the bus. TBSAT suggests a DAS of 2.05 mph, which is the typical walking speed. Similar to access speed, if the user prefers another destination access speed, it can be entered here.

5. Acceptable Destination Access Time (ADAT):

TBSAT suggests an ADAT of 15 minutes as a default. This assumes that walking is the mode for accessing final destination from reachable stops. The user may also specify this value.

6. Waiting Time/Headway Ratio

As discussed in section 4.3.3, this research suggests a series of waiting time/headway ratios that can be used to express different traffic conditions. Using the TBSAT factor setting form the user can choose one of these recommended ratios from the drop-down box depending on the traffic conditions in user's scenario. If none of the suggested ratios satisfies the TBSAT user's demand, the user may simply enter his preferred ratio in the waiting time/headway ratio box.

For system maintainers, the list of suggested waiting time/headway ratios can be updated by clicking the *Edit waiting time / headway ratio* button in factor setting form.

Once all six factors are correctly specified, the user clicks the *Find Reachable Stops* button in the factor setting form. The TBSAT database will remember the input values of these factors and use these values to automatically generate the list of reachable stops through the processes described in appendix sections E.3.3 through E.3.6.

E.3.2 Route Information Maintenance

The bus route related information in the TBSAT database must be consistent with the bus service in the region where TBSAT is applied. In the TBSAT database, the first two tables shown in the right section of the factor setting form in Figure 61, record different types of information regarding the bus service system in the analysis region.

1. Route Schedule Table

As mentioned in 4.3.1, TBSAT records the bus route schedule in the format of absolute travel time differential (ATTD). Thus, the route schedule of the bus service system must be prepared in ATTD format and input into the route schedule table.

Table 36: Example of Route Schedule Table in TBSAT

Route Schedule

Route	STOP	ATTD	Direction
10	347011	0.00	E
10	357201	13.00	E
10	357203	11.00	E
10	357301	16.00	E
10	367206	15.00	E
10	367209	18.00	E
10	367308	17.00	E
10	337010	15.00	W
10	347011	18.00	W
10	357201	7.00	W
10	357203	5.00	W
10	357302	2.00	W
10	367209	0.00	W

The user may click on the *Edit Route Schedule* button in the factor setting table to open the table for editing. Table 36 is an example of the ATTD format route schedule table. As mentioned in appendix section E.2.1, the naming convention for bus stops in the route schedule table must be consistent with that used for the bus stop locations layer of the ASNAL.

In Table 36 (line 1), the ATTD of Route 10E at Stop 347011 is zero because this stop is the first stop of Route 10E. Conversely, the ATTD of Route 10W at Stop 337010 (line 8) is 15 minutes, which means it takes 15 minutes for the Route 10W bus to travel from the first stop of Route 10W

(Stop 367209) to Stop 337010. Database maintainers must provide the correct ATTD for each stop of each bus route.

2. Route Headway Table

Another essential piece of bus route information used in TBSAT is the scheduled headway for each bus route.

Table 37: Example of Route Headway Table in the TBSAT Database Component

Route Headway Table

Route	Peak_H	OffPeak_H
10	15	15
22	12	12
23	12	12
304	0	0
32	30	60
328	0	0
522	15	15
58	30	0
60	15	30
68	15	30
81	30	30

Clicking the *Edit Route Headway* button in the factor setting form opens the TBSAT route headway table, as shown in Table 37. Both the peak headway and the off-peak headway for a bus route must be input by the TBSAT system maintainer before the general users can run TBSAT.

Note that Routes 304 and 328 require special headway information. These two routes run only once a day, which means a traveler has one opportunity per day to ride a bus on this route. A bus route that runs only once per day has a headway value of infinity (that is, the time gap between two successive buses of the same route on the same day is infinite).

According to Casello's theory regarding to the waiting/headway ratio (discussed in section 4.3.3), bus riders becomes aware of the passenger waiting time if the headway of a bus route is more than 30 minutes.[68] In such a case, the maximum waiting time Casello suggests for bus route that has its

[68] Jeffrey M. Casello, "Transit competitiveness in polycentric metropolitan regions," *Transportation Research Part A: Policy and Practice* 41, no. 1 (2007).

headway more the 30 minutes is the average time of 15 minutes. Following Casello's theory, since the headway of a route that runs only once a day is infinite, the estimated waiting time for these routes should be 15 minutes. As a result, when the TBSAT system maintainer declares a bus route that runs only once a day, TBSAT automatically set the peak hour waiting time for this bus route as 15 minutes.

Conversely, TBSAT assumes the off-peak period waiting time of a bus route that runs only once a day to be 9,999 minutes (or infinite in terms of TBSAT). The reason behind this assumption is, for a bus route that runs only once a day, it usually tends to run during the peak hours. As a result, during the off-peak period people will never be able to ride on this route. Thus, when the TBSAT system maintainer declares a bus route that runs only once a day, TBSAT automatically sets the off-peak waiting time for this route to be 9,999 minutes to symbolize the infinite waiting time that the traveler would spend waiting for this bus route during off-peak period.

To declare a bus route as a route that runs only once a day, the TBSAT system maintainer simply assigns a value of 0 (zero) to both the peak headway and the off-peak headway fields for that route. Then, the default headway values (15 minutes for peak period and 9,999 minutes for off-peak period) are assigned during runtime.

E.3.3 Generate List of Accessible Routes

After the user specifies all factors within the data preparation stage, the first process in Phase 2 may be executed. This is a query process that the TBSAT database component executes to generate the *list of accessible routes*. This list is the final output of the second step of the TBSAT six-step procedure.

As mentioned in section 4.2.3, TBSAT cross-references the list of accessible stops (located in file ABS.dbf, generated in Phase 1), and the route schedule table, to identify the routes available at each accessible stop.

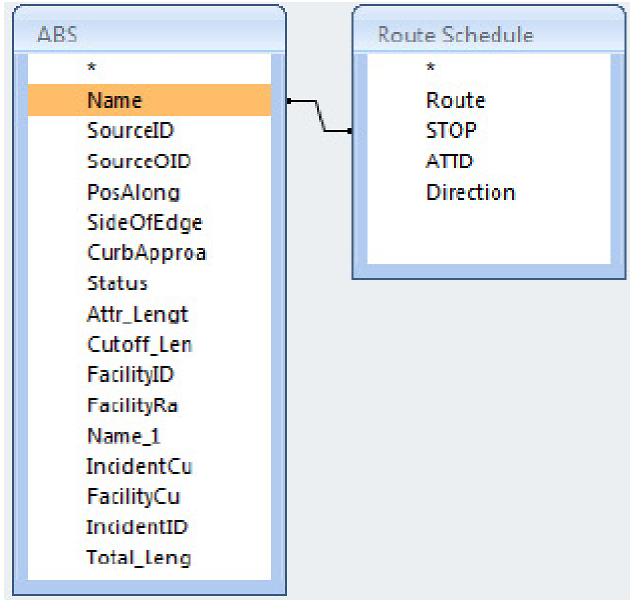


Figure 62: Relate the List of Accessible Stops and the Route Schedule Table

Figure 62 shows that TBSAT relates the *list of accessible stops* (ABS.dbf) and the route schedule table by the name of the bus stops. After the query is executed, as shown in Table 38, each bus route available at each accessible stop appears as a record in the *list of accessible routes*. Also included is the access distance from the trip origin to each corresponding accessible stop where each accessible route is available. This value is recorded in the Total_Leng field in the ABS.dbf file.

Table 38: Example of List of Accessible Routes

Accessible Routes

STOP	Route	Direction	ATTD	AccessDistance
316909	81	W	32.6	0.4024
316915	81	E	20.2	0.4318
326801	60	N	22.8	0.3469
326802	60	S	31.6	0.3280
326810	60	N	23.6	0.3919
326901	32	W	1.8	0.3872
326901	60	N	26.0	0.3872
326901	81	W	29.0	0.3872
326906	81	W	30.8	0.4318

E.3.4 Generate Route Max ATTD Tables

As discussed in section 4.3.4, TBSAT calculates the bus travel time of an SRD plan[69] according to one of three equations, depending on the relative location between this SRD plan's accessible stop and its disembarkable stop.

$$\text{Bus Travel Time} = ATTD_D + ATTD_A$$

Equation 9: Calculate Bus Travel Time (Type I)

$$\text{Bus Travel Time} = ATTD_{MAX} - ATTD_A + ATTD_D$$

Equation 10: Calculate Bus Travel Time (Type II)

$$\text{Bus Travel Time} = (ATTD_{MAX} - ATTD_A) + ATTD_{MAX\text{-}Opposite} + ATTD_D$$

Equation 11: Calculate Bus travel Time (Type III)

To calculate the $ATTD_{MAX}$ and the $ATTD_{MAX\text{-}Opposite}$ (in Equation 10 and Equation 11), TBSAT generates two tables which record the maximum ATTD of each direction for each bus route. These tables are accessed during the process of calculating the bus travel time for each SRD plan. These two tables are created and saved as the *Route Max ATTD* table and the *Route Opposite Max ATTD* table during the runtime of the TBSAT database component.

[69] An SRD plan describes the combination of the accessible **S**top, the accessible **R**oute, and the **D**isembarkable stop that is used during a simple bus trip (see section 4.3.1).

Table 39: Example of Route Max ATTD Table and Route Opposite Max ATTD Table

Route Max ATTD

Route	Direction	ATTDOfMax
10	E	18.00
10	W	18.00
22	E	115.00
22	W	99.50
32	E	51.00
32	W	48.50
522	E	81.00
522	W	80.00
60	N	59.00
60	S	54.00

Route Opposite Max ATTD

Route	Direction	OppMaxATTD
10	W	18.00
10	E	18.00
22	W	115.00
22	E	99.50
32	W	51.00
32	E	48.50
522	W	81.00
522	E	80.00
60	S	59.00
60	N	54.00

Table 39 contains an example of the *Route Max ATTD* table and the *Route Opposite Max ATTD* table that TBSAT generates. The *Route Max ATTD* table records the maximum ATTD for each direction of each bus route. This value represents the total bus travel time from the first route stop to the last route stop in a single direction. The *Route Opposite Max ATTD* table records the maximum ATTD for the bus route's opposite direction. For example, in Table 39, the maximum opposite ATTD of Route 60S is 59 minutes. This is also the maximum ATTD of Route 60N, because Route 60N is Route 60S' opposite direction.

E.3.5 Generate Arrival Timetable

As discussed in section 4.3, Step 3 of TBSAT identifies the remaining available time (T_r) for all disembarkable stops along accessible routes. The values are stored in the *Arrival Timetable*. To complete this process, TBSAT executes a series of actions:

(1) Identify all SRD plans possible from the trip origin.

As discussed in section 4.3.1, an empty *arrival timetable* that includes all SRD plans from trip origin must be produced so that the access time, the passenger waiting time, the bus travel time, and the remaining available time of each SRD plan can be calculated and stored.

TBSAT automatically queries its database to generate the *Arrival Timetable*. As discussed in 4.3.1, the TBSAT creates an empty *Arrival Timetable* that records each SRD plan's accessible stop (boarding stop), the accessible route it takes, and the disembarkable bus stop it chooses, by referring to both the *list of accessible routes* (ABS.dbf) and the *route schedule table*.

Table 40 is an example of an empty TBSAT arrival timetable.

Table 40: Example of Arrival Timetable in TBSAT

Arrival Time Table

Boarding Stop	Board Dir	Route	Arrival Stop	Direction	Access Time	tb	tw_Peak	tw_OPeak	Tr_P	Lr_P	Tr_OP	Lr_OP
336903	E	32	137702	E		55.00						
336902	W	32	137702	E		48.30						
326910	E	32	137702	E		56.00						
326901	W	32	137702	E		47.70						
336903	E	32	137805	W		51.00						
326910	E	32	137805	W		52.00						
336902	W	32	137805	W		46.80						
326901	W	32	137805	W		46.20						
336902	W	32	147713	E		47.30						
336903	E	32	147713	E		54.00						
326901	W	32	147713	E		46.70						
326910	E	32	147713	E		55.00						
326910	E	32	147803	W		52.50						
336903	E	32	147803	W		51.50						
326901	W	32	147803	W		46.70						
336902	W	32	147803	W		47.30						
326901	W	32	147805	W		44.87						
336902	W	32	147805	W		45.47						

At this stage, TBSAT creates a clean arrival timetable simply by generating all SRD plans possible from the trip origin. The bus travel time ($t_{b)}$ is already known because the chosen boarding stop, chosen bus route, and the chosen disembarkable stop for each record (SRD plan) is already known.

(2) Obtain the access time for each SRD combination.

According to the discussion regarding the calculation of the access time in section 4.3.2, the access time of an SRD plan is determined by its access distance from trip origin to boarding stop. The access distance to each accessible stop is obtained from the *list of accessible routes* when TBSAT generates the arrival timetable (see appendix section E.3.3).

With the access distance known and the access speed (V_a) specified in the factor setting form, the access time can be easily calculated by multiplying the access distance by the access speed.

(3) Obtain peak and off-peak waiting times for each SRD plan.

The primary function for calculating waiting time was derived as Equation 8 in section 4.3.3. The equation is reproduced here for convenience.

$$\text{Waiting Time } t_w = (\text{Scheduled Headway}) \times (\text{Waiting Time/Headway Ratio})$$

Equation 8: Waiting Time Estimate in TBSAT

Both the peak waiting time and the off-peak waiting time can be obtained through this function, using the scheduled headway during both peak and off-peak as recorded in the route headway table. Be aware, as mentioned in appendix section E.3.2, the value of the waiting time does not use this equation if the bus route which an SRD plan takes runs only once a day. In this case, TBSAT adjusts the peak waiting time to 15 minutes and the off-peak waiting time to 9,999 minutes.

(4) Obtain bus travel time for each SRD plan.

As discussed above, depending on the relative location between the boarding stop and the disembarkable stop that each SRD plan uses, the bus travel time t_b of each SRD plan is calculated according to one of the three equations (Equation 9, Equation 10, and Equation 11) identified in section 4.3.4, and then stored in the empty arrival timetable.

(5) Calculate peak and off-peak T_r for each SRD plan.

Completing the four actions discussed above, TBSAT calculates and stores the access time, the peak and off-peak waiting times, and the bus travel time for each SRD plan in the arrival timetable. TBSAT then calculates the remaining available time for each SRD plan using Equation 1 and Equation 2, identified in section 3.3 and repeated here for convenience.

$$T_r = t_{max} - (t_a+t_w+t_b)$$

Equation 1: Calculate Remaining Available Time

$$T_r = ADAT \; (\mathit{If}\ T_r > ADAT)$$

Equation 2: Constrain Remaining Available Time

First, the T_r for each SRD plans is calculated according to Equation 1. Then, for each SRD plan with a T_r greater than the acceptable destination access time, TBSAT adjusts T_r to be equal to the value of the ADAT that has been specified in factor setting table, according to Equation 2.

(6) Calculate peak and off-peak Remaining Available Length L_r.

As discussed in section 4.5.3, ArcGIS generates reachable areas from each disembarkable stop according to the remaining available length instead of the remaining available time T_r. With T_r obtained and *destination access speed* (DAS) specified in the factor setting form, TBSAT easily converts T_r into L_r by multiplying T_r by the DAS.

After the execution of all six actions discussed above, all fields in the arrival timetable are filled with the corresponding calculated values.

Table 41: Example of the Completed Arrival Timetable

Arrival Time Table

Boarding Stop	Board Dir	Route	Arrival Stop	Direction	Access Time	tb	tw_Peak	tw_OPeak	Tr_P	Lr_P	Tr_OP	Lr_OP
316915	E	81	396603	E	12.64	21.30	15	15	11.06	0.3780	11.06	0.3780
336902	W	32	237412	W	13.92	20.13	15	30	10.95	0.3741	-4.05	-0.1384
326810	N	60	297603	N	11.47	30.15	7.5	15	10.88	0.3717	3.38	0.1155
326914	W	81	266807	E	9.83	24.30	15	15	10.87	0.3714	10.87	0.3714
316909	W	81	266701	E	11.78	22.40	15	15	10.82	0.3698	10.82	0.3698
326907	S	60	326002	N	14.55	27.13	7.5	15	10.82	0.3698	3.32	0.1135
336903	E	32	247301	W	13.21	21.00	15	30	10.79	0.3687	-4.21	-0.1438
326901	W	81	256601	E	11.33	23.00	15	15	10.67	0.3645	10.67	0.3645
326901	W	81	256601	W	11.33	23.00	15	15	10.67	0.3645	10.67	0.3645
326802	S	60	326301	N	9.60	32.23	7.5	15	10.67	0.3645	3.17	0.1082
326901	W	32	217402	W	11.33	23.13	15	30	10.54	0.3601	-4.46	-0.1524
326910	S	60	326102	N	11.74	30.29	7.5	15	10.48	0.3580	2.98	0.1018

Table 41 is an example of a completed arrival timetable. All necessary fields, including the access time, the peak and off-peak waiting times, the bus travel time, the remaining available time, and the remaining available length, are calculated.

In the next process, TBSAT uses the completed arrival timetable to generate the list of reachable stops. This is the final output of Phase 2.

E.3.6 Generate List of Reachable Stops

As described in section 3.2.2 (the definition of reachable stops), TBSAT verifies whether a disembarkable stop is a reachable stop by testing the value T_r for that stop. If the value is greater than zero, the stop is defined as reachable. Thus, to generate the complete list of reachable stops, first TBSAT identifies each SRD plan that can reach its disembarkable stop with positive T_r remaining. This is a reachable stop. TBSAT generates a table that contains the disembarkable stops for these SRD plans. This is the total list of reachable stops. Additionally, the remaining available time (T_r) and the remaining available length (L_r) that is available at each reachable stop is included in this list.

Table 42: Exclude SRD Plans that Cannot Reach Their Disembarkable Stops within the Travel-Time Limit

Arrival Time Table

Boarding Stop	Board Dir	Route	Arrival Stop	Direction	Access Time	tb	tw_Peak	tw_OPeak	Tr_P	Lr_P	Tr_OP	Lr_OP
326802	S	60	326601	N	9.50	41.17	7.5	15	1.72	0.0589	-5.78	-0.1973
326802	S	60	326613	S	9.50	6.38	7.5	15	15.00	0.5125	15.00	0.5125
326802	S	60	326622	S	9.50	4.38	7.5	15	15.00	0.5125	15.00	0.5125
326802	S	60	326622	N	9.50	40.38	7.5	15	2.52	0.0862	-4.98	-0.1700
326802	S	60	326624	S	9.50	4.38	7.5	15	15.00	0.5125	15.00	0.5125
326802	S	60	326624	N	9.50	40.38	7.5	15	2.52	0.0862	-4.98	-0.1700
326802	S	60	326625	S	9.50	5.38	7.5	15	15.00	0.5125	15.00	0.5125
326802	S	60	326701	S	9.50	1.75	7.5	15	15.00	0.5125	15.00	0.5125
~~326802~~	~~S~~	~~60~~	~~326702~~	~~N~~	~~9.50~~	~~43.58~~	~~7.5~~	~~15~~	~~-0.68~~	~~-0.0231~~	~~-8.18~~	~~-0.2793~~

As shown in the example arrival timetable in Table 42, the last SRD plan does not reach its disembarkable stop within the given travel-time limit, either during the peak or the off-peak period, because both the peak and off-peak remaining available times are negative. Thus, the disembarkable stop of this SRD plan (with Arrival Stop 326702) fails to qualify as a reachable stop. Conversely, the disembarkable stops for the other SRD plans listed in Table 42 are reachable stops because they can be reached from the trip origin through these SRD plans within the travel-time limit. This is indicated by at least one positive value in their remaining available time for the peak or off-peak period. Note that one or the other field may be negative, but not both.

Note that both Arrival Stops 326622 and 326624 can be reached within the time limit via two different SRD plans. As discussed in section 3.2.2, TBSAT assumes that a traveler tries to maximize his T_r at each reachable stop in order to maximize the size of the reachable area from each reachable stop. Thus, according to the discussion in the last paragraph of section 4.3, if a reachable bus stop can be reached by multiple SRD plans within the allotted time, TBSAT uses the SRD with the greatest T_r.

Executing these two actions discussed above, TBSAT generates the *list of reachable stops* based on the arrival timetable. To do this, TBSAT executes the Access database query named *Produce List of Reachable Stops*. The generated list of reachable stops is similar to Table 43.

Table 43: Example of List of Reachable Stops

Reachable Stops

Stop	Tr_P	Tr_OP	Lr_P	Lr_OP
326406	9.52	2.02	0.3254	0.0692
326408	15.00	15.00	0.5125	0.5125
326501	4.86	0.00	0.1660	0.0000
326502	15.00	15.00	0.5125	0.5125
326504	15.00	15.00	0.5125	0.5125
326506	6.02	0.00	0.2058	0.0000
326508	3.69	0.00	0.1261	0.0000
326601	1.72	0.00	0.0589	0.0000
326613	15.00	15.00	0.5125	0.5125
326622	15.00	15.00	0.5125	0.5125

The list of reachable stops contains unique reachable stops that posses a single set of peak and off-peak T_r and L_r values. This list is stored in the table of *Reachable Stops* in the database, and is automatically output to a Microsoft EXCEL file named *Reachable Stops.xls* ready for input to ArcGIS. In Phase 3, based on this list of reachable stops, TBSAT completes Step 5 and Step 6, generating reachable areas and the complete time-based service area map in the ArcGIS environment.

E.4 Phase 3: Generate Time-Based Bus Service Area

In Phase 3, TBSAT returns to the ArcGIS component to complete Step 5 and Step 6, the last two steps of the TBSAT six-step procedure. TBSAT first uses the service area analysis[70] function in ArcGIS to calculate the peak and off-peak reachable areas surrounding each reachable stop. The service area analysis function calculates the reachable area from each of the given *facilities* according to the given information. In the TBSAT application, since the reachable areas are developed from the reachable stops, the facilities are the reachable stops. The calculated reachable areas are placed on two separate

[70] The service area analysis is one of the four ArcGIS network analysis functions. It identifies the service area within the given distance from the designated facilities (locations).

service area analysis layers, one for the peak period values and the other for off-peak.[71] Second, using the dissolve function of ArcGIS,[72] TBSAT merges all identified peak reachable areas into a single peak time-based service area polygon and then merges all off-peak reachable areas into an off-peak time-based service area polygon. Each of these polygons represents the peak and the off-peak bus service area under the user's pre-determined condition.

[71] The service area analysis layer is a group layer where ArcGIS stores all essential information/layers for a service area analysis. A service area analysis layer contains one facilities layer, which contains the facilities from which ArcGIS will develop service area. Also, the result of a service area analysis, which is the polygon(s) that indicates the service area from each of the facilities, is generated and stored in another layer in the service area analysis layer named as the polygons layer after the service analysis is performed.

[72] The dissolve tool of ArcGIS merges multiple polygons from the same layer into a single, large polygon.

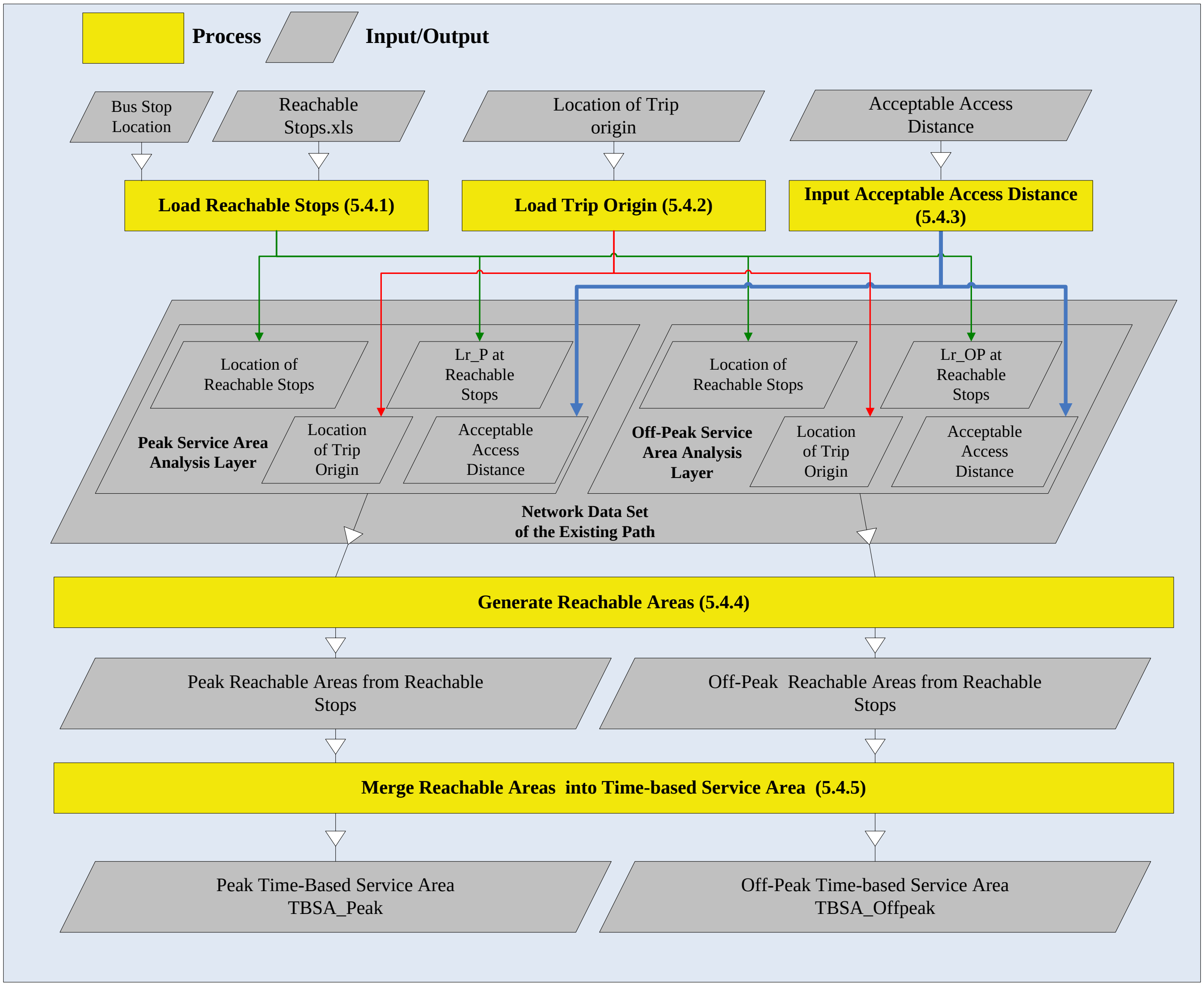


Figure 63: Phase 3 Flowchart

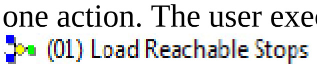
Figure 63 displays the process flowchart for Phase 3. TBSAT creates two service area network analysis layers named *Peak Service Area Analysis Layer* and *Off-Peak Service Area Analysis Layer*. After inputting the location of reachable stops and their corresponding T_r and L_r during the peak hours into the *Peak Service Area Analysis Layer,* TBSAT generates the reachable areas during the peak hours from the reachable stops. Similarly, the *Off-Peak Service Area Analysis Layer* generates reachable areas during the off-peak hours from the reachable stops.

However, as discussed in section 3.2.1, the defined TBSA in this research also includes the accessible area. This is the area around the trip origin that can be reached without taking buses. To identify this accessible area, TBSAT includes the trip origin into both service area analysis layers (as one of the facilities). ArcGIS uses the data in these two layers to generate the service areas. From the trip origin ArcGIS generates a service area polygon as it does for the other reachable stops. After the configurations of the two service area analysis layers are complete, the user may execute the tool within the TBSAT toolbox to generate the peak and off-peak reachable areas in each of the service area analysis layers. Finally, by merging the reachable area polygons, the user obtains a set of peak and off-peak time-based service area polygons that depict the areas that can be reached from the trip origin within the total travel-time limit.

E.4.1 Load Reachable Stops

TBSAT inputs the location of the reachable stops as facilities into both the peak and off-peak service area analysis layers. From this, ArcGIS generates polygons to indicate the reachable areas from these reachable stops. In order to load reachable stops to peak and off-peak service area analysis layers, TBSAT must specify the spatial location of these reachable stops to ArcGIS. However, the list of reachable stops, which TBSAT generates in Phase 2, does not contain the geographic coordinate of these reachable stops. Instead, it contains only the bus stop name, the remaining available time (T_r) at each, and the remaining available distance (L_r)at each.

The geographic coordinate of the reachable stops is available from the bus stop locations layer generated by the Accessible Stops Network Analysis Layer (ASNAL) in Phase 1. The bus stop locations layer records the location of all bus stops in the bus system. TBSAT joins the *list of reachable stops* to the *bus stop locations* table in the ASNAL. This assures that each bus stop in the joined bus stop location table (which has a matching bus stop in the list of reachable stops) will be appended with a non-null remaining available time (T_r) and a remaining available time distance (L_r). After the join, the bus location table contains both the spatial location and the remaining available time and distance for each reachable stop. TBSAT inputs both the geographic location of these reachable stops and their corresponding remaining available distance into the peak and off-peak service area analysis layers.

TBSAT must then execute four processes in order to load the location of reachable stops into both peak and off-peak service area analysis layers as facilities. TBSAT provides the user a tool to automatically complete these four processes in one action. The user executes the *Load Reachable Stops* tool


, found in the TBSAT Phase 3 toolset, to load the location of reachable stops into both peak and off-peak service area analysis layers (see Step 8 in Appendix A: TBSAT USER'S QUICK MANUAL).

The *load reachable stops* tool in the TBSAT toolbox executes the following four processes:

1. Join the list of reachable stops to bus stop locations table.

As discussed above, the first process that the *load reachable stops* tool performs is to join the list of reachable stops into the bus stop locations table. Since the list of reachable stops was saved as the *Reachable Stops.xls* (see appendix section E.3.6), the *load reachable stops* tool can directly import the list into ArcGIS as a table.

Table 44: Join List of Reachable Stops into Bus Stop Locations Table

Attributes of VTA Bus Stops

ObjectID	Shape	Name	SourceID	SourceOID	PosAlong	SideOfEdge	CurbApproach	Status	Attr_Length	Cutoff_Length
5820	Point	276803	4Counties	55916	0.861393	Left Side	Either side of vehicle	OK	0	<Null>
5821	Point	276805	4Counties	477	0.511515	Right Side	Either side of vehicle	OK	0	<Null>
5822	Point	276806	4Counties	484	0.548326	Right Side	Either side of vehicle	OK	0	<Null>
5823	Point	277001	4Counties	296	0.289338	Right Side	Either side of vehicle	OK	0	<Null>
5824	Point	277002	4Counties	309	0.848361	Right Side	Either side of vehicle	OK	0	<Null>
5825	Point	277006	4Counties	289	0.506631	Right Side	Either side of vehicle	OK	0	<Null>
5826	Point	277201	4Counties	208	0.41562	Left Side	Either side of vehicle	OK	0	<Null>
5827	Point	277202	4Counties	170	0.528593	Left Side	Either side of vehicle	OK	0	<Null>
5828	Point	277203	4Counties	208	0.208776	Right Side	Either side of vehicle	OK	0	<Null>
5829	Point	277204	4Counties	182	0.018749	Right Side	Either side of vehicle	OK	0	<Null>
5830	Point	277205	4Counties	183	0.955649	Right Side	Either side of vehicle	OK	0	<Null>
5831	Point	277302	4Counties	64821	0.195591	Right Side	Either side of vehicle	OK	0	<Null>
5832	Point	277303	4Counties	162	0.626582	Right Side	Either side of vehicle	OK	0	<Null>

Record: 1 Show: All Selected Records (3 out of 4456 Selected) Options

Attributes of 'Reachable Stops$'

Stop	Tr_P	Tr_OP	Lr_P	Lr_OP
276803	6.87149	6.87149	0.234776	0.234776
277201	15	8.767604	0.5125	0.29956
277204	15	7.867604	0.5125	0.26881
286802	15	15	0.5125	0.5125
286803	15	15	0.5125	0.5125
286804	5.87149	5.87149	0.200609	0.200609
286806	4.87149	4.87149	0.166443	0.166443
287201	15	9.667606	0.5125	0.33031
287810	7.667604	0.167604	0.261976	0.005726
296801	15	15	0.5125	0.5125

Record: 1 Show: All Selected Records (0 out of 208 Selected) Options

As shown in Table 44, the lower table of reachable stops contains the name of reachable stops (field: Stop), and the upper table of bus stop location contains all bus stops in the system (field: Name). Consequently, the tool can join (append) the four fields in the lower table (which are the peak and off-peak remaining available time and distance fields) into the upper table by matching the bus stop names.

Table 45: Joined Bus Stop Locations Table

Selected Attributes of VTA Bus Stops

Facilities.ObjectID	Facilities.Shape	Facilities.Nam	'Reachable Stops$'.Lr_OP	Facilities.SourceID	Facilities.SourceOID	Facilities.PosAlong	Facilities
5820	Point	276803	0.234776	1	55916	0.861393	
5821	Point	276805	<Null>	1	477	0.511515	
5822	Point	276806	<Null>	1	484	0.548326	
5823	Point	277001	<Null>	1	296	0.289338	
5824	Point	277002	<Null>	1	309	0.848361	
5825	Point	277006	<Null>	1	289	0.506631	
5826	Point	277201	0.29956	1	208	0.41562	
5827	Point	277202	<Null>	1	170	0.528593	
5828	Point	277203	<Null>	1	208	0.208776	
5829	Point	277204	0.26881	1	182	0.018749	
5830	Point	277205	<Null>	1	183	0.955649	
5831	Point	277302	<Null>	1	64821	0.195591	

Table 45 shows the result of the join action. Now only a few of the bus stops of the system are assigned a non-null value in T_r and L_r. These are the reachable stops.

2. Select reachable stops in the joined bus stop locations table.

As shown in Table 45, TBSAT only needs the bus stops that contain non-null value in their T_r and L_r fields to be loaded into the peak and off-peak service area analysis layers. Thus, in the second process of *the load reachable stops tool*, the TBSAT selects only these records (bus stops) from the entire joined bus stop location table.

3. Add reachable stops to the peak and off-peak service area analysis layers.

In the third process of the *load reachable stops tool*, TBSAT loads the location of the reachable stops into both the peak and the off-peak service area analysis layers. In addition, the peak and off-peak remaining available distances (L_r) for each reachable stop is loaded into each of these two layers, along with its corresponding reachable stops as the *breaks*[73] of each reachable stop. The breaks of a reachable stop specifies the distance of reachable area that can be generated from this reachable stop.

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[73] *Breaks* in a service area analysis of ArcGIS represents the specified maximum range of the service area from the facility. For example, if the breaks value of a reachable stop is 0.5 miles in a service area analysis, ArcGIS generates a polygon that indicates what area can be reached from this stop within 0.5 miles.

4. **Remove join between the list of reachable stops and the bus stop locations table.**

The last process of the *load reachable stops* tool executed removes the join relationship between the bus stop location table and the current list of reachable stops. This is similar to the actions described in appendix section E.2.6. Since the bus stop location table in the ASNAL may be joined by a different list of reachable stops in the next TBSAT run, the relationship (the join) between these two objects must be removed after loading the reachable stops into the peak and off-peak service area analysis layers. By executing the remove join action, in future TBSAT runs the bus stop location table can be again joined to the new list of reachable stops.

After running the *load reachable stops* tool, ArcGIS contains the information regarding the location of the reachable stops and the breaks (the remaining available distance) loaded in both peak and off-peak service analysis layers. TBSAT is now ready to generate the reachable areas.

E.4.2 Load Trip Origin

As discussed in the beginning of appendix section E.4, except for the reachable areas generated from reachable stops, the accessible area around the trip origin should also be generated as a polygon and merged with all reachable areas in order to complete the time-based bus service area map. Thus, similar to loading reachable stops and their remaining available time into peak and off-peak service area analysis layers, the location and the breaks of the trip origin must be loaded into both the peak and the off-peak service area analysis layers so that the accessible area around the trip origin can be generated.

Using the *load trip origin tool* (02) Load Trip Origin in the TBSAT toolbox allows the user to quickly load the location of the trip origin into both peak and off-peak service area analysis layers (see Step 9 in Appendix A: TBSAT USER'S QUICK MANUAL).

E.4.3 Input Acceptable Access Distance

After loading the location of the trip origin into both the *peak* and the *off-peak service area analysis layers*, the TBSAT user must set the breaks for the trip origin. This is the range used to control the size of the accessible area around the trip origin. The value of the breaks for the trip origin is the acceptable access distance that the user calculated using the acceptable access distance calculator (see appendix section E.2.1). The acceptable access distance represents the greatest distance the traveler is willing to travel to without taking a bus.

To specify the breaks for the trip origin in the *peak service area analysis layer*, the user must switch to the *peak service area analysis layer* and open the property window. In the *analysis setting* tab of the Layer Properties window, the breaks value for the trip origin must be input into the *default breaks* box.

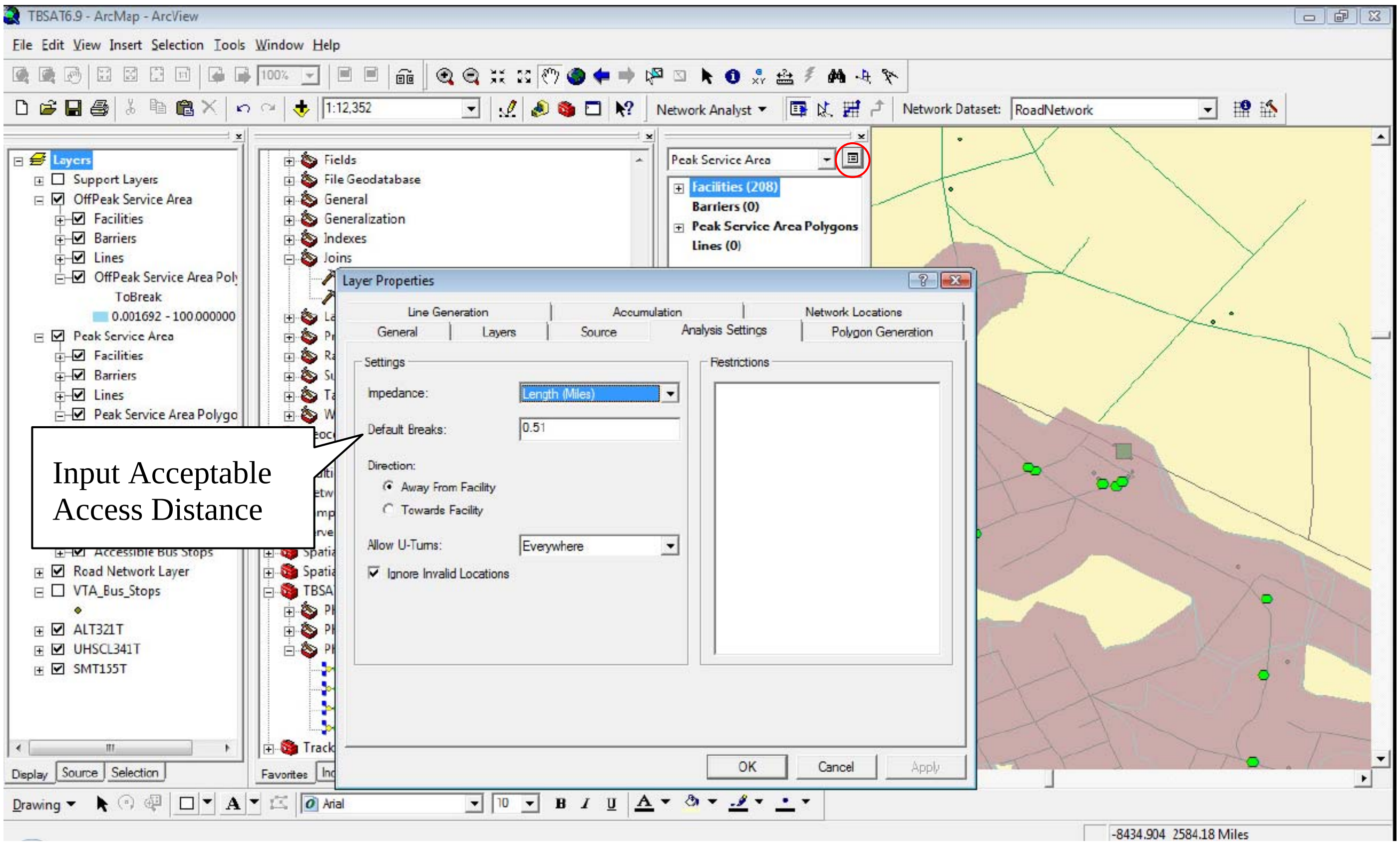

Figure 64: Input Breaks for Trip Origin

Figure 64 shows the Layer Properties window opened by the user to input the breaks for the trip origin. Similar to specifying the breaks for the trip origin in the *peak service area analysis layer*, the same breaks value must also be entered in the default breaks box in the Layer Properties window of the *off-peak service area analysis layer* according to the description.

Once the location and the breaks for the trip origin are correctly specified and loaded, TBSAT generates the reachable areas from each reachable stop, and generates a service area polygon that indicates the accessible area around the trip origin.

E.4.4 Generate Reachable Areas

TBSAT uses the *Calculate Time-Based Bus Service Area* tool (03) Calculate Time-Based Bus Service Area in the TBSAT toolbox to generate one reachable area for each reachable stop and the accessible area from the trip origin that is loaded in the *peak* or *off-peak service area analysis layer*. The generated peak reachable areas are stored in the *peak service area polygon layer* of the *peak* *service area analysis layer*. Similarly, the off-peak reachable areas are stored in the *off-peak service area polygon layer* of the *off-peak service area analysis layer*, as shown in the left side of Figure 65.

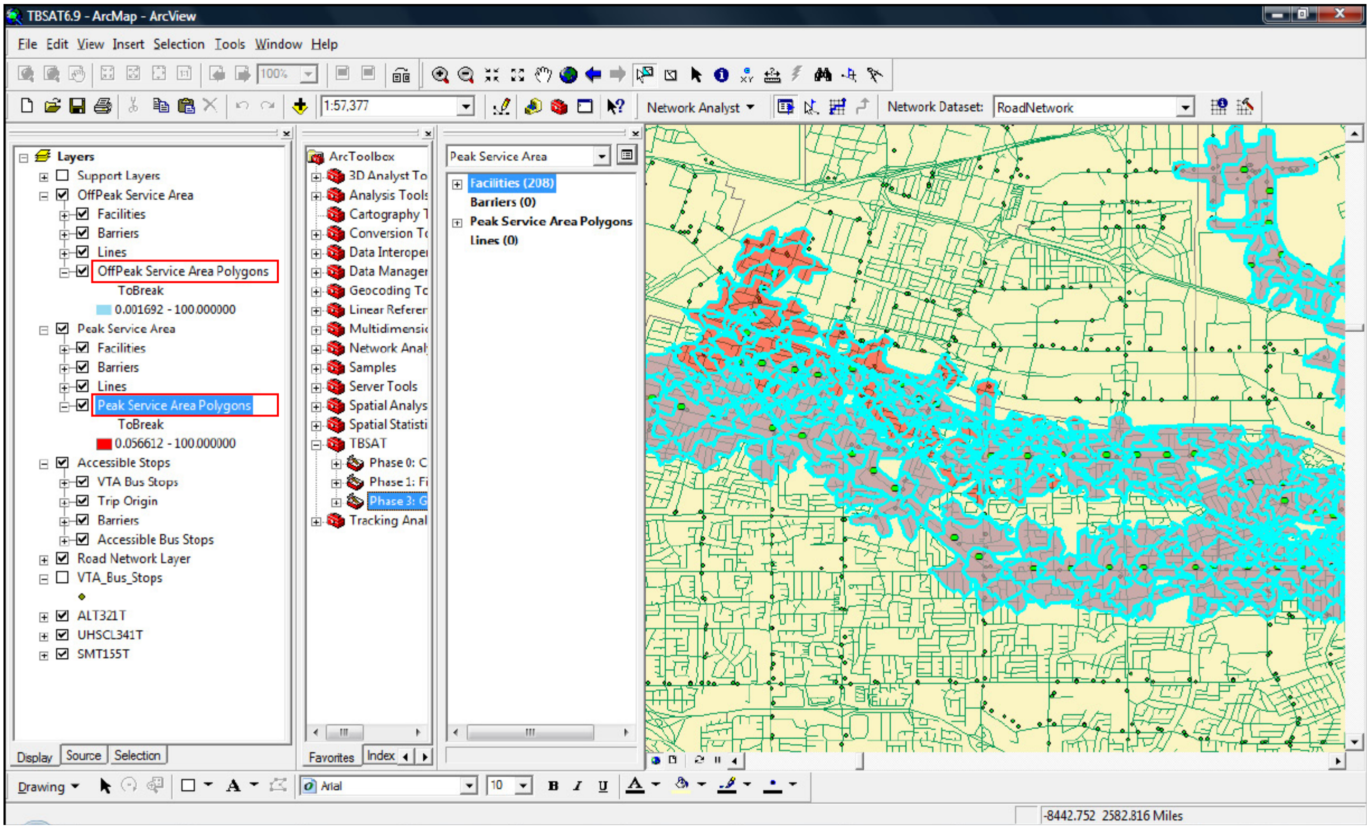

Figure 65: Overlaid Reachable Areas

As shown in Figure 65, after running the *Calculate Time-Based Bus Service Area* tool, the generated reachable areas are displayed on the map. The overlay of all reachable areas reveals the entire time-based bus service area. The red polygons represent the peak reachable areas and the light purple polygons represent the off-peak reachable areas. Thus, the last process left is to merge all reachable areas into one single polygon to represent the entire time-based bus service area.

E.4.5 Merge Reachable Areas into a Single Time-based Service Area

To merge the reachable area polygons into a single polygon that represents the entire time-based bus service area, TBSAT uses the *dissolve* function in ArcGIS. This aggregates all polygons in the same layer into a single large polygon. In TBSAT, this process is integrated with the generated service area pieces process introduced in appendix section E.4.4, the *Calculate Time-Based Bus Service Area* tool (03) Calculate Time-Based Bus Service Area in the TBSAT toolbox.

Thus, when the user executes the *Calculate Time-Based Bus Service Area* tool, it not only generates the reachable areas for reachable stops but also merges all peak and off-peak reachable areas into two, respective, time-based bus service area polygons. Both of the peak and off-peak time-based service area polygons are stored in a *personal geodatabase*[74] file named *TBSAT_Merged_Service Area.mdb*, as two separate polygon feature classes:[75] *TBSA_Peak* and *TBSA_Offpeak*.

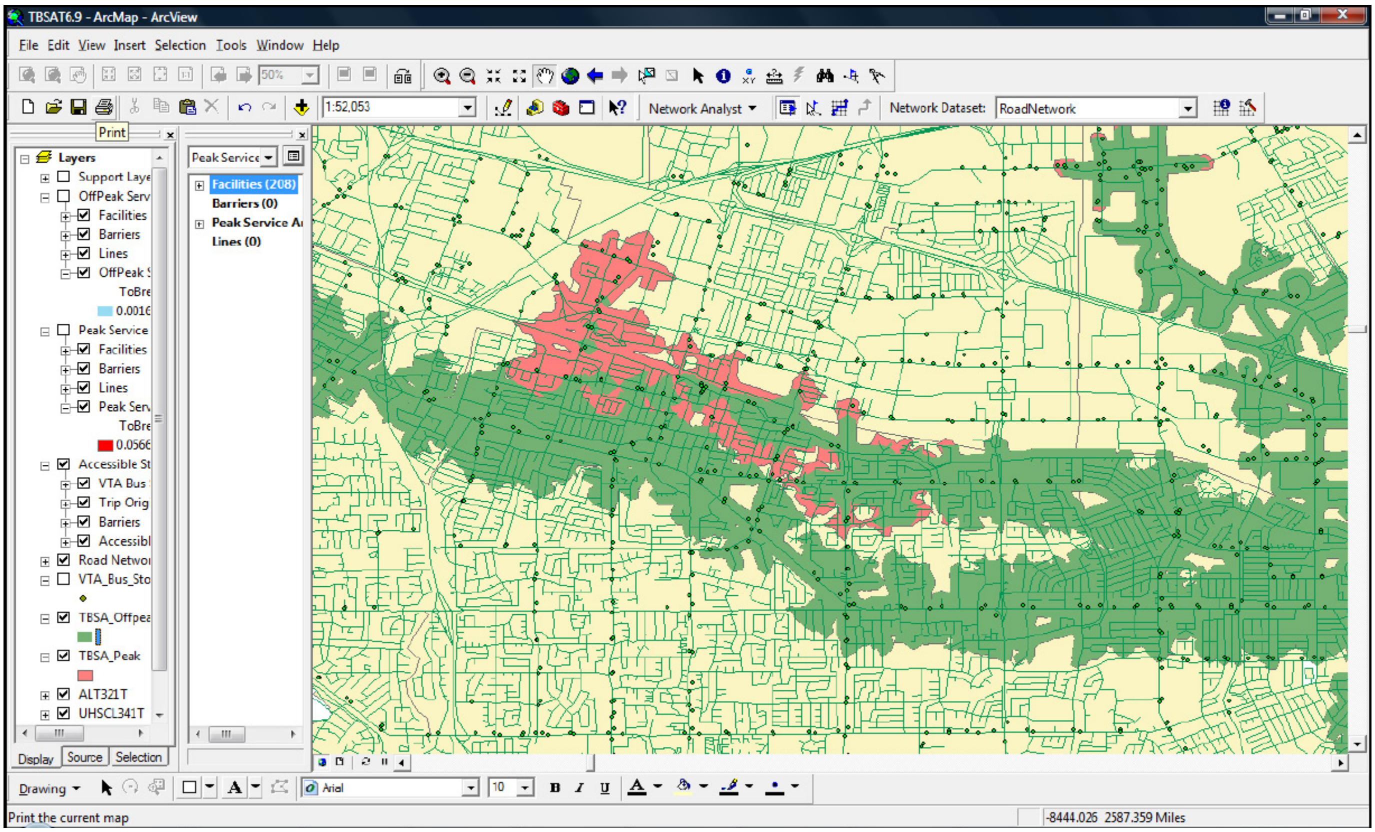

Figure 66: Peak and Off-Peak Time-Based Service Area

[74] The *personal geodatabase* is a special database file for ArcGIS to store the information of the objects (dots, lines, or polygons) located in a geographic area. In a personal geodatabase the geomertry and the location of its contained objects are recorded. For example, TBSAT_Merged_Service Area.mdb (used by TBSAT) is a geodatabase that records the geometry and the location of both the peak and off-peak time-based bus service area polygons. In addition, other attributes of an object, if any, can also be stored in a personal geodatabase. For example, the size of the peak or off-peak time-based service area is an attribute of the time-based bus service area polygons. It can be stored in the same TBSAT_Merged_Service Area.mdb along with the geometry and the location of the time-based bus service area polygons.

[75] A *polygon feature class* records the geometry and the location of one or more polygons for ArcGIS. TBSAT saves the peak and off-peak time-based bus service areas as two separate polygon feature classes so that each can be loaded into ArcGIS at any time.

As shown in Figure 66, the final results of one TBSAT run are two time-based service area polygons. The green shape represents the off-peak time-based bus service area. The red shape, which actually includes the area beneath the green shape and the red shape, represents the peak time-based bus service area. In Figure 66, most of the red shape is overlapped by the greed shape, thus, the visible red shape shows only the area that can be reached during the peak hours but not the off-peak hours. Since the peak bus waiting time is usually less than the off-peak passenger waiting time, the traveler from the trip origin should be able to reach some places that cannot be reached during off-peak hours.

E.5 Clean Old Results Tools

Before each TBSAT run, some results of the last TBSAT run that remain stored in the TBSAT ArcGIS component must be cleared so that the results of the next run can be correctly stored. These results can be divided into two categories: Phase 1 results and Phase 3 results. Phase 1 results to be cleared include the location of the trip origin and the list of accessible stops. Phase 3 results that need to be cleared are the location of the reachable stops and the generated reachable area polygons.

TBSAT provides two tools to the user in the *Clear Last Output* toolset in the TBSAT toolbox. The *Remove Old Trip Origin/Accessible Stops* tool (01) Remove Old Trip Origin/Accessibile Stops clears the designated trip origin and the generated list of accessible stops in the last TBSAT run so that a future user may designate a new trip origin to generate the new list of accessible stops correctly during Phase 1. The *Remove Old Reachable Areas* tool (02) Remove Old Reachable Areas removes the locations of reachable stops and the generated reachable area polygons so that the new list of reachable stops can be correctly imported and the reachable area polygons can be correctly generated during Phase 3.

The user must remember to run these two cleanup tools at the beginning of each TBSAT run to ensure that the results of the last run do not affect the current run (see Step 2 in Appendix A: TBSAT USER'S QUICK MANUAL).

Appendix F: GLOSSARY

Term	Definition	Reference Section
Absolute Travel Time Differential (ATTD)	The time a bus needs to travel from the first stop of this bus route to another bus stop on this route. This value is both route and bus stop specific.	4.3.1
Acceptable Access Distance	The longest distance a bus rider is willing to travel from the trip origin to the boarding bus stop. In TBSAT, acceptable access distance is obtained by converting acceptable access time (AAT) through the given access speed.	4.2
Acceptable Access Time (AAT)	The maximum time a bus rider is willing to spend on accessing to nearby bus stops. TBSAT default AAT is 15 minutes, which is a recommended acceptable access time for walking.	3.3, 4.1.7
Acceptable Destination Access Time (ADAT)	The maximum time a bus rider is willing to spend on accessing possible destinations after disembarking.	3.3
Access Distance	The distance from trip origin to each bus stop along streets.	4.1.3
Access Speed (V_a)	The speed in which a bus rider access to the boarding stops. TBSAT suggests an access speed of 2.05 mph if walking is assumed to be the mode people use to access to accessible stops.	4.1.5
Access Time (t_a)	The duration of accessing a bus stop from the trip origin.	3.3, 4.1.6
Accessible Route	Bus routes which are available at accessible stops.	3.2.2
Accessible stop	Bus stops which a bus rider can access from the trip origin within their total travel time budget and within their acceptable access range.	3.2.2
Arrival Timetable	A “container” which records the all possible simple bus trips that may occur from the trip origin.	4.3

Breaks	*Breaks* in the service area analysis of ArcGIS represents the maximum range of the service area from a facility.	5.4.2
Bus-travel time (t_b)	The in-vehicle time from an accessible stop to a possible descending bus stop through accessible routes.	3.3
Coefficient of Variance of Headways	Standard Deviation of Headway Deviations/Mean Schedule Headways. Coefficient of variance of headway reflects the impact on waiting time due to the traffic condition.	4.3.3
Cutoff	The range that ArcGIS uses to search for facilities around trip origin in a closest facility analysis.	E.2.1
Disembarkable Stop	The bus stops on accessible routes where a bus rider can disembark the bus. Each disembarkable stop can be reached from the trip origin within different amount of time.	3.2.2
Group Network Analysis Layer	A group layer contains multiple layers that are required in one GIS process. A group network analysis layer contains multiple layers that are required in a single network analysis process.	E.2.1
List of Routes to Accessible Stops	The intermediate result layer of the *TBSAT Find Accessible Stops* tool. It lists all routes from the trip origin to each accessible bus stop and the length of these routes (Total_Length). In TBSAT, this list will change depending on the location of trip origin, the access speed, the acceptable access time, and the layout of the existing path.	E.2.2
Reachable Area	The area a bus rider can reach from a reachable stop within the remaining available time. The geometry of the reachable area around a reachable stop is decided according to the remaining available travel time the bus rider possess after disembarking at that stop, and the existing paths around that reachable stop along which the traveler can move away from that bus stop.	3.2.2
Reachable Stop	Bus stops which a bus rider from the trip origin can reach through an accessible route within the total travel-time limit.	3.2.2

Remaining Available Length (Lr)	The distance that a reachable area is allowed to be developed from a reachable stop. Remaining available length is generated by multiplying the remaining available time with the destination access speed.	4.5.3
Remaining Available Time (Tr)	The remaining time budget a person possesses after disembarking at a bus stop along an accessible route. The value of the remaining available time at a bus stop is the difference between the travel time limit and the total travel time from the trip origin to that bus stop.	3.2.2, 4.3.7
Scheduled Headway	The scheduled time-interval between two successive buses of the same bus route.	4.2
Serviced Area	The proportion of an geographical area that is covered by a time-based bus service area.	5.5.1
Simple Bus Trip	A bus trip that involves in no route transfer behavior. A simple bus stop also allows only one mode when accessing the boarding bus stop, and only one mode to reach the final destination after disembarking the bus.	3.1
SRD Plan	Possible combinations among the accessible stop, the accessible route, and the disembarkable stop. An SRD plan represents a series of choices of an traveler from trip origin, including which accessible bus stop to access to, which accessible route to take, and at which bus stops to disembark.	4.3
Time-Based Bus Service Area (TBSA)	The bus service area of a given location, which represents the area a traveler can travel to by bus under a travel time limit.	2.3, 3.2.1
Waiting time (t_w)	The waiting time before the arrival of a bus route at a bus stop. The value of the waiting time ranges from zero to the route's scheduled headway if the headway between buses is kept as scheduled.	3.3
Waiting Time/Headway Ratio	The ratio between the time a person have to spend on waiting for their desired bus route and the real scheduled headway of that route.	4.2