Using Automatically Collected Data for Bus Service and Operations Planning

by

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Abstract

Transit agencies have traditionally used manual data to measure performance and plan service, but many transit agencies now fulfill these tasks by using automated data collection systems (ADCS), including Automatic Vehicle Location (AVL), Automatic Passenger Counters (APC), and Automated Fare Collection (AFC) systems. ADCS enable service planners to make more informed decisions due to the larger, more ubiquitous, and timelier sets of performance data.

This thesis evaluates current MBTA bus service in Somerville and Medford using several types of ADCS-based performance indicators. Route profiles are developed for each route in the study area and demand is analyzed for each route and its segments. Archived AVL running times are analyzed and recommendations are produced to improve reliability by adjusting the current scheduled running times where appropriate. This thesis evaluates several service planning scenarios using GIRO Inc.'s NetPlan software package, which is a sketch service planning and timetabling tool linked to its HASTUS automated scheduling system. The outputs of the ridership and running time analyses are used as inputs into bus service scenario planning process. The service change scenarios include implementing even, clock-face headways, utilizing interlining, improving the scheduled running times and layover times, modifying frequencies based on demand, synchronizing routes that serve the same route segments, and incorporating selected changes in routing. The number of buses required to serve each timetable scenario is the primary output of interest.

This thesis finds that automated sketch service planning tools, such as NetPlan, can improve the efficiency of timetables by performing thousands of iterations that would otherwise be impractical. In the resource-constrained AM peak, timetabling inefficiencies in the existing schedule were reduced to improve reliability, increase frequencies, and modify routings. The peak period service frequency changes resulted in an expected net passenger wait time and scheduled delay savings of 165 hours. For the most comprehensive timetabling scenarios, interlining was found in 72 percent of the optimized vehicle blocks indicating that transit agencies can create timetables that use highly reliable cycle times and equitable headways based on current route ridership and cost considerations.

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1 Introduction

This thesis explores how automatically collected data can be used to enhance bus network service planning. The portion of the MBTA network serving the Boston suburbs of Somerville and Medford will be used as a case study. The research explores primarily short-term alterations to bus service but also with consideration to medium-term and long-term planning.

Many U.S. transit agencies have been using automated data collection systems (ADCS) of one or more types for many years. These data have replaced or reduced the use of many traditional manual methods of data collection due to the low cost, high reliability, and large datasets available with ADCS. The use of ADCS in service planning is becoming increasingly popular as new and improved ways of using the data are invented.

Transit service planning is often carried out in an ad hoc incremental fashion with adjustments made one route at-a-time. There is often little consideration of the effects of the changes on the network. An agency may go many years, or even decades, without performing an in-depth study of bus routes in a sub-area of the network. This is why capital projects that increase the accessibility to rapid transit are, in principle, good opportunities to analyze the affected portion of the bus network. However, it requires a good deal of effort to analyze the existing bus service and to predict ridership and justify the resources needed following the extension, so there has been a wide range in the extent to which bus routes have been studied.

1.1 Motivation

This thesis is relevant, because transit agencies must rely on available data when making service planning decisions. They desire to know as much as possible about the existing service performance and demand for their system. Poor service, whether it is due to overcrowding, unreliability, scheduling and operating inefficiencies or deficiencies, infrequent or irregular schedules, or poor network design, is of particular interest to agencies, because this is the main reason they lose customers.

The entire service planning process is usually considered only prior to service operations, but data from operating the service can be used as input into the service planning process. Often times, many service changes are implemented at the same time and then only minor changes are made over the next several years. If the relationship between service planning and operations were more cyclical, transit agencies would be better equipped to make incremental changes to all routes for each timetable (or scheduling pick) after the entire network is close to optimal.

1.2 Research Objectives

This thesis will explore the use of automatically collected data for service planning and operations for a bus network. To frame the question, the following questions will be addressed:

- What types of service planning tools can be developed using automatically collected data both single and in combination?
- Do these tools replace other ones? Are they cost-effective?
- How can this information be used to improve decision making within a transit agency?
- How effective can macro-scheduling software be in analyzing service changes?

In order to answer these questions, this thesis will achieve the following objectives:

- Examine current practical and theoretical methods for analyzing automatically collected data
- Create a route profile for each study area bus route that includes the alignment, span of service, frequency of service, and daily ridership
- Measure the ridership for segments of bus routes
- Estimate an origin-destination (O-D) matrix for trips by public transportation that start, pass through, or end in the study area. Determine if there are origin destination pairs which currently require transfers that could cost-effectively be served by one-seat rides
- Analyze the existing running times
- Identify ways to use limited resources, specifically buses and operators, more efficiently by optimizing scheduled running times, cycle times, frequencies, and use of interlining
- Determine if there are locations that are either under-served or over-served by public transportation given constrained resources

1.3 Research Approach

The goal of this research is to develop service planning tools for a set of routes in a bus network. The performance of the bus routes will first be summarized based on the schedules and manually-collected data traditionally available to the transit agency. Prior research on automatic data collection systems and how they could be used by transit agencies in service planning will be reviewed.

Following these reviews of current practice, the automatically-collected and manually-collected data will be used in various analyses of demand and performance. Route Profiles, which include frequency of service, span of service, and the loading profiles, are developed for each route. The loading profiles are used to determine the key locations on the route, along with the locations of peak loading. Ridership numbers from ride checks, automatic passenger counts (APC), and automated fare collection (AFC) datasets will be compared. APC data will be used to identify overcrowded buses. Distributions of actual running times for each route will be derived from the automatic vehicle location (AVL) data and analyzed based on common industry practices to improve service reliability at a reasonable cost. Other analyses will be performed on the study area routes including results from a community bus survey, an estimated origin-destination (O-D) matrix, transfer rates, public transportation trip rates on route segments, and on-time performance.

Once the analysis of the existing bus service has been completed, the final part of the research involves testing changes to scheduled running times, frequencies, and interlining strategies using scheduling software (specifically GIRO's NetPlan). For existing conditions, it may be possible either to decrease the number of buses required to serve the Somerville and Medford routes or to increase the frequency on the routes by shifting departure times of trips on some routes or by increasing the use of interlining. For future scenario testing, the proposed cycle times will be used and frequencies on the bus routes will be modified based on the results of the demand analysis and the O-D matrix. The first scenario will be based on the routes having the same number of buses as are currently used. The second scenario will relax that assumption. After completing the analyses, specific recommendations will be made to the MBTA for the Somerville and Medford sub-area of the MBTA bus network.

1.4 Inputs for Bus Service Planning

The following subsections describe the types of manual and automatic data collected by transit agencies, and how they are used in the bus service planning process.

1.4.1 Manual Data Collection

Manually-collected data requires "checkers" to record performance and demand data over a limited time and/or limited portion of the transit network. All data used in the service planning process, such as ridership by stop, the ridership percentage of each fare type, actual observed running times, etc. used to be obtained from these manual counts. Although transit agencies have reduced or eliminated many of their manual data collection efforts, manual data is still used by service planners for some measures that are complex to automate. For example, many transit agencies still use passenger surveys to estimate passenger Origin-Destination matrices. However, even this use can be replaced by combining automatically-collected data systems (Wang, 2009).

1.4.2 Automated Data Collection Systems (ADCS)

There are three main types of Automated Data Collection Systems (ADCS) used by transit agencies; Automatic Vehicle Location (AVL), Automatic Passenger Counts (APC), and Automated Fare Collection (AFC).

Automatic Vehicle Location (AVL)

AVL devices frequently poll the location of buses for real time operations control and to enhance driver and passenger safety systemwide. Archived AVL datasets are currently used to analyze on-time performance and running times.

Automatic Passenger Counts (APC)

An APC system determines the number of boarding and alighting passengers at bus stops and determines the loading on the bus. APC systems are useful for providing summary statistics for National Transit Database reporting (Clever Devices, 2010b). In addition, APC they are often used for dwell time analyses and locating peak load points.

Automated Fare Collection (AFC)

AFC systems do as their name suggests; they collect fares using automated readers and electronic media that maintain records of all fare transactions. They are especially useful for determining passenger travel patterns in a network, because there is a unique identifier for every person who uses a smartcard.

1.5 Service Planning

The manually and automatically data are inputs to the bus service planning process. Cedar and Wilson detail the 5-step transit planning process as shown in Table 1-1 (1986). The output of each planning activity is used as a primary input into the next activity. The first step in the process is network design, which uses supply and demand data as inputs as well as other indicators of route performance. Service planners have several options to consider if the network design is ineffective. First, they can modify some of the existing routes. Secondly, it may be more beneficial to simply add new routes. Lastly, new operating strategies could be used that allow the agency to improve the performance of the existing routes. The second step in the transit planning process is setting the frequencies for all routes. Frequencies are constrained in the network by the subsidy and resources available, the service policies that guide planning decisions, and the current patronage. The third step is the development of the timetable, which is setting when trips depart and arrive at key points on the route. The times of the first and last bus trips are constrained by span of service standards and protecting connections with the last rapid transit trip at transfer nodes. Running times are assigned by time period, and, therefore, the times of trips are largely constrained by the frequencies from the previous step. The fourth step in the process is bus scheduling. Recovery times and deadhead times are inputs. The fifth and final step in the process is driver scheduling. The driver work rules, which are often set by agreements with driver unions, are inputs into where it is possible to cut the vehicle blocks into pieces of work.

Although transit agencies generally follow all five steps of the planning process whenever service is adjusted, most planning resources in the U.S. are spent on steps 4 and 5 (vehicle blocking and run cutting) (Cedar and Wilson, 1986). Fortunately, these steps have been largely automated for the last several decades.

Independent Inputs	Planning Activity	Output
Demand Data	Network Design	Route Changes
Supply Data		New Routes
Route Performance Indicators		Operating Strategies
Subsidy Available	Frequency Setting	Service Frequencies
Buses Available		
Service Policies		
Current Patronage		
Demand by Time of Day	Timetable Development	Trip Departure Times Trip Arrival Times
Times for First and Last Trips		
Running Times		
Deadhead Times	Bus Scheduling	Bus Schedules
Recovery Times		
Schedule Constraints		
Cost Structure		
Driver Work Rules	Driver Scheduling	Driver Schedules
Run Cost Structure		

Table 1-1. Transit Planning Process (Cedar and Wilson, 1986)

Transit network design is set prior to timetabling, because it is used as an input to frequency setting. The topology of the area and origin-destination matrices are the two main inputs into designing the transit network (Guihare and Hao, 2008). The alignment of routes is constrained by the road network, because buses can only travel along roads that are wide enough and relatively flat (especially in cities where snow and/or ice are common). Routes of the existing network may be considered constraints for network design, because they may exist due to political or other reasons. In addition to satisfying demand, a well-designed transit network should have a high percentage of its service area within walking distance, relatively direct routes, and relatively direct trips (short access and egress distances and low numbers of transfers). A transit agency may also desire to minimize the total route length so that it can either use fewer vehicle and/or crew resources or increase frequencies on routes. The type of network, such as grid, radial, or timed transfer may also be an input in the design of a network.

Guihare and Hao describe how frequencies in transit networks are set (2008). The transit route network is the critical input for this step. The frequencies are constrained by the available bus fleet, so running times by time period are also needed. Finally, some measure of demand, such as a detailed O-D matrix, is necessary for creating the most effective timetable. Frequencies are constrained by minimum or excessively large headways and standards on the tolerable level of crowding.

A transit network timetable shows all runs on all lines and includes the time that each run leaves its initial terminal, the scheduled arrival and/or departure times at the major stops (called timepoints) of the route, and the scheduled arrival time at the terminus. The major inputs into the design of the timetable are the transit network, the times of the first and last trips, the scheduled running times, and public demand, such as O-D matrices. The main objectives of the timetable are to satisfy passenger demand, coordinate transfers, and be within the fleet size constraint (Guihare and Hao, 2008).

Finally, vehicle scheduling is the process to "obtain a feasible sequence of line runs" (Guihare and Hao, 2008). A transit agency may use the objective of minimizing the number of vehicles required based on constraints, such as recovery time needed between successive runs and the requirement that a route be served by a particular (set of) garage(s).

Transit agencies measure performance mainly for the three following reasons: for reporting purposes, for communicating results, and for self-improvement (TCRP 88, 2003). This thesis will focus on the purpose of improving service. The transit agency should evaluate its performance from multiple viewpoints, including the customer, the community, the agency, and the vehicle/driver. It is important for transit agencies to define their goals and objectives well so the correct performance measures can be chosen. Service design standards use performance measures to indicate where resources should be allocated. If routes do not meet minimum levels of ridership, they may be subject to re-evaluation and possible elimination (TCRP 88, 2003).

Fijalkowski makes several recommendations for how transit agencies can make the most of ADCS when planning bus service (2010). Firstly, transit agencies should seriously invest in information technology resources, well-trained staff, and a commitment to focus on reliability so that the raw data can be processed, cleaned, and catalogued efficiently. Secondly, route profiles should be created that include contextual information (e.g. schedule, routing, span of service, customer complaints, etc.) and summarize the results of the following performance categories: bus loading, service reliability, passenger demand, and cost effectiveness. System profiles use data from 12 to 24 months to show changes in ridership over time, especially from season-to-season. Thirdly, transit agencies should evaluate past service changes by analyzing performance over a sufficiently long period of time prior to and after a service change to determine whether it has produced its desired effect. In addition, service type change evaluations should periodically be conducted to "determine the impacts that specific types of service changes (e.g. increased running time) have on the typical performance of affected routes" (Fijalkowski, 2010). Finally, ongoing service review at the route and corridor (or subarea) levels should identify and resolve service problems.

1.5.1 Macro-Scheduling Software

The first several steps in service planning have not enjoyed the same degree of automation as vehicle blocking and crew scheduling. However, macro-scheduling software, such as GIRO's NetPlan module are intended to reduce the gap and to enhance the entire service planning process by integrating the timetabling and vehicle scheduling (Martinais, 2009). NetPlan is a sketch service planning tool that creates and then optimizes a timetable based on the standard inputs; the transit network, the frequencies of the routes, and the scheduled running times. Once the initial information of the transit network is entered into NetPlan, it is relatively easy to test different planning scenarios.

NetPlan will be used to test the impact of service changes for the 15 bus routes in the MBTA Green Line Extension study area in this research.

1.6 Thesis Outline

The remainder of this thesis consists of four chapters that culminate in recommended service modifications for the bus routes in the study area. The chapters are arranged as follows:

- Chapter Two provides an overview of manual and automatic data collection, including the types of data collected, the performance indicators used in service planning, and the benefits and limitations of each data collection system.
- Chapter Three summarizes the history of public transportation in the Somerville/Medford area. It also describes the bus service planning process used for the Red Line extension to Alewife in the 1980s to modify MBTA bus routes. Finally, planned public transportation projects, including the Green Line Extension to Somerville/Medford, are described with special consideration given to bus service changes that service planners should consider.

- Chapter Four describes the existing public transportation network in Somerville and Medford. Performance and demand analysis results are presented at the route-level using both manual and automatically-collected data. The outputs of the bus service analyses will be used as inputs into the timetabling step of the planning process.
- Chapter Five tests several bus service planning scenarios using NetPlan. Bus service changes are added sequentially including evening out the headways, utilizing interlining, improving the scheduled running times and layover times, modifying frequencies based on demand, synchronizing routes that serve the same route segments, and incorporating changes in routing. The number of buses required to serve each timetable will be a primary output. Additionally, the expected wait time (for frequent routes) and scheduled delay (for infrequent routes) savings will be estimated when service frequencies are increased.
- Chapter Six summarizes the findings and recommendations of the research, presents conclusions, and discusses areas of future research.

2 Data Collection and Performance Indicators for Bus Service Planning

This chapter presents an overview of current bus planning practice for both manual and automatic data including the data types and collection methods. Performance indicators that are derived from the data and industry trends are summarized. Each type of data has its limitations and these are described in this section as well as what can be done to control these limitations. Additionally, considerations required when processing the raw automatically-collected data are included. The chapter argues that automatically-collected data can improve performance measurement and support a range of bus service design decisions within the transit agency.

2.1 Manual Data Collection

The common characteristic in manual transit data collection is that trained staff must be present to record the observations. This makes manual data collection expensive and, as a result, manual checks are typically limited in size and scope. Samples collected manually are often called "checks," because they only capture the system at one point in time and, therefore, only limited conclusions can be drawn from them. This section describes (1) the data collection methods and data types, (2) the performance measures developed from these methods, and (3) the limitations of manually collected data.

2.1.1 Data Collection Methods and Types of Data

This section describes the following three types of manually-collected data: ride checks, point checks, and fare checks.

Ride Checks

Ride checks are one of the most common forms of manual data used by bus service planners. Trained traffic checkers are assigned to a sample of trips on a route over one (or more) days. The traffic checkers ride the bus, so they are able to record the numbers of alightings and boardings, as well as time at each stop. The frequency at which a route is surveyed varies by agency; some require yearly ride checks, whereas others may use a five-year (or more) cycle to sample routes (Furth, 2000). Some agencies perform at least an occasional "all-day" ride check for a route that is selected for detailed evaluation. Collecting data for all trips on one day is much preferred to collecting some trips over several days, because the loads and operating irregularities may differ across days (Boyle et al, 2009). However, it is impossible to account for day-to-day variation in loading from a one-day ride check.

Point Checks

Point checks are similar to ride checks in that the traffic checkers record the same basic information—alightings, boardings, loading, and arrival time; however, for point checks, the traffic checkers are assigned to a particular stop, usually a key transfer location or the maximum load point on the line. If the bus stop is used by multiple routes, then the traffic checkers can usually collect data for all of the routes passing the selected point. Checkers do not typically board the bus, because this is viewed as detrimental to operations (Furth, 2000). Additional information, such as load profiles and running time between points, can also be obtained with point checks if checkers are stationed at all timepoints on a route (Boyle et al, 2009).

Fare Checks

Another manual data collection method is fare checks. Fare checks are made on-board and record the fare category for boarding passengers by stop (Furth, 2000).

2.1.2 Performance Indicators

These manually-collected data are often used to analyze the performance of routes in terms of load profiles and trip and schedule adherence summaries. Other lesser-used indicators derived from manually-collected data are also described.

Load Profiles and Trip Summaries

Load profiles are graphical summaries derived from ride checks showing the boardings, alightings, and load levels on a route by stop. Load profiles are typically aggregated either by time period (for planning and scheduling purposes) or over the course of the day (for planning route modifications or for studying stop utilization) (Furth, 2000). Passenger miles, which are reported to state and federal agencies, can be estimated by multiplying the load by the distance between stops. Agencies use two basic definitions for "peak load." The first is that the peak load is where the most passengers are on-board regardless of location. This definition of peak load is helpful for assessing passenger comfort. The second definition of peak load is the location of the greatest loading over a planning period. For this definition, the location may be determined by historical data or by a given dataset. A comparison between ridership demand and service capacity can be made using this definition (Furth, 2000).

Trip summaries are basically the same as load profiles except that they are presented in tabular format. Additional information, such as the minimum and maximum alightings by stop and schedule adherence at timepoints, is sometimes included.

Schedule Adherence Summaries

Transit agencies create summary reports of schedule adherence at either the route or system level. Ride and point checks are the primary manually-collected data source for schedule adherence analyses. The definition of "on-time" varies across agencies due to differences in variables such as road congestion and agency priorities. For most agencies, service standards state that buses should depart the starting point no more than 1 minute early or arrive at other timepoints no more than 2 to 10 minutes late (Furth, 2000). Some agencies also differentiate between "late" and "significantly late." Ideally, schedule adherence summaries should tabulate late buses by the number of minutes late.

Schedule adherence is most important for low frequency routes on which most passengers plan to catch a specific bus. On high-frequency routes, headway deviation is of greater importance. The average passenger waiting time is shown in Equation 2-1, where H is the headway and C_V is the coefficient of variation in headways (standard deviation divided by mean). Thus, as headway variability increases, the average passenger waiting time also increases. Other derived measures of headway reliability include (1) the fraction of headways that are (at least) 50 percent more than the average headway and (2) the estimated percentage of passengers that have to wait more than the scheduled headway (Furth, 2000).

$$E(w) = \frac{H}{2}[1 + C_V^2] \qquad \text{(Equation 2-1)}$$

Other Indicators

Other indicators can be derived from manually-collected data which are not as widely used for route-level planning. Trip time analyses are used to determine the percentage of time that a bus spends in motion, at stops, and stuck in traffic. This type of analysis is especially important for routes that are suspected to have higher-than-needed scheduled running times. Another measure is economic performance, which can have several indicators; the productivity or cost recovery ratio, the ratio of some measure of output to some measure of input, or the ratio of revenue to cost (Furth, 2000). Routes that are performing poorly are subject to service review. Finally, system-level schedule adherence is an additional indicator from manual data sources that transit agencies use in service planning.

2.1.3 Limitations of Manually-Collected Data

On-board ride checks generally provide accurate measures of boardings and alightings, although measurement errors that require corrections can occur. These errors can be minimized if handheld devices are used that prevent loads from being negative or above a maximum level (Furth, 2000). There can be biases associated with ride checks, however, since drivers know that they are being observed and may take unusual measures on ride check days to give the impression that they are doing everything in their control to stay on-time. AVL data eliminates this bias, because every trip is observed. Thus, AVL data are much more useful for a transit agency in understanding the actual performance of its routes. More importantly, the cost of performing ride checks is large, which is why some transit agencies, such as the MBTA, have decided no longer to perform ride checks.

For point checks, there is a higher probability of measurement errors, especially for buses with tinted windows, or that are "wrapped" with advertisements. Fortunately, the range of errors (as high as 10 percent) is generally acceptable for scheduling and operation monitoring decisions. However, previous studies have found that as loading increases, measurement errors are increasingly problematic. For example, one agency found that when the actual load on the bus is 50 passengers, most observations were in the range of 49 to 69 passengers (Furth, 2000). Measurement errors this large are problematic when service planners are making decisions, but they can be reduced by re-training the worst-performing ride checkers. An additional issue with point checks with multiple checkers is that clocks must be synchronized for all checkers to get accurate running times (Boyle et al, 2009).

It is also sometimes difficult for a traffic checker to determine the fare category during fare checks. The measurement error can be minimized if the operator communicates with the traffic checker (Furth, 2000).

Manually-collected data from one day is often used as an approximation of an "average" day. However, the day-of-the-week, month, weather conditions, whether school is in session, and the presence (or absence) of traffic accidents are some of the factors that will affect the data (Boyle et al, 2009). Thus, with all of these day-to-day variations, there is no such thing as too much manually-collected data.

2.2 Automatic Data Collection Systems (ADCS)

Automatic data collection systems (ADCS) which were initially developed for operations and accounting purposes are increasingly used for scheduling and service planning decisions. This section describes the three main types of ADCS—vehicle location, passenger counts, and fare collection. Common measurement errors and data inconsistencies for each data type are also summarized for each type of system.

2.2.1 Automatic Vehicle Location (AVL)

At the core of all ADCS is an on-board computer, which supports full automation, single point log-on, and all intelligent transportation systems (ITS) applications (Clever Devices, 2010a). Transit agencies use automatic vehicle location (AVL) devices to record the location of every bus periodically usually through the use of triangulation of signals from orbiting satellites (Furth et al, 2006). The Global Positioning System (GPS) receiver is polled typically at 60 to 120 second intervals although at least one transit agency polls as frequently as every 15 seconds (Parker, 2008). Agencies use different rules of thumb to determine when a bus has arrived at or departed from a stop; some agencies use a buffer area (e.g. radius of 25 to 200 feet) around the stop, whereas others are triggered by sensors for the bus door opening (and/or closing). The bus status (early, late, on-time, no GPS, no communications) and location is sent to the operation control center, which allows the dispatcher to make informed, real-time operating decisions (Avail Technologies, 2011). The AVL system records at the following levels: at timepoints (which are key stops on the route) and whenever an announcement is made on-board (e.g. the next stop or "Stop requested"). The AVL devices record the date, timestamp (recorded to the second), latitude, longitude, route, run number, and the type of announcement made (if applicable). The data can be presented in summary or detailed forms. Within the past ten years, it has become common practice for transit systems to use AVL data for off-line running time and schedule adherence analysis.

For more information on AVL systems, the reader is referred to Furth (2000), Furth et al (2006), and Parker (2008).

2.2.2 Automatic Passenger Counts (APC)

An automatic passenger count (APC) system "manages passenger boarding and alighting data" by using "infrared technology at bus doors, along with on-board and post-processing software" (CleverDevices, 2010b). The door sensors determine the number of passengers boarding and alighting at each stop based on the direction of motion across the sensors, and the devices are also able to ignore other objects, such as bags. The devices maintain a running total of the number of riders on the bus, which is re-set to zero at the end of every run to prevent cumulative measurement error. When APCs are integrated with AVL systems, the marginal cost of counting passengers is reduced significantly (Furth et al, 2006).

Most APC systems utilize GPS tracking (usually provided by a companion AVL system) to determine the location of the bus. The APC counts are stored on the bus and uploaded to a database at the end of the day. APC systems are increasingly common in U.S. transit agencies, although typically only a fraction of buses in any fleet have APC devices. The buses with these devices should be ideally rotated through all trips so that a more comprehensive ridership analysis can be performed. As described in TCRP Synthesis 34, when typical amounts of bad data and sampling inefficiency are accounted for, a transit system with approximately 10 percent of its buses equipped with APC devices should allow each weekday run to be sampled 5 to 15 times per year with efficient vehicle rotation (Furth, 2000). This frequency is usually high enough for ridership analysis, but it is generally too low for precise trip-level running time and schedule adherence analyses. For routes that have small samples of APC data, supplemental AFC or ride check data should be combined to give a more complete analysis of all trips.

TCRP Report 113 states that APC systems recover only 25 to 75 percent of all possible data points, although this rate is typically higher for systems that match door openings to bus stops (Furth et al, 2006). There are several types of measurement errors that can occur with APC devices including hardware malfunctions, miscounting passengers (an average of 5 percent undercounts), failing to identify the correct stop, incorrectly starting the next trip (due in part to the operator changing the headsign before passengers alight at the final stop), and incorrect or missing trip identification information (Furth, 2000). One issue with using APC systems for running time analyses is that the start time of the trip is usually recorded as the time that the doors close. Thus, if the doors close for a period of time before the bus actually starts a trip, the layover time may be undervalued and the running times overstated.

2.2.3 Automated Fare Collection (AFC)

Automated fare collection (AFC) systems are used by many transit agencies to count passengers, verify and process various types of fare, and record fare transactions. They are also beneficial to passengers, because ticketing procedures are simplified and security is improved (Trepanier, Morency, and Agard, 2009). As of 2000, most large transit agencies had 100 percent of their buses equipped with electronic fareboxes (Furth, 2000). High-end AFC devices record data from contactless "smart" cards or magnetic-stripe cards. The newest AFC systems also allow passengers to pay by credit/debit card and cellular phone (Cubic, 2011). In general, the drivers on AFC-equipped buses have only limited interactions with passengers. Their main fare collection duties include pressing a button to indicate the fare type for passengers that the AFC device cannot otherwise identify (e.g. a senior paying with cash) and to provide transfer receipts, as necessary.

AFC records include the date, a timestamp (recorded to the second), the type of fare (cash, stored value card, monthly pass, paratransit pass, etc.), the unique pass or ticket number, a number corresponding to the location as either a rapid transit station or a particular route number, and the AFC device number. In recent years, AFC systems have begun to record entries for every transaction (e.g. adding value to a transit pass) and to include timestamps and locations in the dataset (Furth, 2000). Data from AFC devices are usually uploaded to a computer when the bus returns to the garage at the end of the day. The revenue and passengers by fare category are aggregated differently by various transit agencies; some aggregate by the trip, others by the route, and a few by day.

Hardware or software malfunctions can occur for some trips or parts of trips, so these data require manual adjustments. Other common measurement errors include the operator not knowing how to record the fare type or recording it incorrectly, the operator failing to sign-on or enter the trip number, and data being lost or assigned to the wrong day. AFC ridership tallies are typically less than the actual ridership for two reasons. First, riders are not always required to interact with the farebox, especially if the rider has a monthly pass and is known to the operator.

Second, a small percentage of riders evade payment by entering through the rear doors of the bus.

Despite these limitations, there are many advantages for transit agencies to use AFC datasets, as outlined by Bagchi and White (2005). First of all, it gives transit agencies access to large sets of individual passenger data. Secondly, there are few gaps in the data. AFC data can be archived and analyzed with respect to time. Finally, AFC data gives transit agencies a better understanding of groups of transit users.

The MBTA uses an AFC system that records whenever a rider boards and pays a fare on a bus, trolleybus, bus rapid transit (non-gated stations), or light rail (non-gated stations), as well as when a rider enters a gated station on the rapid transit network. There are plans to expand the system to include all commuter rail lines and ferries. In October 2010, Metro West Regional Transit, which is one of eleven regional transit agencies that have agreed to the MassDOT Interoperability Program—a common fare system for all participating agencies, began allowing the MBTA Charlie Card smartcards to be used on its routes (MBTA, 2010).

2.2.4 Data Processing of Automatically-Collected Data

Raw automatically-collected data, like manually-collected data, must be processed to identify and eliminate errors. For example, AVL data should have a record at every polling interval or stop, so there should not be large gaps in the data when a bus is in revenue service. Bad data is removed during the processing stage, which does not require much time or effort once the process has been automated. Thus, the cost savings in processing and, to a larger extent, collecting the data are reasons why most large transit agencies strongly favor automatic data collection systems; however, none have yet completely eliminated manual counts. After the data are processed, they are uploaded to a database that can be queried by staff in different departments for their own purposes. The planning department uses the data to create performance metrics, which can be aggregated by time period and/or portions of the transit network as desired. Examples of these performance indicators are presented in the next section.

2.2.5 Performance Indicators for Automatically-Collected Data

This section takes a look at the following performance indicators: running time analysis, schedule adherence and headway regularity, and targeted analyses. Other lesser-used measures derived from automatically-collected data are also described.

Running Time Analysis

AVL data can be used to adjust schedules. Historical data could be used to fine-tune scheduled running times and recovery times for different times of the day, days of the week, months and seasons. In practice, most transit agencies use constant running times for a time period on any route. The time periods are set by the transit agency, perhaps aided by statistical tests on the observed running times and to refine the time periods. One method for setting running times is proposed in Chapter Four. APC can also be used to understand the factors affecting running time. After the route-level running time is set, further analysis can be performed to set the running time between time points. This type of analysis is especially useful for transit systems that coordinate with other local agencies to install traffic signal priority at intersections, because it can help set priorities on which intersections should receive signal priority (Parker, 2008). Another component of running time analysis is dwell time analysis, which uses all three automatic data systems to determine the effect of alightings, boardings, and interactions with the farebox on time spent at a bus stop (Furth et al, 2006).

Schedule Adherence and Headway Regularity

AVL data can also be used to summarize schedule adherence and headway regularity for low-frequency and high-frequency schedules, respectively. AVL datasets (as well as datasets of other ADCS) are very large, so there are no issues in excluding outliers from analyses that are not focused on the extreme observations. For trip planning, most passengers do not base their trip time simply on the "average trip," because they may be very late on days when the bus trip is much longer than usual. Transit agencies are increasingly using performance measures that try to account for how customers perceive their service. These measures are based on higher values of the running time distribution—typically between the 85th and 95th percentiles. An additional tool for routes with short headways is bunching analysis, which investigates the deterioration of even headways by utilizing the AVL data plus the alightings and boardings from the APC data (Furth et al, 2006).

Targeted Investigations

Transit agencies will occasionally need to investigate customer complaints, legal claims, and payroll disputes. Frequent AVL polling data can be used to determine the time, location, speed, and acceleration of the bus before, during, and after the incident (Furth et al, 2006).

Other Performance Indicators

Other automatically-derived performance indicators include using AVL data to approximate the smoothness of a ride and measure performance of operators (Furth et al, 2006).

Automatic data can be also used in higher levels of analysis such as transfer analysis, which is discussed further in Appendix E.

2.2.6 Trends and Limitations of Automatically Collected Data

TCRP Report 113 presents five trends in the use of automatic data (Furth et al, 2006):

- The greater use of the full distribution, not just averages. One example is to set recovery times to improve the likelihood of starting the next trip on-time.
- Supplementing traditional operator-oriented measures with customer-oriented measures. One example is estimating the number of passengers who have long waits for their bus.
- Planning for operational control, such as making real-time decisions to short-turn buses or to have them run express.
- Increasing ability to measure road congestion and determine whether signal prioritization is beneficial to all affected routes.
- The "discovery of hidden trends." One example is the ability to monitor the running time of individual operators, because there can be significant running time variation when all other trip characteristics are the same.

The benefits of using automatically-collected data have been described in the previous sections, but there are also tradeoffs to using automatically collected data. A primary concern with the data is measurement error. However, the large datasets make it possible to exclude data that have errors after the raw data have been processed. The system design of the automatic devices has historically not considered the full potential contribution of the data to functions across the agency. The expertise and/or resources required for implementing more robust performance measures have been insufficient in many transit agencies, which forces schedulers and service planners to use measures that are more cumbersome and less accurate.

2.3 Summary

Automatic data have the capability to correct the limitations of manual data collection discussed in Section 2.1. The quantity and (potential) quality of the automatic data make it desirable for use in performance metrics as a part of the service planning and scheduling process. The resources required to collect, process, and analyze automatic data are less than with manually collected data, which makes more sophisticated analyses possible.

3 Historical and Current Public Transportation Planning in Somerville & Medford

Rapid transit extensions are excellent opportunities to review bus service, because passengers are more likely to accept major modifications to bus routes when other major service changes are occurring. Changes in travel behavior require transit agencies to adjust routes, especially so that they provide access to the new rapid transit nodes.

This chapter is divided into three sections. The first section describes how the bus routes in the study area of the MBTA Red Line Extension to Alewife were modified in one of the last major extensions of the MBTA rail network. The second section describes the MBTA Green Line Extension and other capital transportation projects in Somerville and Medford. Finally, the third section provides information about its expected connections between the Green Line Extension and the bus network.

3.1 Bus Service Changes in the Green Line Extension Study Area (since 1985)

The Massachusetts Bay Transportation Authority (MBTA) plans to begin construction on its 4.5-mile Green Line extension into Somerville and Medford in early 2011. There are fifteen bus routes that may be directly impacted by the project which will be used as a case study throughout this thesis.

The Green Line Extension Project is of real significance for The Commonwealth of Massachusetts. The existing residential development in this corridor is very dense by U.S. standards. It would be expected that these residents would have access to high quality transit; however, only a small portion of the population currently lives within walking distance of rapid transit service. Furthermore, most local bus service in this area has low frequency typically requiring use of a bus schedule to avoid long waits as peak period headways are generally in the 15 to 20 minute range. The travel behavior of many Somerville and Medford residents can be expected to change after the Green Line Extension becomes operational, because many of the residents will be within walking distance of a Green Line station. The MBTA has limited financial and staff resources, so it is important to use them efficiently so that the full potential benefits of the extension project are realized.

The last major addition to the public transportation network in the cities of Cambridge, Somerville, and Medford, was the extension of the Red Line to Alewife. This section discusses how modifications to the pre-Red Line bus services were considered. Bus service changes since the Red Line Extension are also described.

3.1.1 Red Line Extension to Alewife

The Northwest Corridor Service Study is a compilation of reports and memos concerning bus service that were written prior to the extension of the Red Line to Alewife Station in early 1985. The five primary objectives for the project were the following (Cambridge Systematics, 1985):

- Improve overall service quality for MBTA riders
- Increase total transit ridership in the MBTA district
- Implement the comprehensive service plan by January 1985
- Contain or reduce the cost of operating the bus system
- Minimize the negative impacts of service and facilities on local traffic and residential neighborhoods

There were three main ways in which Cambridge Systematics, the consultant retained for the study, received public comments for the extension to Alewife; contacts with local officials and staff, local workshops, and project coordinating meetings. Many of the topics discussed in the Northwest Corridor Study will be summarized in this section.

One issue highlighted in the Study was bus ridership changes. The Northwest Corridor Study used the Red Line opening to Alewife as a base case. Thus, ridership impacts due to the following factors for each stop: walk-ins to the new stations, transfers at the new stations, "backtracking" (i.e. traveling outbound first in order to go inbound) of bus riders to the new stations, and diversions to other routes. Cambridge Systematics used a three-step process to estimate the number of passengers affected at each stop (1985). Firstly, the existing ridership was set equal to the number of alightings found in the most recent ride check. Secondly, the number of passengers transferring to rapid transit stations (route-level only) was estimated. Thirdly, the relative portion of the bus stop buffer area within walking distance of the new Red Line stations was estimated.

The ridership changes anticipated by the modifications to the services are shown in Table 3-1. A few of the routes were estimated to have only minor changes in ridership when the Red Line was extended to Alewife. As for major changes in ridership, Routes 77A and 83 were expected to have their loading at the peak location on the route reduced by 60 percent. The routes were served by 68 buses during the peak periods, and it was estimated that only 57 buses would be required after the service modifications. Also, during the midday hours, service requirements were estimated to be reduced from 24 to 21 buses (Cambridge Systematics, 1985).

Route	Route Description	Reduction in Daily Pk. Load	Notes
76	Hansom Field - Harvard	0%	
77	Arlington Heights - Harvard	3%	
77A	North Cambridge - Harvard	60%	
80	Arlington Ctr. - Lechmere	31%	Diversion to Route 96
83	Rindge Ave. - Central Sq.	61%	
84	Arlmont - Harvard	0%	
87	Clarendon Hill - Lechmere	35%	via Somerville Ave; Peak location is now Davis (was Central St.)
88	Clarendon Hill - Lechmere	39%	via Highland Ave.; Peak location is now Davis (was City Hall)
89	Clarendon Hill - Sullivan Sta.	33%	Diversions to Routes 87 & 88
90	Davis Sq. - Wellington	19%	
96	Medford Sq. - Harvard	2%	

Table 3-1. Ridership Impacts due to Red Line Extension (Cambridge Systematics, 1985)

The Northwest Corridor Service Study received input from officials representing the cities where bus service changes were being considered. Many of the comments received from Somerville and Medford for that study are also relevant for the Green Line Extension Project, such as (Cambridge Systematics, 1985):

- Concern over traffic impacts, especially of buses, in Davis Square—particularly on College Avenue
- Desire to improve access to Davis Square from Somerville neighborhoods and Tufts University
- Concern about cost to Somerville of service between Davis Square and Harvard Square on Route 96

- Concern about cost to Somerville of possible re-routed Route 350
- Concern about access to Boston Avenue (e.g. Tufts) from Somerville
- Concern about environmental impact—noise, fumes, and odor—of buses in Davis Square busway
- Desire to encourage use of Davis Square businesses by Tufts students, faculty, and employees
- Desire to re-route Route 96 over Winthrop Street bridge when opened (spring 1984)

Another important issue that was considered in the Northwest Corridor Service Study was route modifications. The planning staff first conducted a largely-qualitative analysis of possible routings, and later calculated more detailed impacts of the feasible alternatives. The criteria used to evaluate routing alternatives were service quality, ridership, cost, technical feasibility, and local impacts. The existing routing was considered for all of the routes, and many of the routes also looked at the feasibility, especially with regard to negative impacts on current users, of redirecting them to Alewife. The Study also investigated through-routing, eliminating poorly-performing portions of routes, and extending routes. The extension of the Red Line to Alewife should also increase the willingness of people in the surrounding areas to take public transportation, so additional routes were considered. Options considered included providing service for reverse commuters to industrial areas during the peak period, re-routing Routes 72 and 75 to provide service to the Huron Tower senior housing complex in Cambridge, a shuttle service from Alewife Station to nearby businesses, and local and express services to some outer cities, such as Burlington and Bedford. However, most of these options were not pursued due to low levels of expected ridership. These potential services could be reconsidered if at least one of the following occurs: cities provide park-and-ride facilities, employment around Alewife grows significantly, reverse commuters can be accommodated, or highway improvements are made near Alewife (Cambridge Systematics, 1985).

Routing modifications considered during the Northwest Corridor Study for routes in Somerville and Medford are shown in Table 3-2. The options recommended for further study are given a checkmark. The Study also stated that Route 83 should be moved back to Beacon Street when that bridge had been re-built to allow heavy vehicles; however, that routing has not changed as of

2010. On a similar note, the third option for Route 96 was considered a possible alternative, because the Winthrop Street Bridge had just opened up at the time of the Study.

Route	Option	Details	Study Further
80	**1**	**Existing routing**	✓
	2	Add loop to Davis Sq. (adds 16 min. of round-trip travel time)	✓
	3	Reverse route (terminus at W. Medford) & serve Davis Sq.	✓
83	**1**	**Existing routing (not able to connect to Alewife)**	✓
87	**1**	**Existing routing**	✓
	2	**Extend to Arlington Center**	✓
	3	Provide service along College Ave. to Powderhouse Sq.	
88	**1**	**Existing routing**	✓
	2	Extend to Arlington Center	✓
	3	Provide service along College Ave. to Powderhouse Sq.	
89	**1**	**Existing routing**	✓
	2	Extend to Arlington Center	
	3	Provide service along College Ave. to Powderhouse Sq.	
90	**1**	**Existing routing**	✓
96	**1**	**Existing routing (which follows Boston Ave. & High St.)**	✓
	2	Terminate at Davis Sq. (instead of Harvard Sq.)	✓
	3	**Re-route via Winthrop St. (saves 8 min. of travel time)**	✓

Note: Options that are in bold are the routings that exist in 2010.

Table 3-2. Bus Routing Modifications Considered for Red Line Extension to Alewife (Cambridge Systematics, 1985)

3.1.2 Bus Route Modifications after the Red Line Extension

The routing modifications to the Somerville and Medford bus routes since the Red Line Extension to Alewife, Davis Square, and Porter Square Stations are shown in Table 3-3. Most of the changes occurred in 1985 when the Red Line Extension opened, and, in general, the routes in Somerville and Medford have been largely untouched since. Route CT2 is the only new bus route in the area, improving the accessibility of Somerville residents to job opportunities in the Kendall Square, MIT, Boston University, and the Longwood Medical areas.

Route #	Route Name (in 2010)	Routing Differences (most changes before 1988)
80	Arlington Center - Lechmere	N/A
83	Rindge Ave. - Central Sq.	N/A
85	Spring Hill - Kendall/MIT	The Spring Hill loop extended north to Highland Ave.
86	Sullivan Station - Reservoir	There are a few minor differences in the roads used
87	Arlington Center - Lechmere	The route was not extended to Arlington Center
88	Clarendon Hill - Lechmere	Followed Rt. 85 near the Somerville Hospital
89	Clar. Hill or Davis - Sullivan	The route was not extended to Davis Square
90	Davis Station - Wellington	The terminal was Sullivan Sq. (rather than Wellington)
91	Sullivan - Central Sq.	N/A
92	Assembly Sq. - Downtown	The route was not extended to Assembly Square Mall
94	Medford Square - Davis	The terminal was Sullivan Sq. (rather than Medford Sq.)
95	West Medford - Sullivan	The route may have followed a road closer to the Mystic River
96	Medford Square - Harvard	The route traveled along Boston Ave. (similar to Rt. 94)
101	Malden - Sullivan	Known as Rt. 101A; Rt. 101 went to Salem St. (Medford)
CT2	Sullivan - Ruggles	Did not exist until recently

Note: Lowell Commuter Rail had a stop at Tufts University until October 1979.

Table 3-3. Routing Modifications to Somerville-Medford Routes since 1985 (MBTA, 1980 & 1988)

The frequencies of the Green Line Extension study area bus routes have changed over the years, as shown in Table 3-4. Service on Route 94 increased from 1980 to 1988. There were also modest improvements to the frequency of service on Routes 91 and 101. The only route that increased frequency during the off-peak hours from 1980 to 1988 is Route 85, which went from 50-minute to 30-minute headways. Compared with current headways, only Routes 86 (which now runs on about 12-minute headways) and CT2 have more frequent service during the peak hours than in 1988. Many of the bus routes have decreased frequencies at least slightly. The peak period headway of Route 85 has increased from 10 minutes in 1980 to 35 to 40 minutes in 2010.

Route #	Route Name (in 2010)	Headways--1980		Headways--1988		Headways--2010		
		Peak	Off-Peak	Peak	Off-Peak	AM*	PM*	Off-Peak
80	Arlington Center - Lechmere	7/10	17	15	35	20	20	35
83	Rindge Ave. - Central Sq.	10	20	8/15	30	15	20	30
85	Spring Hill - Kendall/MIT	10	50	18	30	35	40	40
86	Sullivan Station - Reservoir	15	30	18	30	15/9	12/17	30
87	Arlington Center - Lechmere	15	17	16	25	18/21	15	30
88	Clarendon Hill - Lechmere	6/9	17	8/12	25	15	18	30
89	Clar. Hill or Davis - Sullivan	6	15	9	30	9	10	30
90	Davis Station - Wellington	45	45	30/35	70	45	40	70
91	Sullivan - Central Sq.	10	20	25	25	30	30	25
92	Assembly Sq. - Downtown	15	30	15/20	30	15	15	32
94	Medford Square - Davis	45/50	--	6/10	20	20	20	48
95	West Medford - Sullivan	12	20	15	30	20	20	30
96	Medford Square - Harvard	8	15	15	30	18	18	48
101	Malden - Sullivan	12	15	8/10	30	9/15	12	30
CT2	Sullivan - Ruggles	--	--	--	--	20	20	30

* 2010 Headways are in the format Inbound/Outbound (where necessary).

Table 3-4. Headways for Somerville-Medford Routes in 1980 & 1988 (MBTA)

3.2 Transportation Capital Projects in Design for Somerville and Medford

The improvement of transit service to Somerville and Medford has been discussed for decades. This area is close to downtown Boston with many roads in the area highly congested during the peak hours when commuters from the north cut across from Interstate 93 to get to workplaces in Boston and Cambridge. A second reason why better public transportation is vital in Somerville and Medford is that density is already high in the area and may increase further as land is re-zoned. The Green Line Extension Project and the Assembly Square Orange Line Station are two projects that will improve transportation options for residents and trip generators in Somerville and Medford.

These projects (including both phases of the Green Line project), as well as the McGrath Highway Re-construction, are described in this section.

3.2.1 Green Line Extension Phase 1—College Ave. and Union Square

Although originally planned as a single project, the Green Line Extension Project has been divided into two phases so that the main portion of the project can become operational as soon as possible. Phase 1 of the Green Line extension will extend the Green Line by 3.25 miles from Lechmere Station to College Avenue along the Lowell Commuter Rail Line and by approximately 0.75 miles from Lechmere Station to Union Square along the Fitchburg Commuter Rail Line, as shown in Figure 3-1. As part of the NorthPoint condominium development plan, Lechmere Station will be relocated to the northeast side of the Monsignor O'Brien Highway. The College Avenue branch will include the following five stations in Phase 1: Brickbottom (at Washington Street), Gilman Square, Lowell Street, Ball Square, and College Avenue.

Transit travel times between Boston and the Somerville-Medford area should improve significantly with the Green Line Extension. Assuming 45 seconds dwell time per station, the ride will be 9.5 minutes from Lechmere to College Avenue compared with 23 minutes scheduled on Route 80 during the PM peak (Massachusetts EOT, 2009). The headway on the College Avenue branch will be 5 minutes during the peak periods and 10 minutes off-peak.

The Union Square spur will connect the relocated Lechmere Station to a Union Square station at Prospect Street. The travel time from Lechmere to Union Square will be 4.5 minutes and the headway will be 5 to 6 minutes during the peak periods and 10 minutes off-peak (Massachusetts EOT, 2009).

Another important component of Phase 1 is that a Green Line maintenance and train storage facility will be built in the Inner Belt area near the MBTA Commuter Rail facility. The Green Line currently has limited storage for trains all located on the western branches of the system. Thus, the storage facility should improve operations and reduce the amount of non-revenue service required.

The Draft EIR estimates that the Green Line project will generate 52,000 new daily boardings, including a new systemwide transit ridership of 7,900 boardings, and reduce vehicle travel by 25,000 miles per day by 2030 (Massachusetts EOT, 2009).

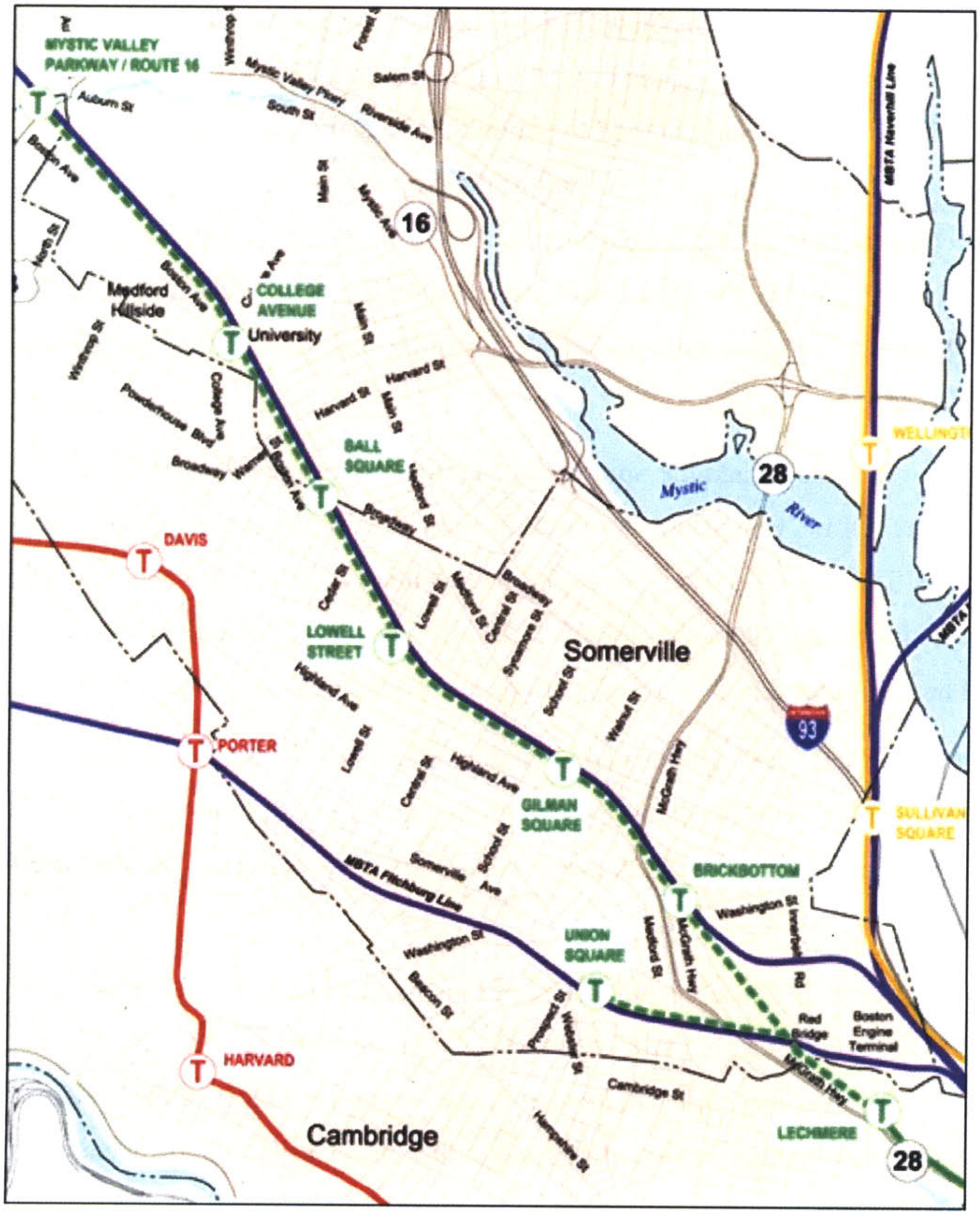

Figure 3-1. MBTA Green Line Extension—Phases 1 & 2 (Green Line Extension, 2010)

3.2.2 Green Line Extension Phase 2—Mystic River Valley Parkway

Phase 2 of the Green Line extension will further extend the Green Line by less than a mile from College Avenue to the planned terminus at Mystic River Valley Parkway (Route 16) along the Lowell Commuter Rail Line.

The timetable for the completion of Phase 2 is not yet defined, so the Mystic River Valley Parkway Station may not come on-line until years after Phase 1 is complete. The area around this station is currently served only by MBTA Routes 80 and 94. In addition, the residents and business owners in the Medford Hillside neighborhood have been expecting for years that all of the Green Line Extension stations would become operational at the same time. Rail was chosen as the preferred alternative due to benefits from improved corridor mobility, improved regional air quality, improved transit service reliability, increased services to people living in "environmental justice" areas, and the capability to support "future smart growth initiatives and sustainable development" (VHB, 2005). Although it will not be as beneficial as a one-seat Green Line ride to Boston, an increase in the bus frequency from the neighborhood near the Mystic River to the College Avenue, which is that neighborhood's closest connection to the Green Line, may be a compromise until Phase 2 is complete.

3.2.3 Assembly Square Mall Orange Line Station

The Assembly Square Mall is located next to the Mystic River in East Somerville. A developer is planning to add mixed development that will include apartments, restaurants, and offices. As part of the re-development, an Orange Line station will be added halfway between Wellington Station and Sullivan Square Station. The addition of Assembly Square Station will increase the running times on the Orange Line slightly. Bus routes 90 and 92 may also be re-configured to provide better access to the station. It may also be advantageous for some of the routes that terminate at Sullivan Station to terminate instead at Assembly Square Mall.

3.2.4 McGrath Highway Re-construction

The Monsignor O'Brien/McGrath Highway (MA Route 28) starts near Lechmere Station. It parallels the Lowell Commuter Rail Line with an elevated section and then continues north as an at-grade highway until it reaches I-93. The Highway, especially the elevated section, is badly deteriorated, and the city of Somerville and MassDOT are considering an alternative to replace the highway with an at-grade boulevard. Although this is a highway project and not a transit project, the design and construction of the roadway will have major impacts on public transportation in Somerville, particularly for Routes 80, 87, and 88, which currently have stops on the McGrath Highway. An at-grade boulevard, one of the options being considered, could spur economic development along the corridor. Additionally, improved walking conditions and more accessible bus stops would encourage greater use of public transportation.

3.3 Network Connectivity

The quantitative analysis of bus service alternatives presented in this thesis is for changes in the short- to medium-term. Long-term modifications that will occur after the Green Line Extension opens are, for the most part, outside of the scope of this paper. For a study of long-term modifications to bus routes following the expansion of a rapid transit system, the reader is referred to Guillot (1984).

A new or extended rapid transit line should modify the alignments of bus routes in the area. Most stations should be served directly by bus routes that serve as feeders/distributors to nearby residences and businesses that are not within easy walking distance of the station. For routes that already serve the street(s) closest to the rapid transit station, the simplest modification is to add stops in both directions as close to the station as possible.

The Green Line Extension stations where transfers are expected from the Somerville and Medford routes are shown in Table 3-5. Except for Lowell Street, all of the Green Line Extension stations have direct connections to at least one bus route. The Lowell Street Bridge above the proposed Green Line Extension has one lane in each direction and a steep grade. Thus, the Green Line Project staff has determined that no routes can travel along Lowell Street.

The connectivity of the Green Line Extension Phase 1 stations to other MBTA rail stations by bus routes is shown in Table 3-6. All of the routes involved in the connections are ones used in this case study, except for Route 69, which provides service from Lechmere to Harvard Square along Cambridge Street. Connections that would require at least a couple of minutes of access time from a specific bus route to a Green Line station are shown in parentheses. For example, Route 88 currently runs close to the proposed Brickbottom Station, but it would require passengers to walk a short distance east along Washington Street. In addition, potential desirable connections between the Green Line and the Orange Line or Red Line are designated with a checkmark in Table 3-6. Porter Square could be better connected to the Green Line Extension if a route was modified to serve the Gilman Square Street Station. Malden Center could be connected to the Green Line Extension by modifying Route 101 to serve the College Avenue or Ball Square Stations. Finally, Wellington and Assembly Square will be somewhat connected to the Green Line Extension at Gilman Square and Lowell Street Stations by Route 90, although more direct connections may be possible at Ball Square or College Avenue Stations.

Route #	Route Name	Green Line Extension Stations
80	Arlington Center - Lechmere	Union Square College Ave. Ball Square Gilman Square (Brickbottom) Lechmere
83	Rindge Ave. - Central Sq.	N/A
85	Spring Hill - Kendall/MIT	Union Square
86	Sullivan Station - Reservoir	(Union Square) Brickbottom
87	Arlington Center - Lechmere	(Union Square) Lechmere
88	Clarendon Hill - Lechmere	Union Square (Lowell Street) (Gilman Square) (Brickbottom) Lechmere
89	Clar. Hill or Davis - Sullivan	Ball Square
90	Davis Station - Wellington	(Lowell Street) (Gilman Square)
91	Sullivan - Central Sq.	Brickbottom Union Square
92	Assembly Sq. - Downtown	N/A
94	Medford Square - Davis	College Ave.
95	West Medford - Sullivan	N/A
96	Medford Square - Harvard	College Ave.
101	Malden - Sullivan	N/A
CT2	Sullivan - Ruggles	Brickbottom Union Square

( ) = route is a 5-minute walk from Green Line station.

Table 3-5. Bus Service Connections at Green Line Extension Phase 1 Stations

LINE/ STATION	**Red Line**					**Green Line**	**Orange Line**			
	Davis	**Porter**	**Harvard**	**Central**	**Kendall**	**Lech-mere**	**Malden**	**Welling-ton**	**Assembly Sq.**	**Sullivan**
Lechmere	87 / 88	87	69			N/A				
Brickbottom	(88)		86	91	CT2	(80) / (88)				86 / 91 / CT2
Gilman Sq.	(88)	X				80 / (88)		(90)	(90)	(90)
Lowell St.	(88) / (90)					(88)		(90)	(90)	(90)
Ball Sq.	89					80		✓	✓	89
College	94 / 96	96	96			80	✓	✓	✓	
Union Sq.	(87)	(87)	(86)	91	85 / CT2	(87)				(86) / 91 / CT2

( ) = route is a 5-minute walk from Green Line station. Transfer could be improved by re-routing the bus to the station, where possible.

✓ = potential network connection that would require a major bus route re-routing

Table 3-6. Network Connectivity after Green Line Extension Phase 1

4 Analysis of Public Transportation Service in Somerville and Medford

In order to begin to plan bus service changes for the study area routes, it is necessary to analyze the existing service. One task for service planners is to identify routes that are under-performing. If loading is irregular, adjustments can be made to the timetable or service frequencies. If the problem is that a route has many trips that are consistently late, a running time analysis should show that the running time and/or recovery time should be increased.

This chapter provides a summary of the existing public transportation options in Somerville and Medford. The chapter is divided into four sections. The first section provides an overview of the existing public transportation in the area, including bus route profiles. The second section analyzes the demand of public transportation in the study area. The third section is the running time analysis that will be used as an input into the service planning scenarios tested in Chapter 5. The fourth section assesses the service and operations through other analyses, including a bus passenger survey, transfer rates, an estimated O-D matrix, trip rates, and on-time performance.

4.1 Overview of Public Transportation in Somerville and Medford

The MBTA is the primary public transportation provider for the Boston metropolitan area. It is the fifth largest transit system in the United States in terms of average daily ridership. In August 2010, the system recorded an average of 1.25 million daily riders, including a bus ridership record of 390,000 riders (Commonwealth of Massachusetts, 2010). The MBTA provides service on many different modes—subway, light rail, commuter rail, ferry, bus, bus rapid transit, and trolleybus. For bus, there are 183 routes operated by over 900 diesel and compressed natural gas (CNG) buses operating out of eight garages.

Somerville and Medford are fringe cities located 3 to 6 miles northwest of Boston. The towns are served by MBTA commuter rail, rapid transit, and buses. Most public transportation users in Somerville and Medford travel either by bus or by bus-and-rail. The available public transportation options are described in the following sections.

4.1.1 Commuter Rail

The only commuter rail station in Somerville or Medford is West Medford on the Lowell Commuter Rail Line, which also serves the following stations northwest of Boston: Wedgemere, Winchester Center, Mishawum, Anderson/Woburn, Wilmington, Haverhill, North Billerica, and Lowell. The Lowell Line has 9 morning (inbound) and 6 afternoon (outbound) peak period trips serving the West Medford station. Porter Square is the final inbound stop on the Fitchburg Commuter Rail Line before it arrives at North Station, so it provides non-stop service to North Station with limited frequency from the Somerville neighborhood close to Porter Square. The Fitchburg Line has 6 morning (inbound) and 6 afternoon (outbound) peak period trips. Thus, the commuter rail coverage area includes a small part of western Somerville.

4.1.2 Rapid Transit

Most of Somerville and Medford is not within walking distance of MBTA rapid transit service. There are two rapid transit stations located in the cities; Davis Square, which is on the Red Line in the northwestern corner of Somerville, and Wellington, which is on the Orange Line in eastern Medford. The Porter Square Red Line station is slightly west of Somerville and is the only other rail transit stop currently located within a short walking distance of part of the study area. For public transportation users living in the study area who wish to access the rapid transit system, at least one Somerville-Medford bus route serves each station listed in Table 4-1. The stations on the Red Line have the most frequent rapid transit service, especially in the Evening and Late Night periods. Route 86 provides connections to the B, C, and D Branches of the Green Line that are not listed in Table 4-1; residents in the study area transfer at those locations infrequently.

Rapid Transit Line	**Stations Served by Somerville-Medford Buses**	**Wkdy. Rail Headways (minutes)**			
		Peak Period	**Midday**	**Evening**	**Late Night**
Green Line--C Branch	Haymarket	7	10	7	14
Green Line--E Branch	Lechmere, Haymarket	6	8	10	14
Orange Line	Malden, Wellington, Sullivan, Haymarket	5	8	10	10
Red Line	Davis, Porter, Harvard, Central, Kendall/MIT	4.5	6.5	6	6

Table 4-1. Headways of Rapid Transit Lines near Somerville & Medford

4.1.3 Bus Routes

Transit agencies make many planning decisions for the bus service that they provide, including the following:

- Routing—the path that a route takes, including the locations of terminals and connections to rapid transit nodes, is usually fixed in the short-term, but it should be reviewed whenever road construction is scheduled or new transit service is planned. The MBTA has a coverage guideline that states that transit service shall be provided within a ¼-mile walk of residents that live in areas where the population density is greater than 5000 persons per square mile. On Sundays, the distance is increased to a ½-mile walk (MBTA, 2009).
- Service span—some routes operate until 1 a.m. (or later) every day of the week, whereas others operate on weekdays only until the early evening. The MBTA has minimum span of service standards for all of its services.
- Frequencies—transit agencies also set the frequency of service, which is constrained in the short-term by the budget as well as by the number of buses and bus drivers available. The MBTA has minimum frequency of service standards for all of its services.

This section begins with an overview of the routes in the Green Line Extension area and then presents a profile for each route including the routing, service span, and frequencies.

The MBTA system map for Somerville, Medford, and Cambridge is shown in Figure 4-1. The Green Line Extension area is loosely bounded by Cambridge Street (MBTA Route 69) to the south, the Red Line between Harvard and Davis plus MBTA Route 87 to the west, High Street (MBTA Routes 80 and 94) to the north, and Mystic Avenue (MBTA Route 95) plus Lechmere Station to the east. There are 15 MBTA bus routes that serve the Green Line Extension area, including 14 local routes and 1 cross-town (limited-stop) route. Of these routes, Route 92 is the only one that provides service directly to downtown Boston. Each bus route (in numerical order) is described in this section. The bus routes primarily operate out of three bus garages—Charlestown, Fellsway, and Somerville—although Route CT2 operates out of Cabot Garage.

Ridership numbers in this section are taken from 15 days of AFC data from Fall 2009 (October 18th to 31st). The raw AFC weekday counts have been averaged and multiplied by 1.12 to account for AFC undercounting, which is discussed in Section 4.2.2.

Route 80—Arlington Center to Lechmere Station

Route 80 is a 6-mile (one-way) route that provides local service from Arlington Center to the Lechmere Green Line Terminus Station. Its alignment proceeds east along Medford Street, which turns into High Street as it crosses the Mystic River. It then runs along Boston Avenue through Medford Hillside paralleling the Lowell Commuter Rail Line. At College Avenue, Route 80 travels south to Powderhouse Square. From there, it heads east along Broadway Avenue passing over the Lowell Line to Medford Street. Next, Route 80 proceeds south along Pearl Street crossing over the Lowell Line to the McGrath Highway. Finally, it heads south and then east along the McGrath Highway to Lechmere Station.

The weekday span of service for Route 80 is from 5:05 a.m. to 1:21 a.m. The route has the following headways (in minutes): AM Peak—20, Midday—35, PM Peak—20, Night—60, Saturday—35, and Sunday—60. The daily weekday AFC-adjusted ridership is about 2030 passengers.

Route 83—Rindge Avenue to Central Square Station

Route 83 is a 3.5-mile route that provides local service from Russell Field (east of the Alewife Station terminus of the Red Line) to Central Square Station, also on the Red Line. It travels east along Rindge Avenue and then continues along Massachusetts Avenue to Porter Square Station where it turns on to Somerville Avenue. It parallels the Lowell Line until it crosses over it at Park Street. From there, it heads southeast along Beacon Street to Inman Square. Finally, it travels south along Prospect Street, crosses Massachusetts Avenue, and loops around to its terminus near the entrance to the Red Line inbound trains at Central Square.

The weekday span of service for Route 83 is from 5:10 a.m. to 1:24 a.m. The route has the following headways: AM Peak—15, Midday—30, PM Peak—20, Night—60, Saturday—25, and Sunday—50. Daily weekday ridership is about 2220 passengers.

Route 85—Spring Hill to Kendall/MIT Station

Route 85 is a 2.5-mile route that provides local service from Spring Hill (Avon Street-Central Street) in Somerville to the Kendall-MIT Red Line Station. It proceeds east along Summer Street to Union Square. Due to one-way streets, the inbound path through Union Square differs from the outbound path. Inbound Route 85 travels west along Bow Street, then east along

Figure 4-1. Map of Green Line Study Area Bus Routes (MassDOT, 2010)

Somerville Avenue, and finally south along Webster Avenue. Outbound, the route follows Prospect Street to Somerville Avenue and then via Somerville Avenue to Summer Street. Both directions follow Webster Street between Prospect Street and Cambridge Avenue. Between there and Hampshire Street, inbound trips take Windsor Street whereas outbound trips take Columbia Street. Route 85 continues along Hampshire Street to Broadway and finally loops around to the Kendall-MIT Station on Main Street.

The weekday span of service for Route 85 is from 6:00 a.m. to 7:53 p.m. The route has the following headways: AM Peak—35, Midday—40, and PM Peak—40. The route does not operate on weekday nights, Saturdays, and Sundays. Daily weekday ridership is about 600 passengers.

Route 86—Sullivan Square Station to Reservoir Station

Route 86 is a 6.5-mile route that provides local service from the Sullivan Square Orange Line Station to the Green Line Reservoir Station (Cleveland Circle). It proceeds west along Cambridge Street (which turns into Washington Street) over the Lowell Line and across the McGrath Highway. At Union Square, Route 86 turns on to Somerville Avenue and then continues on Washington Street (which turns into Kirkland Street). It stops at Harvard Square, heads south on Eliot Street and then N. Harvard Street. Next, Route 86 heads west on Western Avenue and then south on Market Street through Brighton Center. Market Street turns into Chestnut Hill Avenue, and the buses continue on to serve the following Green Line stops: Chestnut Hill Avenue on the B Branch, Cleveland Circle of the C Branch, and Reservoir on the D Branch.

The weekday span of service for Route 86 is from 5:06 a.m. to 1:03 a.m. The route has the following headways: AM Peak—15/9, Midday—30, PM Peak—12/17, Night—60, Saturday—25, and Sunday—50. Daily weekday ridership is about 5830 passengers.

Route 87—Arlington Center (or Clarendon Hill) to Lechmere Station

Route 87 is a 5.5-mile route that provides local service from Arlington Center to the Lechmere Green Line Station during most runs, although one variation begins at Clarendon Hill in Somerville. It proceeds east along Broadway, passing over the Alewife Brook and by Clarendon Hill. Next, Route 87 turns onto Holland Street heading south providing service to the Red Line at Davis Square. It continues south along Elm Street with a stop that is within a few blocks of the Porter Square Red Line Station. Route 87 parallels the Fitchburg Line on Somerville Avenue through Union Square. Somerville Avenue turns into the Monsignor Obrien Highway, which it travels along to Lechmere Station.

The weekday span of service for Route 87 is from 5:10 a.m. to 1:17 a.m. The route has the following headways: AM Peak—18/21, Midday—30, PM Peak—15, Night—30, Saturday—25, and Sunday—20. Daily weekday ridership is about 3660 passengers.

Route 88—Clarendon Hill to Lechmere Station

Route 88 is a 4-mile route that provides local service from Clarendon Hill to the Lechmere Green Line Station. During the morning peak period, one bus also provides shuttle-style service between Davis Square and Clarendon Hill. Route 88 begins near the intersection of Alewife Brook Parkway and proceeds east along Broadway. Next, it turns onto Holland Street heading south to serve the Red Line at Davis Square. Route 88 turns onto Highland Avenue heading east paralleling the Lowell Line and serving the Somerville Hospital and the Somerville High School. It then turns onto the McGrath Highway heading south and then east to Lechmere Station.

The weekday span of service for Route 88 is from 5:06 a.m. to 1:03 a.m. The route has the following headways: AM Peak—15, Midday—30, PM Peak—18, Night—30, Saturday—20, and Sunday—25. Daily weekday ridership is about 4000 passengers.

Route 89—Clarendon Hill or Davis Square Station to Sullivan Square Station

Route 89 is a 4-mile route that provides local service from two terminuses--Clarendon Hill and the Davis Square Red Line Station--to the Lechmere Green Line Station. The Clarendon Hill variation proceeds east along Broadway to Powderhouse Square. The Davis Square variation proceeds north along College Avenue to Powderhouse Square. From there, both variations head east along Broadway providing service to Magoun Square and Winter Hill and finally to Sullivan Square.

The weekday span of service for Route 89 is 4:33 a.m. to 1:22 a.m. The route has the following headways: AM Peak—9, Midday—30, PM Peak—10, Night—60, Saturday—30, and Sunday—60. Daily weekday ridership is about 3860 passengers.

Route 90—Davis Station to Wellington Station

Route 90 is a 5.5-mile route that provides local service from the Davis Square Red Line Station to the Wellington Orange Line Station. It proceeds east along Highland Avenue past Somerville High School to the McGrath Highway. From there, it heads north on Cross Street to Broadway. Next, it travels east on Broadway and services the Sullivan Square Orange Line Station and then travels north along Assembly Square Drive past the Assembly Square Mall to Wellington Station, also on the Orange Line.

The weekday span of service for Route 90 is from 6:30 a.m. to 10:25 p.m. The route has the following headways (in minutes): AM Peak—45, Midday—70, PM Peak—40, Saturday—60, and Sunday—60. Daily weekday ridership is about 1020 passengers.

Route 91—Sullivan Square Station to Central Square Station

Route 91 is a 2.5-mile route that provides local service from the Sullivan Square Orange Line Station to the Red Line Central Line Station. It proceeds west along Cambridge Street (which turns into Washington Street) past the Lowell Line (and future Green Line corridor) and across the McGrath Highway. At Union Square, Route 91 turns on to Somerville Avenue and then south on Webster Street (the outbound direction travels north along Prospect Street to Washington Street). Next, it turns onto Newton Street and then south on Springfield Street to Inman Square. Then, Route 91 travels east along Beacon Street and then south on Prospect Street. Finally, it travels south along Prospect Street, crosses Massachusetts Avenue, and loops around to its terminus near the entrance to the Red Line (inbound) Central Square Station entrance.

The weekday span of service for Route 91 is from 5:15 a.m. to 12:57 a.m. The route has the following headways: AM Peak—30, Midday—25, PM Peak—30, Night—60, Saturday—20, and Sunday—40. Daily weekday ridership is about 1480 passengers.

Route 92—Assembly Square to Downtown

Route 92 is a 4.5-mile route that provides downtown service from two northern terminals—Assembly Square Mall and the Sullivan Square Orange Line Station—to Downtown Crossing. It proceeds south along Assembly Square Drive to Sullivan Station. From there, it crosses over Rutherford Avenue and then heads south on Main Street through Charlestown. Next, it crosses the Charlestown Bridge into Boston. Route 92 travels south along Washington Street (providing service to the Green and Orange Lines at Haymarket Station) and then to Congress Street. Finally, it makes a figure 8 as it comes to its terminus on Franklin Street near Downtown Crossing.

The weekday span of service for Route 92 is from 5:00 a.m. to 10:10 p.m. The route has the following headways: AM Peak—15, Midday—32, PM Peak—15, and Saturday—35. Route 92 does not operate on weekday nights or Sundays. Daily weekday ridership is about 1140 passengers.

Route 94—Medford Square to Davis Square Station

Route 94 is a 4-mile route that provides local service from Medford Square to the Davis Square Red Line Station. It proceeds west along High Street to Boston Avenue passing through Winthrop Circle, West Medford, and Medford Hillside. Next, Route 94 follows Boston Avenue paralleling the Lowell Line to College Avenue. It heads south on College Avenue through Powderhouse Square, terminating at Davis Square.

The weekday span of service for Route 94 is from 5:19 a.m. to 1:01 a.m. The route has the following headways: AM Peak—20, Midday—30, PM Peak—20, Night—60, Saturday—30, and Sunday—60. Daily weekday ridership is 1400 passengers.

Route 95—West Medford to Sullivan Square Station

Route 95 is a 5.5-mile route that provides local service from West Medford to the Sullivan Square Orange Line Station. It proceeds south along Playstead Road to High Street. Next, it travels east along High Street past the West Medford Commuter Rail Station to Medford Square. Route 95 turns south onto Main Street and then heads east along Mystic Avenue past Assembly Square Mall to Sullivan Square Station.

The weekday span of service for Route 95 is from 5:17 a.m. to 1:24 a.m. The route has the following headways: AM Peak—20, Midday—30, PM Peak—20, Night—60, Saturday—30, and Sunday—60. Daily weekday ridership is about 1870 passengers.

Route 96—Medford Square to Harvard Square Station

Route 96 is a 4.5-mile route that provides local service from Medford Square to the Harvard Square Red Line Station. It begins by looping around Medford Square and then south on Main Street. It turns onto George Street and heads west to Winthrop Street. Next, Route 96 heads south passing over the Lowell Line. It parallels the Lowell Line on Boston Avenue providing service to Tufts University. At College Avenue, it heads south past Powderhouse Square. Route 96 provides service to the Davis Square Red Line Station prior to heading south on Holland Street. At Beech Street, it cuts over to Massachusetts Avenue and stops at Porter Square Red Line Station. From there, Route 96 continues along Massachusetts Avenue to the Harvard Upper Busway.

The weekday span of service for Route 95 is from 5:35 a.m. to 1:21 a.m. The route has the following headways: AM Peak—18, Midday—48, PM Peak—18, Night—50, Saturday—35, and Sunday—60. Daily weekday ridership is about 1760 passengers.

Route 101—Malden Center Station to Sullivan Square Station

Route 101 is a 6-mile route that provides local service from Malden Center Station to Sullivan Square Station, which are both on the Orange Line. It proceeds west along Pleasant Street, which turns into Salem Street. Route 101 proceeds to Medford Square and then south on Main Street to Winter Hill, where it turns onto Broadway. From there, Route 101 continues on Broadway until Sullivan Square Station.

The weekday span of service for Route 101 is from 4:56 a.m. to 12:57 a.m. The route has the following headways: AM Peak—9/15, Midday—30, PM Peak—12, Night—60, Saturday—30, and Sunday—60. Daily weekday ridership is about 5000 passengers.

Route CT2—Sullivan Square Station to Ruggles Square Station

Route CT2 is a 7-mile route that provides cross-town limited-stop service from Sullivan Square Station to Ruggles Station, both on the Orange Line. It proceeds west along Cambridge Street (which turns into Washington Street) over the Lowell Line and across the McGrath Highway. Inbound Route CT2 travels west along Somerville Avenue and then south along Webster Avenue. Outbound, the path follows Prospect Street to Somerville Avenue. Both directions travel along Webster Street between Prospect Street and Cambridge Avenue. Between there and

Hampshire Street, inbound trips take Windsor Street whereas outbound trips take Columbia Street. Route CT2 continues along Hampshire Street to Broadway and then loops around to the Kendall-MIT Red Line Station on Main Street. From there, it continues west along Vassar Street past MIT. It cuts over to Memorial Drive on Amesbury Street. Route CT2 heads west along Memorial Drive and then south on the BU Bridge over the Charles River. It crosses over the B Branch of the Green Line and heads east on Mountfort Street. Next, Route CT2 crosses over the C and D Branches of the Green Line while heading south on Park Drive. It travels south along Brookline Avenue and then east along Longwood Avenue past the Longwood Medical Area. At Huntington Avenue, Route CT2 heads east to the Museum of Fine Arts, providing service to the E Branch of the Green Line. Finally, it heads east on Ruggles Street to the Ruggles Station.

The weekday span of service for Route CT2 is from 5:55 a.m. to 7:38 p.m. The route has the following headways: AM Peak—20, Midday—30, and PM Peak—20. Route CT2 does not operate during weekday nights, Saturdays, or Sundays. Daily weekday ridership is about 2270 passengers.

4.1.4 Assessment of Spans of Service and Frequencies

The spans of service for bus routes are important for the connectivity of the transit network. For a transit network with both rapid transit and local bus service, most bus routes should cover at least the span of service of the rapid transit lines. One reason for this is that passengers travelling by rapid transit at night may still have a relatively long distance to travel from the station to their home.

The MBTA Service Delivery Policy specifies minimum spans of service for each mode. Bus routes are categorized into the following types: local, community, express/commuter, and key (major). All of the bus routes in the project area are local bus routes, which have a minimum span of service of 7 a.m. to 6:30 p.m. Additionally, local bus routes in high-density areas are required to operate on Saturdays from 8 a.m. to 6:30 p.m. and on Sundays from 10 a.m. to 6:30 p.m. (MBTA, 2009).

As shown in Table 4-2, all the existing Somerville and Medford bus routes satisfy the minimum span of service requirements. Three routes—Routes 85, 90, and CT2—do not begin service until about 6 a.m., which is after the rapid transit lines have begun service but still satisfy the minimum span of service guidelines. All of the routes operate during the evening except for Routes 85 and CT2, which are typically used for commuting. At about 10 p.m., Routes 90 and 92 end service, which coincides with the time that many of the stores close in Assembly Square. All of the other routes end service after the last rapid transit trip, which is at approximately 1 a.m. All routes provide service on weekends except for Routes 85 and CT2 and Route 92, which does not operate on Sundays.

Route #	Route Name	Wkdy. Service Span	
		Begin	End
80	Arlington Ctr. - Lechmere	5:05 AM	1:21 AM
83	Rindge Ave. - Central Sq.	5:10 AM	1:24 AM
85	Spring Hill - Kendall/MIT	6:00 AM	7:53 PM
86	Sullivan - Reservoir	5:06 AM	1:03 AM
87	Arlington Ctr./Clar. Hill - Lechmere	5:10 AM	1:17 AM
88	Clar. Hill - Lechmere	5:16 AM	1:17 AM
89	Clar. Hill or Davis Sq. - Sullivan	4:33 AM	1:22 AM
90	Davis Sq. - Wellington	6:30 AM	10:25 PM
91	Sullivan - Central Sq.	5:15 AM	12:57 AM
92	Assembly Sq. - Downtown	5:00 AM	10:10 PM
94	Medford Sq. - Davis Sq.	5:19 AM	1:01 AM
95	West Medford - Sullivan	5:17 AM	1:24 AM
96	Medford Sq. - Harvard Sq.	5:35 AM	1:21 AM
101	Malden - Sullivan	4:56 AM	12:57 AM
CT2	Sullivan - Ruggles	5:55 AM	7:38 PM

Table 4-2. Spans of Service for Existing Somerville and Medford Bus Routes

For local bus routes, MBTA service standards require that the bus routes operate on a maximum headway of 30 minutes during the AM and PM peaks. For all other periods of the day, as well as Saturdays and Sundays, the maximum headway is 60 minutes.

In general, the routes that serve Somerville and Medford are infrequent and are not viewed as providing “walk-up” service even during the peak periods. Furthermore, several of the Somerville and Medford routes have irregular headways. For example, Route 94 has inbound AM trips beginning at 7:38, 7:50, and 8:20, which means that there is a 12-minute headway followed by a 30-minute headway. One would expect that the loading on the 8:20 trip would be significantly higher than the loading on the 7:50 trip. It is difficult to summarize headways for routes that are irregular; however, a value close to the average is a reasonable approximation.

The typical headways of the Somerville and Medford bus routes throughout the day are shown in Table 4-3. Route 90 does not meet the minimum frequency standard all day, and Route 85 does not meet the minimum frequency standard during the peak periods. Route 91 has the most frequent service during the midday and Saturdays, but its peak frequency of 30 minutes is better than only Routes 85 and 90. Routes 86, 87, and 101 have unbalanced headways (that is, the inbound and outbound frequencies do not match) during one or both peak periods. Routes 87 and 88 are the only routes with headways less than 50 minutes during weekday evenings.

Rt. #	**Route Name**	**Scheduled Headway* (in minutes)**					
		AM Pk.	**Day**	**PM Pk.**	**Night**	**SAT**	**SUN**
80	Arlington Ctr. - Lechmere	20	35	20	60	35	60
83	Rindge Ave. - Central Sq.	15	30	20	60	25	50
85	Spring Hill - Kendall/MIT	35	40	40	N/A	N/A	N/A
86	Sullivan - Reservoir	15/9	30	12/17	60	25	30
87	Arl. Ctr./Clar. Hill - Lechmere	18/21	30	15	30	25	25
88	Clar. Hill - Lechmere	15	30	18	30	20	25
89	Clar. Hill or Davis Sq. - Sullivan	9	30	10	60	30	60
90	Davis Sq. - Wellington	45	70	40	N/A	60	60
91	Sullivan - Central Sq.	30	25	30	60	20	40
92	Assembly Sq. - Downtown	15	32	15	N/A	35	N/A
94	Medford Sq. - Davis Sq.	20	48	20	50	45	60
95	West Medford - Sullivan	20	30	20	60	30	60
96	Medford Sq. - Harvard Sq.	18	48	18	50	35	60
101	Malden - Sullivan	9/15	30	12	60	30	60
CT2	Sullivan - Ruggles	20	30	20	N/A	N/A	N/A

* Headways are in the format Inbound/Outbound (where necessary).

Table 4-3. Headways for Somerville and Medford Bus Routes

4.2 Ridership Analyses

The frequency of public transportation service is largely a function of the ridership along the route. There are three data sources for ridership counts: ride checks, APCs, and AFCs. This section compares APC with ride check data and analyzes the level of AFC undercounting. Additionally, analyses of peak hour boardings and bus crowding for the Somerville-Medford bus routes are also presented.

4.2.1 Comparison of Ride Checks and APC Data

The metropolitan planning agency for Boston is the Central Transportation Planning Staff (CTPS) which is responsible for conducting ride checks on MBTA bus routes. Until recently, ride checks typically occurred every five or six years, although they could be performed more frequently if the Service Planning Department required more recent data. The ride checks only represent one day's worth of trips, although the data collection is often spread over multiple days to accommodate constraints on the number of ride checkers. The latest CTPS ride checks for the Somerville and Medford bus routes are from 2002 to 2009 as shown in Table 4-4.

Route #	Route Name	Date of Ride Check
80	Arlington Center - Lechmere	Fall '04
83	Rindge Ave. - Central Sq.	Winter '03
85	Spring Hill - Kendall/MIT	Winter '06
86	Sullivan Station - Reservoir	Fall '02
87	Arlington Center - Lechmere	Fall '05
88	Clarendon Hill - Lechmere	Winter '04
89	Clar. Hill or Davis - Sullivan	Winter '02
90	Davis Station - Wellington	Winter '07
91	Sullivan - Central Sq.	Winter '09
92	Assembly Sq. - Downtown	Fall '08
94	Medford Square - Davis	Spring '09
95	West Medford - Sullivan	Winter '06
96	Medford Square - Harvard	Winter '06
101	Malden - Sullivan	Winter '09
CT2	Sullivan - Ruggles	Fall '05

Table 4-4. CTPS Ride Check Data

The ride checks and APC data (from a three-month period in Fall 2009) for the study area routes are shown in Table 4-5. Many of the average boardings for the two datasets are not statistically significant (two-tailed t-test at 95 percent confidence level). The major exceptions are Routes 94, 95, and 96, which operate primarily out of the Fellsway Garage which has few APC-equipped buses. Thus, these routes have fewer trips in the APC dataset than other routes with similar frequencies. More significantly, the trips for which APC counts exist are all during the off-peak hours, which typically have significantly lower ridership. Thus, the average number of passengers per trip for these routes over the full day is underestimated and is significantly lower

Route #	Begin	Ride Checks				APC*				Stat. Sig. Diff.
		Daily Riders	# of Bus Trips	Avg. Ons/ Trip	St. Dev.	Daily Riders	# of Bus Trips	Avg. Ons/ Trip	St. Dev.	
80	Arlington Center	1000	41	24.3	13	1040	307	24.8	1.3	
	Lechmere	860	39	21	9	940	315	21.8	2.4	
83	Russell Field	1080	50	21	14.3	1050	326	17.5	1.6	✓
	Central Square	1070	47	23	12.5	1060	327	18.7	2.4	✓
85	Spring Hill	230	22	10.6	12.5	360	89	12.8	2	
	Kendall/MIT	170	22	7.5	8.8	110	93	7.1	1.7	
86	Sullivan Square	1960	46	47.3	19.3	2690	475	38.3	2.7	✓
	Reservoir Station	2200	42	45.5	23.5	2890	393	46	2.1	
87	Arlington Center	1690	52	32.4	22.3	2020	471	34	2	
	Lechmere	1690	53	31.9	19.4	1870	504	31.1	2.7	
88	Clarendon Hill	2000	59	33.2	17.7	1900	573	30.1	2.4	✓
	Lechmere	1790	61	29.3	14.6	1820	543	29.3	3.1	
89	Clarendon Hill/Davis Sq.	1600	68	27	14.8	1670	564	25.5	2.4	✓
	Sullivan Square	1850	63	25.3	10.6	1550	636	23.9	3.4	✓
90	Davis Square	440	23	19.3	7.6	600	300	24.7	1.9	✓
	Wellington Station	480	22	21.6	12	530	300	22.2	1.8	
91	Sullivan Square	710	38	20.2	9.5	820	433	20.7	2.8	
	Central Square	770	38	18.7	8.8	860	433	18.9	2.7	
92	Assembly Square Mall	560	45	12.4	12.2	630	363	13.4	1.8	
	Downtown Boston	500	45	11	9.9	560	320	14.7	2.2	✓
94*	Medford Square	580	34	22.3	12.6	N/A	182	10.2	2.2	✓
	Davis Station	760	35	16.5	14.7	N/A	196	7.1	0.7	✓
95*	West Medford	790	46	17.2	10.3	N/A	150	12.2	2.4	✓
	Sullivan Square	960	45	21.3	13.2	N/A	184	14	1.7	✓
96*	Medford Square	950	38	25	19.6	N/A	225	11.6	1.9	✓
	Harvard Square	830	38	21.9	14.5	N/A	224	15.2	1.1	✓
101	Malden Station	1990	62	32.1	14.5	2340	563	32.6	2.4	
	Sullivan Square	1950	59	33	15.2	2400	578	32	3.3	
CT2	Sullivan Square	790	30	43.2	25.3	N/A	N/A	N/A	N/A	N/A
	Ruggles	758	32	39.3	22.8	N/A	N/A	N/A	N/A	N/A

*Routes 94, 95, and 96 operate primarily out of Fellsway Garage. Limited (off-peak only) APC data available.

Table 4-5. Ridership Estimates using Ride Check and APC Data

than the ride check data estimates. Another route with significant differences is Route 86 inbound, which has 10 fewer boardings per trip, on average, with APC counts than with ride checks data. The difference in average boardings per trip is likely due to the fact that the ride check for Route 86 is from Fall 2002. The total bus trips on Route 86 has likely increased since 2002, so the ride check data is no longer valid. Other routes with statistically significant differences between AFC and APC estimates of boardings per trip are Routes 83, 88 (inbound), 89, 90 (inbound), and 92 (outbound).

This analysis shows that ridership counts from APCs are generally consistent with ride check data. APC datasets are significantly better, however, due to the added benefits of having the most recent data and more trips (and therefore lower standard errors). In addition, APC datasets can be used to determine the locations of long dwell times on trips. APC data should be used where there is sufficient data, although ride checks data can be substituted for routes (i.e. Routes 94, 95, and 96) that do not have an adequate APC sample size.

4.2.2 Comparing AFC and APC Data

Many transit agencies are moving towards using APC data to estimate ridership. Passenger miles, which are reported to the National Transit Database, are directly estimated using APC systems. However, there are often systematic biases associated with APC counts, which are difficult to quantify because manual counts often have even greater measurement error (Furth et al, 2006). To improve the accuracy of ridership counts, some transit agencies ignore trips that have large differences (e.g. 10 percent) between ons and offs. In general, transit agencies consider APC data to be reliable.

Similar to APCs, AFC systems should ideally count every bus passenger so that the transit agency knows exact ridership on each bus route. For this to happen, each passenger must either have a successful transaction with the AFC farebox or the bus driver must press a button to indicate that a passenger has boarded. There are still ways in which a boarding passenger may not be counted by the AFC system, including:

- Passenger and driver mistakenly think that a successful AFC transaction has occurred
- Driver mistakenly thinks that he has pressed the ridership button
- Passenger shows driver her pass but the driver fails to press button
- Driver chooses not to press button for children when they board (in the MBTA system, children under 11 are free)
- Driver discourages passengers from using the farebox so as to leave the stop as soon as possible to avoid falling further behind schedule
- AFC device is not working when the passenger boards

- Passenger boards the bus avoiding the bus driver (e.g. through the back door)

It is also possible for AFCs to overcount ridership, as in the case that either the passenger inadvertently interacts multiple times with the AFC device or the bus driver presses the button more than once. However, these occur infrequently, because extra effort is required. Thus, there is a systematic undercounting with AFC data systems, so ridership numbers should be increased by a correction factor. This correction will be referred to in this thesis as the *AFC undercount factor*.

APC counts are more accurate than AFC counts; however, only a fraction of the bus fleet is equipped with APC devices. If the APC-equipped buses are rotated through all trips, then it is possible to calculate AFC undercount factors for each route. Runs that have valid APC counts can be compared to the corresponding AFC counts. The AFC undercount factor for each run can be calculated by Equation 4-1.

$$\boldsymbol{Undercount\ Factor} = \sum \boldsymbol{APC\ Counts} / \sum \boldsymbol{AFC\ Counts} \qquad \text{(Equation 4-1)}$$

The average AFC undercount factors and standard deviations across trips for the study area bus routes are shown in Table 4-6. Route CT2 did not have any valid APC data, so it does not appear in the table. The average AFC undercount factor for all routes is 1.12 with route averages ranging from 1.01 to 1.21, excluding Route 95, which has AFC undercount factors that are 1.63 and 1.43 for inbound and outbound, respectively. These large values for Route 95 come from only 16 trips which are statistically different than the average for all routes ($p<0.01$). Thus, the Route 95 sample is probably not representative of all trips. Similarly, the variability of the undercount factor across trips is high for Route 83 (standard deviation of 0.37 and 0.48 for inbound and outbound, respectively) and, to a lesser extent, for several other routes, which may be due to different fare verification strategies being used by drivers.

In summary, a different AFC undercount factor can be calculated for each route. Although it is generally a good idea for service planners to use the route-specific undercount factors for detailed investigations of a specific route, some of the samples in this analysis are quite small. Therefore, a weighted average undercount factor for all of the area routes is used for all AFC ridership numbers in this thesis.

Route	Route Name	Inbound			Outbound		
		# Trips	Avg.	St. Dev.	# Trips	Avg.	St. Dev.
80	West Medford - Lechmere	26	1.17	0.47	27	1.11	0.24
83	Russell Field - Central Sq.	53	1.18	0.37	50	1.21	0.48
85	Spring Hill - Kendall/MIT	2	1.08	0.35	3	1.15	0.14
86	Sullivan Sq. - Reservoir	26	1.07	0.10	29	1.09	0.10
87	Arlington Center - Lechmere	53	1.08	0.20	50	1.11	0.21
88	Clarendon Hill - Lechmere	73	1.11	0.15	73	1.11	0.14
89	Clarendon or Davis - Sullivan Sq.	52	1.09	0.10	46	1.08	0.15
90	Wellington - Davis Sq.	20	1.08	0.14	19	1.16	0.13
91	Sullivan Sq. - Central Sq.	43	1.14	0.22	44	1.17	0.21
92	Assembly Sq. Mall - Downtown	40	1.18	0.22	42	1.12	0.27
94	Medford Sq. - Davis Sq.	12	1.12	0.30	7	1.03	0.28
95	West Medford - Sullivan Sq.	8	1.63	0.63	8	1.43	1.05
96	Medford Sq. - Harvard Sq.	13	1.18	0.14	11	1.01	0.09
101	Malden Center - Sullivan Sq.	57	1.13	0.25	51	1.10	0.18
ALL STUDY-AREA ROUTES		478	1.12	0.27	460	1.12	0.28

Table 4-6. AFC Undercount Factors for Somerville-Medford Bus Routes

4.2.3 Boardings, Alightings, and Load Profiles

All ridership numbers in this section are from ride checks, because insufficient APC data is available for some of the routes and a stop-level O-D matrix based on AFC data has not yet been estimated for the study area.

The passenger boardings, alightings, and load for Route 80 inbound and outbound are shown in Figures 4-2 and 4-3, respectively. The patterns of the ons and offs for Route 80 are similar to those for other routes in the service area. First, the stops with the most passenger activity are the terminals, and, in particular, the rail stations. Lechmere Station on the Green Line has over 500 alightings inbound and about 520 boardings outbound. These values are three times the boardings/alightings at the next busiest stop (Arlington Center, the other terminal) and at least eight times greater than at any other stop. A second trend is that there is usually at least one segment near the middle of the run that has a significant number of ons and offs. This is true with Route 80, which has a lower peak of ons and offs along Broadway and Medford Street. A third characteristic is that the ons and offs inbound are simply the reverse of outbound. Finally, maximum loading occurs close to one of the terminals (in this case, Lechmere Station). This is typical for routes with unbalanced loading (e.g. most of the ons or offs occurring at one end of the route). The boardings, alightings, and load profile for the other study area routes are shown in Appendix A.

4.2.4 Key Locations along Routes

For every route, there are key route segments or stops that are particularly important to the transit operator. One type of key location is a stop or segment that has high numbers of boardings and/or alightings, which can be determined by the profiles shown in the previous section. The time that it takes for each passenger to board the bus and interact with the farebox or depart from the bus increases the bus dwell time and, hence, the running time. The key route segments and stops (excluding rapid transit nodes) for the MBTA study area routes are shown in Table 4-7.

Route #	Route Description	Key Route Segments/Stops
80	Arlington Center - Lechmere	Pearl Street Medford Street Broadway Ave.
83	Russell Field - Central Square	Somerville Ave. @ Central St. Beacon St. @ Washington St.
85	Spring Hill - Kendall/MIT	Union Square
86	Sullivan Square - Reservoir	Union Square Western Ave.
87	Arlington Center - Lechmere	Union Square
88	Clarendon Hill - Lechmere	Highland Ave.
89	Clarendon Hill - Sullivan Square	Broadway: Cross St. to Main St.
90	Davis Square - Wellington	Highland: Crocker St. to McGrath Hwy. Sullivan Sq. to Wellington
91	Sullivan Square - Central Square	Inman Sq. (Start of each direction)
92	Assembly Sq. Mall - Downtown	Downtown Boston Charlestown
94	Medford Square - Davis Square	Boston Ave. near Tufts U.
95	West Medford - Sullivan Square	Mystic Ave. near Assembly Sq. Mall
96	Medford Sq. - Harvard Sq.	Tufts to West Medford
101	Malden Center - Sullivan Square	Broadway: Main St. to McGrath Medford Square
CT2	Sullivan Sq. - MIT (and Ruggles)	MIT to Washington St.

Table 4-7. Key Segments/Stops on Somerville-Medford Bus Routes

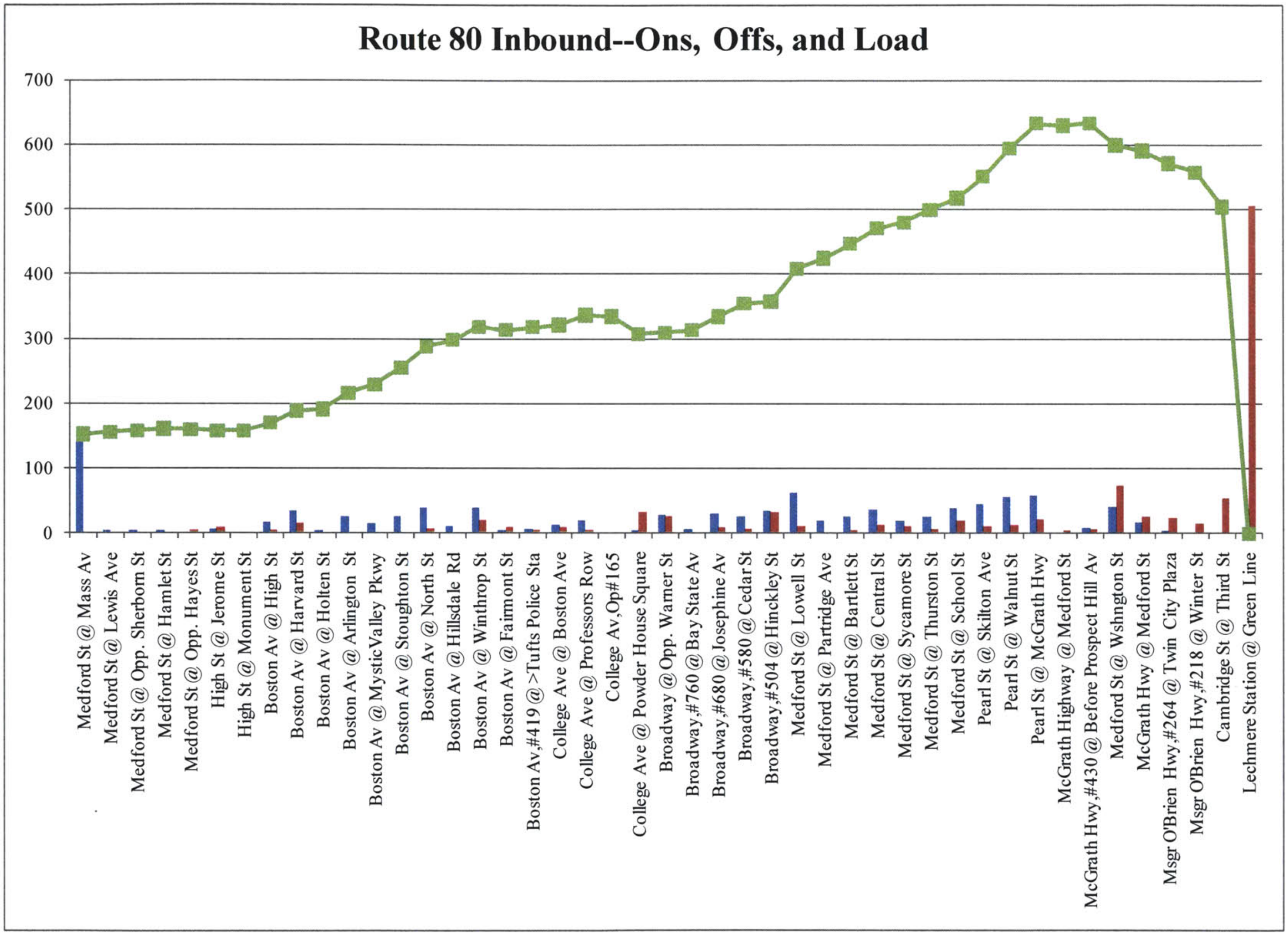
Route 80 Inbound--Ons, Offs, and Load

Figure 4-2. Route 80 Inbound—Ons, Offs, and Load

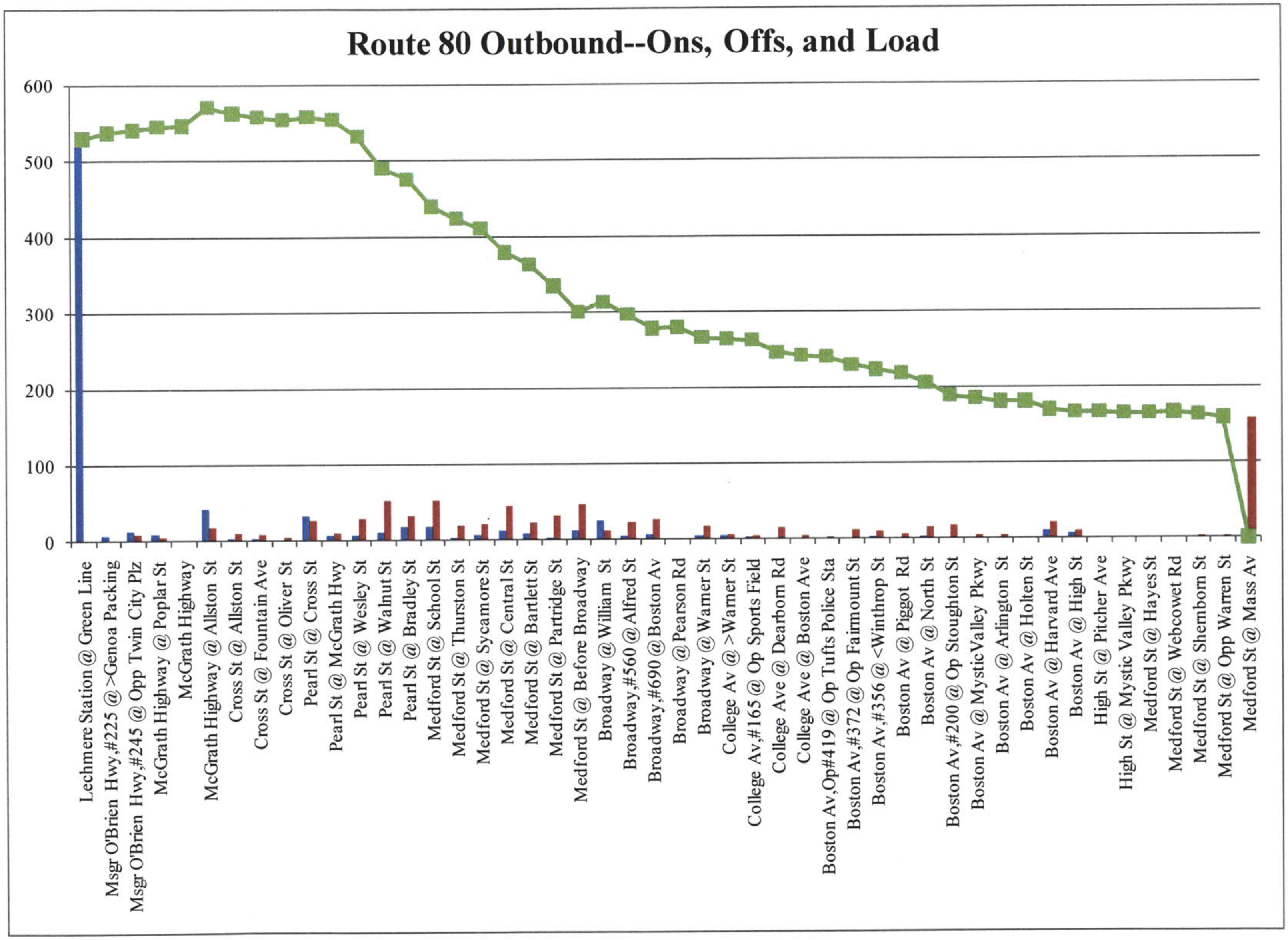

Figure 4-3. Route 80 Outbound—Ons, Offs, and Load

4.2.5 Ridership and Peak Loading

The peak load points for the study area routes are shown in Table 4-8 based on the distribution of boardings and alightings. A route that has close to the same number as boardings as alightings for most portions of the route will have uniform loading, which means that every stop is the peak load point. This is the case for Route 90 between Sullivan Square and Central Square. Routes with unbalanced loading will have peak load points at or near one of the terminals. Routes 94, 95, and 96, especially outbound, are examples of this type of peak loading.

Route	Route Name	Inbound	Outbound
80	Arlington Ctr. - Lechmere	430 McGrath Hwy.	McGrath Hwy. @ Allston St.
83	Rindge Ave. - Central Sq.	Park St. @ Beacon St.	Prospect St. @ Broadway
85	Spring Hill - Kendall/MIT	Windsor St @ Hampshire St.	Hampshire St. @ Card. Meideros
86	Sullivan - Reservoir	west of Harvard Sq.	Harvard Business School
87	Arl. Ctr./Clar. Hill - Lechmere	Holland St. @ Jay St.	Somerville Ave. @ Central St.
88	Clar. Hill - Lechmere	Highland Ave. @ Cedar St.	235 Highland Ave.
89	Clar. Hill or Davis Sq. - Sullivan	Broadway (near Sullivan Sq.)	Broadway @ Kensington Ave.
90	Davis Sq. - Wellington	west of Sullivan Sq. (all)	Highland Ave. (near Davis Sq.)
91	Sullivan - Central Sq.	Inman Sq.	Springfieldt St. @ Concord Ave.
92	Assembly Sq. - Downtown	Main St. @ Park St.	Washington St. @ Commercial St.
94	Medford Sq. - Davis Sq.	College Ave. (near Davis Sq.)	Davis Sq.
95	West Medford - Sullivan	Mystic Ave. @ Wheatland St.	Sullivan Sq.
96	Medford Sq. - Harvard Sq.	Powderhouse Sq.	Davis Sq.
101	Malden - Sullivan	Broadway (near Sullivan Sq.)	Broadway (near Sullivan Sq.)
CT2	Sullivan - Ruggles	Kendall/MIT	Amesbury St. @ Vassar St.

Table 4-8. Peak Load Points on Study Area Bus Routes

The average daily ridership and average hourly boardings during the peak periods for the study area routes are shown in Table 4-9. The total daily ridership for the study area routes is about 38,140 passengers. In general, the ridership in one AM peak hour is approximately 10 percent of the average daily ridership. Route 86, especially in the AM peak, has the most boardings. Routes 85 and 90 have the fewest boardings with fewer than 100 per peak hour. There are interesting observations that can be made by comparing ridership across routes. For example, Routes 88 and 89 have similar ridership, but Route 89 has peak headways that are 6 to 8 minutes shorter than those on Route 88. Also, the PM peak hourly boardings on Routes 91 and 92 are similar, although the headway on Route 91 (30 minutes) is twice that on Route 92. Many of the headways of the study area routes will be revised in Chapter 5 so that the frequencies used on the routes are representative of the observed demand.

Route #	Route Name	Avg. Daily Ridership	Avg. Hourly Boardings		Scheduled Headway*	
			AM Peak	PM Peak	AM Peak	PM Peak
80	Arlington Center - Lechmere	2030	180	170	20	20
83	Rindge Ave. - Central Sq.	2220	240	170	15	20
85	Spring Hill - Kendall/MIT	600	80	60	35	40
86	Sullivan Station - Reservoir	5830	620	440	15/9	12/17
87	Arlington Center - Lechmere	3660	360	340	18/21	15
88	Clarendon Hill - Lechmere	4000	410	300	15	18
89	Clar. Hill or Davis - Sullivan	3860	410	320	9	10
90	Davis Station - Wellington	1020	60	90	45	40
91	Sullivan - Central Sq.	1480	90	120	30	30
92	Assembly Sq. - Downtown	1140	130	120	15	15
94	Medford Square - Davis	1400	120	150	20	20
95	West Medford - Sullivan	1870	200	130	20	20
96	Medford Square - Harvard	1760	200	140	18	18
101	Malden - Sullivan	5000	440	460	9/15	12
CT2	Sullivan - Ruggles	2270	310	240	20	20
TOTAL--ALL ROUTES		38140	3850	3250		

* Headways are in the format Inbound/Outbound (where necessary).

Table 4-9. AFC Ridership Data for Study Area Bus Routes

4.2.6 Overcrowded Buses

Crowding is a serious concern for most large transit agencies, so loading standards are used to reduce the occurrence of overcrowded buses. Most overcrowding occurs during the peak periods when the system demand is the greatest and service is constrained by the number of available buses and drivers. Hence, many passengers are willing to accept more crowding during the peak periods than at other times. When planning service for a set of routes, there may be some routes that have higher probabilities of being overcrowded. These routes should be flagged and studied further to see whether increased frequencies are warranted.

MBTA service standards are that the peak load should be no more than 1.4 times and 1.0 times the number of seats on a bus during the peak and off-peak periods, respectively (MBTA, 2009). With an average bus size in the study area of 39 seats, the peak period load standard is 55 passengers. Table 4-10 shows the timepoints of the study area routes with the greatest percentage of overcrowded buses during the peak hours. Overcrowding is not a major issue for Somerville-Medford routes; however, there are some specific trips on some of the routes that often exceed MBTA service standards for at least a portion of the route. The routes that do not have APC counts for the peak hours are under-represented in Table 4-10. Some of these routes, especially 94 and 96 during the peak periods, would otherwise show up at or near the top of the list. Route 87 inbound at the intersection of Broadway and Holland Street is by far the worst location on the list; two-fifths of the trips during the AM peak are overcrowded.

Route	Direction	Timepoint	Hour of Day	Buses Overcrowded (%)
87	Inbound	Broadway @ Holland St.	8:00 AM	40
87	Inbound	Broadway @ Holland St.	7:00 AM	40
86	Inbound	Somerville Ave. @ Stone Ave.	7:00 AM	14
86	Inbound	Harvard Sq. @ Garden St.	7:00 AM	11
92	Inbound	Main St. @ Park St.	8:00 AM	10
87	Outbound	Somerville Ave. @ Stone Ave.	5:00 PM	8
87	Outbound	Somerville Ave. @ Central St.	6:00 PM	8
87	Inbound	Clarendon Hill Busway	8:00 AM	7
87	Outbound	Somerville Ave. @ Stone Ave.	6:00 PM	7
87	Outbound	Somerville Ave. @ Central St.	5:00 PM	7
89	Inbound	Broadway @ Main St.	4:00 PM	6
87	Inbound	Clarendon Hill Busway	7:00 AM	5
101	Inbound	Broadway @ Cross St.	8:00 AM	4
101	Inbound	Broadway @ Cross St.	7:00 AM	3
89	Inbound	Sullivan Station	6:00 PM	3
101	Inbound	Broadway @ Cross St.	8:00 AM	3
92	Outbound	Chelsea St. @ Warren St.	6:00 PM	3
101	Inbound	Broadway @ Cross St.	7:00 AM	3
89	Inbound	Sullivan Station	5:00 PM	3

Table 4-10. Routes Experiencing Overcrowding—Peak Hours (APC Data)

The timepoints with the more than 10 percent overcrowded buses during off-peak weekdays are shown in Table 4-11. Route 101 has major issues with overcrowding during off-peak hours, especially outbound in the evening. This suggests that the current timetable, which uses headways of 40 minutes from 6:30 p.m. to 8:30 p.m. and then 60 minutes until the end of service, may be inadequate. Routes 87 and 86 also have quite a bit of overcrowding during the off-peak hours.

Route	Direction	Timepoint	Hour of Day	Buses Overcrowded (%)
101	Outbound	Sullivan Station	9:00 PM	50
101	Outbound	Sullivan Station	7:00 PM	46
101	Outbound	Broadway @ Cross St.	7:00 PM	39
101	Outbound	Broadway @ Cross St.	9:00 PM	25
101	Outbound	Broadway @ Cross St.	8:00 PM	25
87	Inbound	Broadway @ Holland St.	9:00 AM	23
86	Inbound	Somerville Ave. @ Stone Ave.	9:00 AM	20
87	Outbound	Davis Sq.	7:00 PM	20
101	Inbound	Broadway @ Cross St.	10:00 AM	18
87	Outbound	Broadway @ Curtis St.	7:00 PM	18
87	Outbound	Somerville Ave. @ Central St.	7:00 PM	14
89	Outbound	Sullivan Station	8:00 PM	13
96	Outbound	College Ave. @ Warner St.	10:00 PM	13
86	Inbound	Harvard Sq. @ Garden St.	9:00 PM	11
96	Outbound	Sullivan Station	9:00 PM	11

Table 4-11. Routes Experiencing Overcrowding—Off-Peak Hours (APC Data)

4.3 Running Time Analysis

This section describes the factors affecting running time, how running times are analyzed, and how running times are set in the scheduling process.

There are many factors that affect scheduled and observed running times. First of all, the schedule must be set so that a high percentage of trips can start the next trip on-time. However, if too much running time is allocated, then the bus driver may reach timepoints early or may drive at a slower-than-necessary pace. Secondly, congestion, especially in the peak-hour peak-direction, directly impacts the minimum time required to complete a trip. Thirdly, dwell time at bus stops can significantly affect the running time, since boarding and alighting take longer when a bus is crowded.

Running times can be analyzed using data for one direction or both directions; this thesis focuses on the full cycle. For one direction of travel, the end-to-end observed running time is the elapsed time from the departure at the origin to the arrival at the end terminus. Round-trip running times are calculated by adding together the trip's running time in both directions. All the trips for a route are summarized by half-hour period of the day. Routes with multiple, frequently-used route variations are summarized by variation. Due to the large quantity of AVL data, it is reasonable to exclude bad data. For this analysis, the following trips are excluded:

- Trips that are missing the start or end terminal timestamps
- Trips that switch drivers en route (which adds to the running time)
- Outlier trips (e.g. observed running time is greater than 1.5 times the scheduled running time)

Many transit agencies use homogenous time periods for all routes when setting running times. While this is an easy way to create the timetables for all routes, every route, in reality, has a different distribution of running times by time of day. For example, it may be ideal to use the same running time from the 9 a.m. to 2 p.m. on one route, whereas it may be beneficial for a different route to have two different running times; one for 9 a.m. to noon and another for noon to 2 p.m. Setting the time periods can be done by inspection (as in the case of this work) or through application of statistical methods.

In practice, some transit agencies set their running times close to the mean observed running times. Additionally, some agencies build in slack to their schedules and use holding strategies at timepoints (Furth et al, 2006). The half-cycle time (running time plus recovery time) is generally set at between the 85th-95th percentile of actual running times for a time period, depending on the stress on reliability. For example, Tri-Met Transit Agency in Portland, OR sets its half-cycle time at the 95th percentile of observed running times. (Furth et al, 2006). Setting the half-cycle time at the 85th percentile means that there is a 15 percent chance that a bus will arrive so late that it will not be able to start the next trip on schedule. The probability of being late is even greater for subsequent trips, because the tardiness propagates.

To illustrate these issues, Figure 4-4 shows the round-trip running time distributions (summarized by half-hour periods) for Route 83 (Rindge Avenue – Central Square) using three months of data from Fall 2009. The running time graphs for the other study area routes are included in Appendix B. Two to three minutes of buffer time (round-trip) have been added to all the observed running times to provide some additional reliability when proposing new cycle and running times. Thus, a bus observed at the 95th percentile round-trip running time should be able to start the next trip on-time provided that the total loading/unloading time at the terminals takes only a few minutes. Compared with a half-cycle running time analysis, the departure time of the return trip may be slightly less than 95 percent on-time, but this difference can be kept low if the half-cycle times are split appropriately (e.g. allocated based on the 95th percentile of the one-way running times). In general, the scheduled running time for Route 83 is currently set too low (it is often below the 50th percentile of observed running times) during the AM peak, PM school, and PM peak. The scheduled cycle time for Route 83 is set too high during the AM peak and midday but is set too low during the PM peak.

The round-trip cycle time is set close to the 95th percentile running time for most of the routes (including Route 83), because the 95th percentile running time is only a few minutes more than the 85th percentile running time for most half-hour periods. There are several half-hour periods where the observed running times are much higher than the observed running times in adjacent half-hour periods. For the time periods including these half hours, the cycle time was set at the maximum 95th percentile observed round trip running time of the other half-hour periods and, when possible, above this level. There are five main running time periods that are proposed for Route 83:

- From 6 to 9 a.m., the cycle time is set at 61 minutes.
- From 9 a.m. to 1:30 p.m., the cycle time is set at 58 minutes.
- From 1:30 to 6:30 p.m., the cycle time is set at 65 minutes.
- From 6:30 to 10 p.m., the cycle time is set at 59 minutes.
- After 10 p.m., the cycle time is set at 51 minutes.

Table 4-12 summarizes the current and proposed cycle and running times for the peak periods. Many of the routes have different cycle and running times currently during the peak periods, so the maximum value of each is included in the summary. Even with this conservative approach, there is less cycle time scheduled currently than this running time analysis would recommend. In particular, the current running time is set, on average, 4 to 5 minutes too low. Route 90 requires the greatest adjustment in running times. The current cycle time only accommodates about 50 percent of the round trips, so the proposed running times are increased by 18 and 10 minutes in the AM and PM peaks, respectively. Route CT2 in the PM peak also requires significantly more cycle time than currently allocated; it is currently set at 117 minutes, but it should be increased to about 127 minutes.

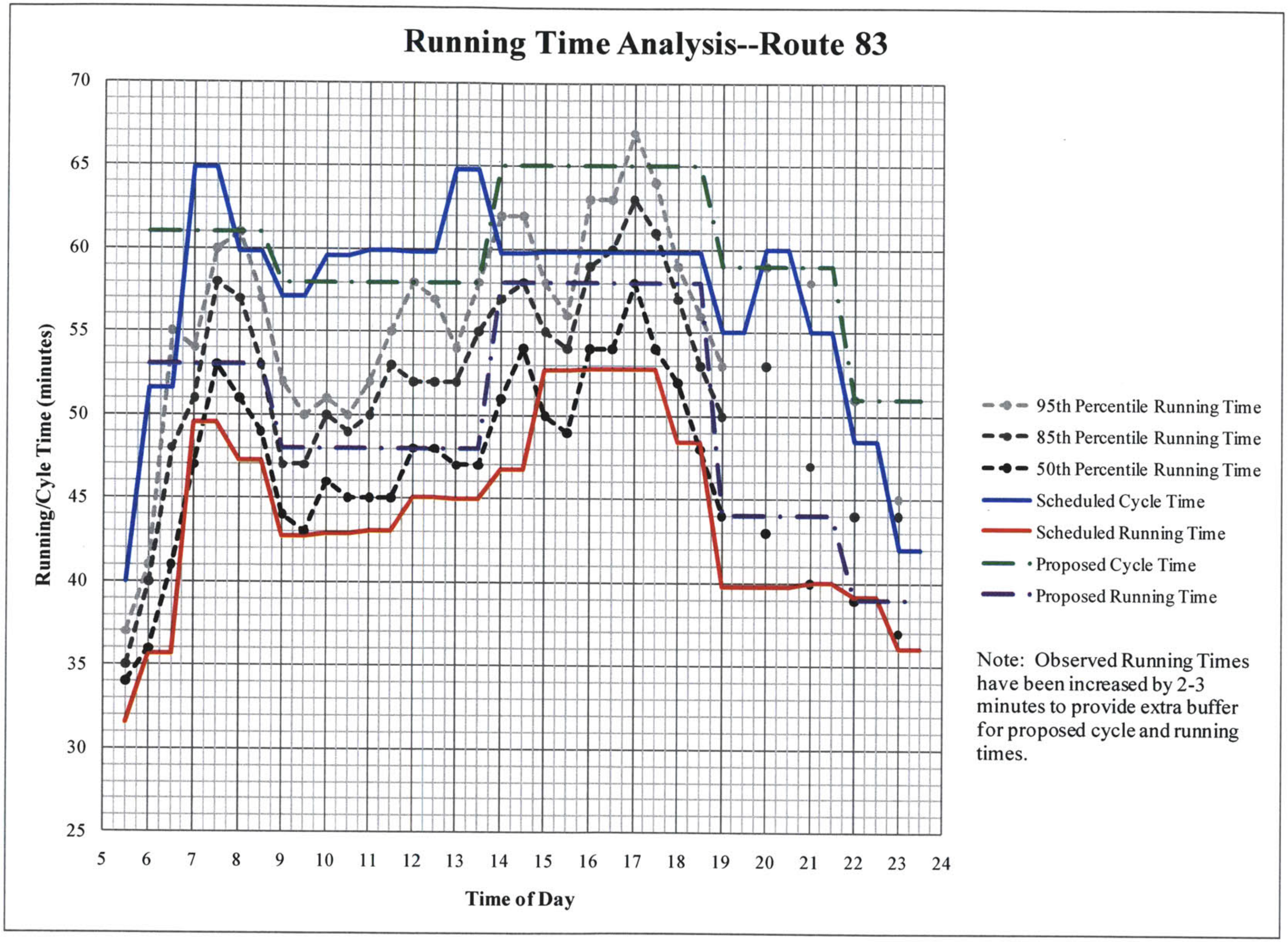

Figure 4-4. Round-Trip Running Time Distributions for Route 83

Rt. #	Route Name	Existing MBTA Schedule				Proposed Schedule			
		AM Peak		PM Peak		AM Peak		PM Peak	
		Cycle Time	Running Time	Cycle Time	Running Time	Cycle Time	Running Time	Cycle Time	Running Time
80	Arlington Ctr. - Lechmere	85	67	80	67	80	68	82	71
83	Rindge Ave. - Central Sq.	65	50	60	53	62	52	67	58
85	Spring Hill - Kendall/MIT	40	30	40	30	41	34	42	36
86	Sullivan - Reservoir	114	86	120	96	106	92	122	99
87	Arlington Ctr. - Lechmere	80	70	80	69	80	69	82	69
88	Clarendon Hill - Lechmere	63	53	72	57	67	56	67	55
89	Clarendon Hill - Sullivan	55	39	58	43	57	45	54	45
89-2	Davis Sq. - Sullivan	55	39	58	43	56	48	55	46
90	Davis Sq. - Wellington	87	67	80	69	95	85	89	79
91	Sullivan - Central Sq.	60	36	60	40	63	52	57	45
92	Sullivan - Downtown	46	41	60	45	50	41	57	45
94	Medford Sq. - Davis Sq.	58	50	60	44	56	46	71	59
95	West Medford - Sullivan	58	50	60	52	63	50	61	47
96	Medford Sq. - Harvard Sq.	73	64	81	64	79	67	87	73
101	Malden - Sullivan	80	69	79	68	82	72	79	64
CT2	Sullivan - Ruggles	113	92	117	94	113	96	127	107

Table 4-12. Summary of Running Times Analysis—AM and PM Peak Periods

Finally, running times should not be considered to be fixed for the medium- to long-term. On-going analysis will refine the running times, but changes to the transportation network or in travel patterns may increase (or decrease) the time required for a bus trip.

4.4 Other Service and Operations Analyses

The first three sections of this chapter provide inputs into the service planning scenarios presented in Chapter 5. Other analyses were performed on the study area routes that are not used in Chapter 5. Some of these analyses will provide the base for future work to be performed by other researchers. The following analyses are included in appendices of this thesis:

- Somerville Community Bus Survey (Appendix C)—the results of a Somerville Transportation Equity Partnership (STEP) community bus passenger survey are discussed.
- MBTA/CTPS Rider Survey Origin-Destination Matrix (Appendix D)—a neighborhood-level O-D matrix is estimated using data from an MBTA/CTPS passenger survey.

- Transfer Rates (Appendix E)—AFC transactions are linked together to estimate transfer rates to and from the study area routes.
- Trip Rates (Appendix F)—the relationship between frequency and ridership is investigated with special consideration for route segments shared by multiple routes.
- On-Time Performance (Appendix G)—the percentage of early, on-time, late, and very late timepoints are estimated using archived AVL data for the study area routes.

4.5 Summary

Public transportation service in Somerville and Medford has been relatively constant over the past 25 years since the Red Line was extended to Alewife. The only service added to the area in that time has been the CT2 limited-stop service; however, that route does not provide service at night or on weekends. Manually-collected data in the form of schedules, ride checks, and passenger surveys are useful for beginning to understand the level of public transportation service in Somerville and Medford. ADCS build upon these analyses by using data from (almost) every trip and passenger, so that more complex analyses such as trip rates can be performed.

The outputs of the analyses, particularly ridership by route segment and the improved scheduled running times, will be used as inputs into the NetPlan scenario testing in Chapter 5.

5 Service Planning Case Study Using Automated Scheduling Tools

Many transit agencies now use commercial software packages, such as Trapeze or GIRO's HASTUS (among others), to automate the production of transit vehicle and operator schedules; however, these software programs by themselves do not provide much help during the early stages of the service planning process. Service planners desire high level information such as how many additional buses would be required if additional service is provided. Fortunately, transit agencies can now turn to newer sketch planning and timetabling software tools such as GIRO's NetPlan module.

This Chapter outlines how automated scheduling tools, such as NetPlan, can be used to evaluate several planning scenarios. First, the features and results of NetPlan are discussed. Next, a number of service planning scenarios have been developed to allow for incremental changes to the study area routes to be analyzed using NetPlan. For comparison, the existing service statistics for the routes in the study are summarized to provide a base level for resources available. Scenario 1 builds upon the existing schedule using only even headways (based on the existing average route headways) and on all routes, allowing for route interlining (between routes) based on shifting trip start times. For Scenario 2, running and cycle times are adjusted when necessary to improve reliability or reduce excess time currently in the schedules based on the running time analysis described in Chapter 4. Scenario 3 modifies the frequencies of routes based on ridership data and perceived market potential, and the expected wait time or scheduled delay savings of passengers is estimated. Finally, Scenario 4 analyzes a few potential routing changes that would enhance service coverage and increase ridership for the routes affected. For each scenario, the timetable is optimized to minimize the number of buses required.

5.1 HASTUS NetPlan Features and Results

GIRO Incorporated's NetPlan, a recently-released public transportation sketch planning and timetabling software tool, is an extension to the HASTUS automated scheduling package. In 2008, the module was already in use by the Dutch agency Connexxion as well as two other large European transit agencies. All three agencies reported that the module improved service quality in their networks (GIRO, 2008).

The first step in NetPlan is to input the public transportation network into a graphical representation of the network called the "Connections Diagram." The Connections Diagram is a schematic drawing that places route terminals and timepoints (called "Places") in their approximate locations. Places are connected by lines based on the "Planning Patterns" (i.e. routes) that are added to the Connections Diagram.

NetPlan uses "Trip Builders" to create all trips in a time period. Trip Builders are specified for each route, one in each direction. NetPlan requires the following inputs for a Trip Builder:

- Planning Study—the multi-hour period of the day (e.g. 7-9 AM) for which all trips will be generated prior to optimization
- Planning Period—the 1-hour time period that will have its timetable optimized
- Running Times—the scheduled running time between Places for the Scheduling Period
- Minimum Layover Time—the typical lowest-allowable layover time on the route
- Headways—the headways for the route during the Scheduling Period. The trips may be specified by frequency (number of trips per hour), regular headway (e.g. one trip every 20 minutes), or irregular (e.g. AM trips start at 7:07, 7:24, and 7:47).
- Start Time—the number of minutes after the hour during the Planning Period that the first trip leaves its origin
- Deadhead Matrix—a table with the times that it takes for a bus to travel from one Place to another in non-revenue service
- Meets—places where synchronization should occur (e.g. transfers or coordination along route segments). A minimum, maximum, and ideal time for a possible Meet needs to be specified.

NetPlan determines the optimal vehicle blocking solution by going through thousands of iterations of shifting Trip Builders at their starting locations. By shifting the start times of trips (and thus their corresponding end times as well) systematically, NetPlan can identify potential new route interlining possibilities that may save a vehicle for the entire route network. If shifting Trip Builders reduces the generalized cost, the start times of the trips are modified. The Trip Builders are shifted in the following order, usually with three loops to each step:

- Shifting One Trip Builder—all trips for one Trip Builder are shifted one minute at a time until all possible shifts have been tried.

- Simultaneously Shifting Two Trip Builders—similar to above, but all trips for two Trip Builders are shifted.
- Shifting One Trip Builder (Second Attempt)
- Shifting Two Trip Builders—a Trip Builder is shifted one minute and then another Trip Builder is shifted one minute at a time until all possible shifts have been tried. This is done until the first Trip Builder has cycled through all possible shifts.

Once the vehicle blocking has been optimized, NetPlan outputs the following:

- The objective cost—an approximation of the generalized cost of operating vehicles for a Planning Period. The optimization minimizes the objective cost subject to the constraints of deadheading, synchronization, and minimum layover times.
- The optimized timetables—includes the start and end times of each trip
- The vehicle blocking—shows the sequence of trips in each vehicle block including whether interlining is used. The minimum number of vehicles required is equal to the number of vehicle blocks operating at any one time.

5.2 Existing Conditions

The number of buses available that will be used to compare timetables from the NetPlan scenarios depends on the trips included in the analysis. The 15 bus routes (including major route variations) that serve the Green Line Extension Project area are the only ones that are analyzed in Chapter 4. Most of these routes share a terminus with at least one other route in the study. However, this is not the case for Route 85 (Spring Hill – Kendall/MIT). Routes 85 and CT2 have a common route segment from Union Square to Kendall/MIT station, but Route CT2 continues on to Ruggles Station. Moreover, there are two other MBTA routes that have Kendall/MIT as their terminus; Routes 64 and 68. Including additional routes, such as these, in the NetPlan scenarios may improve the optimal solution for the study routes; therefore, these two routes plus Route 69, which terminates at Lechmere Station along with other study area routes, are included in the NetPlan scenarios. The following is a more detailed description of the three routes:

- Route 64 Oak Square (Brighton) – Kendall/MIT via Broadway—this variation operates only during the AM and PM peak periods with 23 to 25-minute peak headways. Average weekday daily AFC-adjusted ridership for Route 64 (all variations) is 1570 passengers.
- Route 68 Harvard – Kendall/MIT via Broadway—this route operates on 30 to 35-minute headways during the peaks. Daily weekday ridership is about 390 passengers.
- Route 69 Harvard – Lechmere via Cambridge St.—6 to 20-minute headways during the AM and PM peaks. Daily weekday ridership is about 3400 passengers.

The MBTA provided the HASTUS scheduling data from the Spring 2010 schedule. The scheduling data for each bus garage contains all trips on all routes; thus, the first step in establishing a baseline is to select only trips on the study routes and the three supplemental routes (including all variations). The NetPlan scenarios are for the AM and PM peak periods, so the next step involves removing trips that are not in the peaks. The current version of NetPlan extends the building of trips beyond the peak period by approximately one trip so that all interlining possibilities can be included in the optimal solution. Therefore, to compare NetPlan scenarios to the existing schedule, it is useful to select all trips that start within 30 minutes of the peak period. Outside the peak periods, the frequencies on the routes will be lower, so the number of trips and the number of total vehicle hours will be less in the existing schedule summary than in the NetPlan scenario summary that is set up here with a single (even) headway for each route. This difference is tolerable, because the minimum number of buses required in order to serve the peak-of-the-peak period is the primary variable of interest, and frequencies can later be adjusted lower during the "shoulder" periods as detailed production schedules are built.

Table 5-1 shows a summary of the existing MBTA Schedule for the 18 study routes. The AM peak is the constraining time period; it requires 77 buses, whereas the PM peak requires only 67 buses. Interlining between study area routes is currently used on 20 percent of the vehicle blocks during the AM and PM peak periods.

Schedule	Trip Count*	Duration* (h)	Layovers* (h)	Total* (h)	AM Peak Buses	PM Peak Buses	Blocks w/ Interlining
Current MBTA Schedule	717	321	63	384	77	67	20%

Table 5-1. Summary Statistics for the Existing MBTA Schedule*

5.3 Scenario 1—Regular Headways, Trip Shifting, and Interlining

Some of the routes in the study area currently have irregular headways during the peak periods. As discussed earlier, NetPlan allows for the user to input irregular headways by specifying the start times for all trips during the peak hour; however, regular headways are much easier for customers to use and should result in more even bus loading. To this end, even headways will be used for the NetPlan analysis scenarios. Although it may desirable to modify some individual trips so that school trips or other supplemental trips can be included in the final timetable, these trips are a small fraction of all peak period trips and can generally be ignored during the service planning process (the use of an even headway, set as shown below, should cover the resources needed for the school trip services). An average headway was calculated for the routes with irregular headways using the average headway formula shown below:

$$\boldsymbol{Avg.Headway = 60/(Number\ of\ Current\ Bus\ Trips\ during\ Peak\ Hour)} \qquad \text{(Equation 5-1)}$$

One potential efficiency improvement over the existing MBTA schedule is to increase the use of *interlining*, which involves switching buses between routes (as needed) during a vehicle block to reduce overall bus requirements. The number of buses required for a route is calculated in Equation 5-2. If the number of buses required is not a whole number, then the number must be rounded up unless an appropriate interline can be identified. Currently, the MBTA uses limited interlining during the AM and PM peak periods, so there appears to be some potential for timetabling improvements. Interlining is typically performed on routes that serve the same terminus; however, deadheading, which moves a bus from one location to another typically by taking the bus out-of-service for a short duration, may also improve the vehicle blocking solution in certain situations. Deadhead times are set lower than the scheduled peak period between-stop

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* For all trips operating between the hours of 6:30-9:30 AM and 3:30-7:00 PM.

running times, because deadheading buses do not pick-up or drop-off passengers. For this analysis, deadhead times are set at 80 percent of the minimum scheduled running time during the peak periods. If no routes provide service between two nearby terminals, the deadhead times were approximated. The deadhead matrix for the terminals located in the project area is found in Appendix H. The deadhead times for terminal pairs in the study area range from 4 to 15 minutes; terminal pairs that do not have a value in Appendix H are far apart and are given a default deadhead time of 30 minutes to discourage them from being used.

$$Number\ of\ Buses\ Required = (Cycle\ Time)/(Headway) \qquad \text{(Equation 5-2)}$$

A tabular summary of the required NetPlan inputs for Scenario 1 is shown in Appendix I. There is some variation in the currently scheduled "half-cycle" running and recovery times of peak period trips, even during the peak hour of each period (called "Planning Pattern" in NetPlan). Generally, conservative values for headways (shorter), running times (longer), and layover times (longer) are used as inputs in Scenario 1 so that the number of buses required is not underestimated. However, the maximum values of layover times for each Planning Period are not used if they seem excessively high compared with other trips for the same period. For example, Route 96 outbound in the PM peak had end-of-trip recovery times ranging from 4 to 21 minutes. The 21 minutes of recovery time was much more than all other trips and is an obvious scheduling anomaly, so a value of 8 minutes was used as the input.

Once all of the NetPlan inputs were determined, the NetPlan software was used to analyze the data and optimize the vehicle blocks (using trip start-time shifting and interlining where appropriate). Comparing Scenario 1 optimized results with the existing MBTA schedule in Table 5-2, the NetPlan solution requires only 73 buses during the AM peak, which means that there is some inefficiency in the existing schedule. This savings come mainly from interlining. The minimum number of buses in the PM peak increased by 3 (to a total of 70). The conservative inputs (especially rounding up running and layover times) used in Scenario 1 increased the number of buses in the PM peak by more than the number saved from interlining. The total number of hours is greater in Scenario 1 due to the higher frequencies in the "shoulders" around the peak periods. In addition, the percentage of blocks using interlining in Scenario 1 (43 percent) is more than double the current MBTA schedule.

Schedule	Trip Count	Duration (h)	Layovers (h)	Total (h)	AM Peak Buses	PM Peak Buses	Blocks w/ Interlining
Current MBTA Schedule	717	321	63	384	77	67	20%
NetPlan--Scenario 1	741	357	68	424	73	70	43%

Table 5-2. Summary NetPlan Statistics for Scenario 1

5.4 Scenario 2—Adjustments to Running Times and Layover Times

Scenario 1 is basically an optimized version of the existing MBTA schedule with some additional service during the "shoulders" of the peak hours. Based on the empirical running time analysis discussed in Chapter 4, all of the study routes should have at least slight adjustments made to the running times and the layover times. In general, the cycle and running times are set too low in the current schedule; as a result, buses often their next trips late. Late buses seriously affect the waiting time of passengers and, ultimately, their perception of the quality of service. Bus drivers interact directly with passengers and thus, often bear the brunt of passengers' frustration. In addition, although there are usually no crew reliefs during the peak periods, a driver may have to extend beyond the scheduled end of his piece of work. This is especially problematic for transit agencies that are heavily-constrained by contract-specified work rules.

Proposed cycle times and running times have been set close to the 95th and 50th percentile of observed running times, respectively (see Appendix I). The cycle and running times have been split between inbound and outbound directions based on the distribution of one-way running time. For example, if the proposed cycle time is 72 minutes, and the 95th percentile running times are 36 and 34 minutes for inbound and outbound, the half-cycle times would be set to 37 and 35 minutes, respectively. A detailed running time analysis was not performed on Routes 64, 68, and 69, because they are outside the study area, and instead the current schedule times are used for these routes in Scenario 2 (and the scenarios that follow).

Scenarios 1 and 2 are compared in Table 5-3. The minimum number of buses required increased by one in the AM peak and by three in the PM peak. The total scheduled in-service time increased by 21 hours from Scenario 1 to Scenario 2, which suggests that, overall, the existing scheduled half-cycle times are set below what is ideal. If the schedules are adjusted with the improved half-cycle times, there is still a savings of 3 buses during the AM peak. However, this savings is offset by an increase of 61 vehicle hours over the current MBTA schedule. The actual vehicle hours required to operate the service for Scenario 2 is less than 445 hours due to extra trips in the shoulders of the peak, but there is probably no significant net change in cost from the base case. On a minor note, the optimal solution for Scenario 2 uses a trivial amount of deadheading (8 minutes) whereas Scenario 1 did not require any deadheading. Finally, two-thirds of the vehicle blocks use interlining in Scenario 2, which indicates that cycle times may be set currently to use an integer number of buses on some routes.

Schedule	Trip Count	Duration (h)	Layovers (h)	Total (h)	AM Peak Buses	PM Peak Buses	Blocks w/ Interlining
Current MBTA Schedule	717	321	63	384	77	67	20%
NetPlan--Scenario 1	741	357	68	424	73	70	43%
NetPlan--Scenario 2	748	380	65	445	74	73	67%

Table 5-3. Summary NetPlan Statistics for Scenarios 1 and 2

5.5 Scenario 3—Adjusted Service Frequencies

Once modifications to the running times have been analyzed, it is possible to investigate increasing the frequencies on study area routes to use the excess resources in the existing schedule. With this in mind, the goal of Scenario 3 is to increase the frequencies on study area routes in an equitable way. Increased service on these currently low frequency routes will shift some people to transit from other modes and generate new passenger trips due to latent demand. Although it would be possible to increase the frequencies on all routes slightly, some routes may have their current frequencies set too low (or too high) given the demonstrated demand along the route.

One way to assess the current headways is to use the square-root model, shown in Equation 5-3, to estimate an "equitable" bus headway (h) based on a combination of factors (Furth and Wilson, 1981). The factors in the equation account for costs incurred by both operators and users. The variables in the equation are the operating cost per unit time (c), the cycle time (t) of a route, the value of time for a passenger (b), and the ridership per unit of time (r).

$$h = \sqrt{2\left(\frac{c}{b}\right)\left(\frac{t}{r}\right)} \qquad \text{(Equation 5-3)}$$

While an equitable headway is the ultimate variable of interest, the values of operating cost per unit time and the value of time for a passenger are difficult to quantify without additional data.

As a partial remedy, operator-to-passenger cost ratio (c/b) can be approximated by re-arranging Equation 5-3 and using the current headway (h) on the route, as shown in Equation 5-4.

$$c/b = (\mathrm{h}^2\mathrm{r})/(2\mathrm{t}) \qquad \text{(Equation 5-4)}$$

The calculated operator-to-passenger cost ratios will vary across routes during a peak period, and this variation may be significant if the existing frequencies were not routinely reviewed and modified using the square-root formula or a similar method. However, equity suggests that the actual operator-to-passenger cost ratio should be assumed to be approximately the same for all routes in a contiguous small service area operated by a single transit agency. Using this logic, proposed headways for all routes can be estimated for a specified operator-to-passenger cost ratio that could be chosen based on satisfying a constraint of the maximum number of vehicles available to serve a specific area.

For the Green Line Extension study area routes, operator-to-passenger cost ratios are calculated for the existing headways on the routes, as shown in Tables 5-4 and 5-5 for the AM and PM peak periods, respectively. The values for r are in average (route) boardings per minute (taken from AFC counts except for Routes 88-3 and 68 during the AM peak, which use ride check and APC data, respectively, due to insufficient AFC data) and t is the round-trip cycle time used in Scenario 2. An equitable headway is calculated by setting the operator-to-passenger cost ratio at 8.5, because it is close to the peak period average for the study area. Using this value of 8.5, Route 85 is the route that would have its service increased the most during the peaks. The route has the shortest cycle time of the study area routes (except for the Route 88 AM short-turn shuttle service); consequently, the headway would decrease from 35 to 22 minutes during the AM peak and from 40 to 26 minutes during the PM peak.

In Tables 5-4 and 5-5, the Scenario 3 base headway is the same headway used in Scenarios 1 and 2 except for routes outside the study area or where the calculated headway shows a service decrease for when the operator-to-passenger cost ratio is 8.5 (In this way, we begin with a minimum number of peak vehicles, upon which we will incrementally improve headways in a series of Scenario 3 "trials."). It was determined that, if at all possible, all headways proposed for Scenario 3 be clock-face, so that the time that the bus leaves (minutes past the hour) repeats each hour. These headways are easier for a passenger to remember, understand, and use. In addition, we determined that the existing frequencies of Routes 92, 64, 68, and 69 should be simply rounded to the nearest clock-face headway in Scenario 3 and not be proposed for any other changes here since these routes operate largely outside the study area. We can then start by considering a reduction in frequency on the routes that the square-root model calculates as being over-served; Route 89 for both peak periods and Route 101 for the AM peak. There is some overcrowding on Route 89 in the AM peak and Route 101 in the PM peak in the existing MBTA schedule, so any reduction in service may create capacity issues for the routes.

Route	AM Peak Riders	r (riders/ min.)	t (min.)	Scen. 1 & 2 Hdwy.	Route c/b	Calc. Hdwy.	Scen. 3 Base Hdwy.*
85	170	1.4	41	35	21.2	22	35
88-3	240	2.0	18	18	18.0	12	18
68	110	0.9	35	35	16.0	25	30
87	720	6.0	80	20	15.0	15	20
90	120	1.0	95	45	10.7	40	45
95	400	3.3	63	20	10.6	18	20
91	170	1.4	63	30	10.1	27	30
CT2	620	5.2	113	20	9.1	19	20
96	410	3.4	79	20	8.6	20	20
88	570	4.8	67	15	8.0	15	15
64	360	3.0	102	23	7.8	24	20
80	360	3.0	80	20	7.5	21	20
83	490	4.1	62	15	7.4	16	15
94	240	2.0	56	20	7.1	22	20
86	1240	10.3	106	12	7.0	13	12
69	700	5.8	44	10	6.6	11	10
101	870	7.3	82	12	6.4	14	15
89	810	6.8	58	10	5.8	12	12
92	260	2.2	50	15	4.9	20	15

* These include Scenarios 1 & 2 headways except for where the calculated headways shows a service decrease (with an assumed 8.5 operator-to-passenger cost ratio) or the route is largely outside the project area (rounded to nearest clock-face headway).

Table 5-4. Frequency Setting (Square-Root Formula)—AM Peak Period

The Scenario 3 "trial" frequencies of the routes are shown in Tables 5-6 and 5-7 for the AM and PM peak periods, respectively. The "improved" headway is the square-root model "equitable" headway rounded to the closest clock-face. The estimated passenger wait time (for frequent routes) or scheduled delay (for infrequent routes) savings are calculated by Equation 5-5. For a specific operator-to-cost ratio, the order in which the frequencies are increased and tested in NetPlan is determined by the time savings. The output of interest for each trial in NetPlan (i.e. each trial) is the number of vehicles required, because it is helpful for service planners to know how service frequencies can be most appropriately set if resources change. After all necessary frequency increases with the operator-to-passenger cost ratio set at 8.5 have been made (including resetting the headways that had been increased back to their Scenarios 2 headways), the ratio is reduced by 0.5 and additional route headways are increased (to show priorities for improvement if additional resources are available). This is done until the operator-to-passenger cost ratio is reduced to 6.5, which would require 81 vehicles (an increase of 4 over the existing conditions) during the AM peak.

Route	PM Peak Riders	r (riders/ min.)	t (min.)	Scen. 1 & 2 Hdwy.	Route c/b	Calc. Hdwy.	Scen. 3 Base Hdwy.*
85	160	1.1	42	40	20.3	26	40
91	310	2.1	57	30	16.3	22	30
69	700	4.7	60	20	15.6	15	20
90	220	1.5	89	40	13.2	32	40
88	740	4.9	67	18	11.9	15	18
68	110	0.7	30	30	11.0	26	30
83	430	2.9	67	20	8.6	20	20
87	860	5.7	82	15	7.9	16	15
64	370	2.5	100	25	7.7	26	30
95	340	2.3	61	20	7.4	21	20
94	380	2.5	71	20	7.1	22	20
101	1160	7.7	79	12	7.0	13	12
80	430	2.9	82	20	7.0	22	20
86	1100	7.3	122	15	6.8	17	15
CT2	590	3.9	120	20	6.6	23	20
96	350	2.3	87	20	5.4	25	20
89	810	5.4	55	10	4.9	13	12
92	310	2.1	57	15	4.1	22	15

* These include Scenarios 1 & 2 headways except for where the calculated headways shows a service decrease (with an assumed 8.5 operator-to-passenger cost ratio) or the route is largely outside the project area (rounded to nearest clock-face headway).

Table 5-5. Frequency Setting (Square-Root Formula)—PM Peak Period

$$E[Wait\ Time\ or\ Scheduled\ Delay\ Savings] = 0.5 * (\Delta headway)(peak.pd.riders)$$

(Equation 5-5)

Scen. 3 Trial #	Route	c/b	Scen. 3 Base Hdwy.	Scen. 3 Improved Hdwy.	Wait/Delay Savings (h)	Min. # of Buses
0	(Base)	8.5	N/A	N/A	0	71
1	87	8.5	20	15	30	73
2	101	8.5	15	12	21.8	74
3	85	8.5	35	20	21.3	74
4	90	8.5	45	30	15	76
5	89	8.5	12	10	13.5	76
6	88-3	8.5	18	15	6	76
7	95	8	20	15	16.7	77
8	CT2	7	20	15	25.8	79
9	91	7	30	20	14.2	80
10	88	6.5	18	12	20.3	81
	88-3	6.5	15	12		
11	96	6.5	20	15	17.1	81

Table 5-6. Scenario 3 Trials—AM Peak Period

Scen. 3 Trial #	Route	c/b	Scen. 3 Base Hdwy.	Scen. 3 Improved Hdwy.	Wait/ Delay Savings (h)	Min. # of Buses
0	(Base)	8.5	N/A	N/A	0	73
1	91	8.5	30	20	25.8	73
2	88	8.5	18	15	18.5	74
3	90	8.5	40	30	18.3	74
4	89	8.5	12	10	13.5	74
5	85	8.5	40	30	13.3	74
6	85	7.5	40	20	13.3	75
7	87	6.5	15	12	21.5	77
8	83	6.5	20	15	17.9	79
9	88	6.5	18	12	18.5	79

Table 5-7. Scenario 3 Trials—PM Peak Period

Figure 5-1 shows the cumulative expected wait time and scheduled delay savings for all of the resource levels tested in the Scenario 3 trials. In general, the slope between data points is greatest immediately after the operator-to-passenger cost ratio is decreased and then levels off. At a given resource level, the expected savings are similar for both peak periods. However, the operator-to-passenger cost ratio for the PM peak has to decrease to a level below what is needed in the AM peak to get those benefits. If the same cost ratio is used for both periods, an average of two fewer buses would be required in the PM peak than in the AM peak. The difference is smaller than that found in the current MBTA schedule, but it does suggest that the study area routes require a higher allocation of resources in the AM peak.

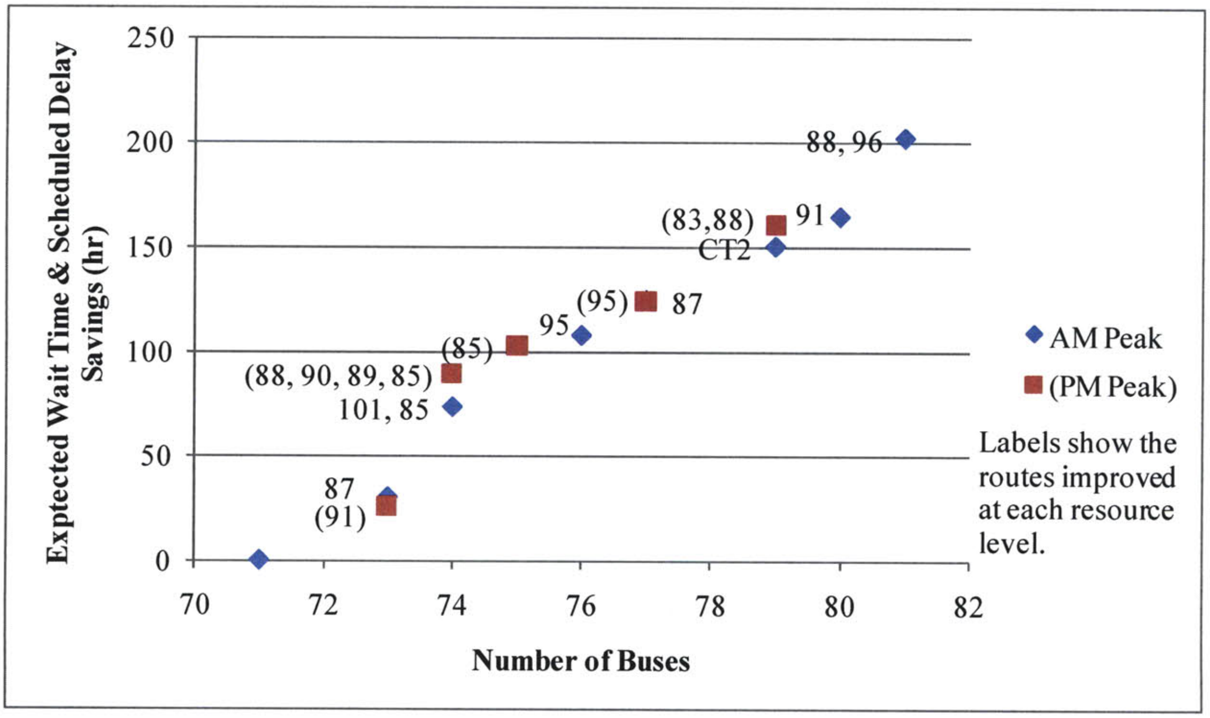


Figure 5-1. Expected Wait Time and Scheduled Delay Savings at Different Resource Levels

For Scenarios 1 and 2, there was no consideration or input for coordination between route timetables; as a result, streets served by different routes may have two buses scheduled for the same time, but then not have another bus serve the segment for 20 minutes. An explicit goal of Scenarios 3 and 4 is to increase levels of service to existing and potential new passengers subject to resource constraints, so there was an effort to improve synchronization for routes on common links where possible.

The way that NetPlan synchronizes routes is through the use of "Meet Builders." The minimum, maximum, ideal headway offset for each pair of routes are required inputs. A synchronization factor can be applied to each Meet Builder, which is used in the timetabling optimization algorithm. For this analysis, two route characteristics were used to calculate the factor for each

Meet Builder: the route ridership and the headway. For all of the route segments in the study area which are served by more than one route, a "composite" synchronization factor was developed based on the respective route ridership and headways of the routes being considered for better coordination and the resulting synchronization factor (shown in a table in Appendix J) were used in the NetPlan cost algorithm to maximize schedule coordination between each of these route pairs. These synchronization factors were applied for all of the Scenario 3 trials.

Table 5-8 compares the results for Scenarios 1, 2, and 3. The trip statistics for Scenario 3 are for the frequency changes that are possible with a maximum of 77 buses (up to and including the changes in trial #7 – Route 95 and trial #5 – Route 85 in the AM and PM peak periods, respectively). The expected total passenger wait time and scheduled delay savings are 124 and 89 hours in the AM and PM peaks, respectively. The frequencies of Routes 89 and 101 were decreased for the Scenario 3 base case, so the net savings are 89 and 76 hours in the AM and PM peaks, respectively. There are 8 minutes of deadheading in Scenario 3, which are included in the total of 454 hours. In addition, 72 percent of the vehicle blocks use interlining in Scenario 3, which indicates that greater frequencies may increase the opportunities for interlining.

Schedule	Trip Count	Duration (h)	Layovers (h)	Total (h)	AM Peak Buses	PM Peak Buses	Blocks w/ Interlining
Current MBTA Schedule	717	321	63	384	77	67	20%
NetPlan--Scenario 1	741	357	68	424	73	70	43%
NetPlan--Scenario 2	748	380	65	445	74	73	67%
NetPlan--Scenario 3	780	392	62	454	77	74	72%

Table 5-8. Summary NetPlan Statistics for Scenarios 1, 2, and 3

5.6 Scenario 4—Alignment Modifications

Routing modifications analyzed in the Northwest Corridor Study (see Chapter 3) served as a starting point for changes that might be analyzed in Scenario 4. About half of the Somerville-Medford Green Line Extension routes were studied at that time. There are two major routing changes to the current study area routes that occurred when the Red Line Extension to Alewife opened. First, Routes 87, 88, and 89 previously had Clarendon Hill as their terminus, and there was a perceived need to extend at least one of the routes to Arlington Center. Route 87 was determined to be the best candidate for the extension. Secondly, Route 94, which had been an infrequently used variation of Route 96, became its own route with headways similar to those on Route 96.

The only modifications considered in this section are those that would take place prior to the beginning of the Green Line Extension service, with the future location of Green Line stations taken into consideration. Analysis of future routing changes to be implemented after the Green Line Extension opens will proceed after the conclusion of this thesis by other researchers. This section describes the new routing possibilities considered for the Somerville-Medford routes; please note that retaining the existing routings is the "default" option for all routes. The routing changes could be made to any of the trials in Scenario 3; however, for this section, trial #7 with 77 buses and trial #5 with 74 buses are the base cases presented in the AM and PM peaks, respectively.

5.6.1 Route 83 Russell Field – Central Square

The Northwest Corridor Study raised the possibility that the Somerville Ave. segment on Route 83 could be re-routed to Beacon St. after the bridge over the railroad was completed, as shown in Figure 5-2 (the modified Route 83 is labeled "831"). The new Beacon Street Bridge should be able to handle bus traffic now. Moving Route 83 to Beacon Street may save about 1 to 2 minutes in each direction, so no changes are anticipated for the number of vehicles required. This portion of Beacon St. is a pretty dense residential area with some commercial retail sites and is currently not served by buses. All of the bus stops on the Somerville Ave. segment would still be served by Route 87, so residents north of the railroad are still connected to the Red Line at Davis Square and to the Orange Line at Sullivan Square.

Figure 5-2. Map of Modified Route 83

Recommendation: Re-route Route 83 to Beacon St.

5.6.2 Route 85 Spring Hill – Kendall/MIT and Route CT2 Sullivan Square – Ruggles Station

The Spring Hill neighborhood north of Union Square accounts for 64 percent of the inbound daily ridership for Route 85, as shown in Table 5-9. This does not include the stops on Summer St. at Vinal Ave. and 51 Bow St. that are included here in Union Square portion of the route, because passengers at these stops could easily switch to a stop in Union Square. From Union Square to Kendall/MIT, Route 85 follows the alignment of Route CT2 but has more stops; Route 85 has 9 stops in this route segment, whereas Route CT2 only has 3 stops. However, the only Route 85 stop currently not served by Route CT2 that has more than 5 ons or offs is Hampshire St. at Webster Ave. (18 outbound offs), and it is about a 1-minute walk from the Hampshire St. at Cardinal Medeiros stop.

Route 85 Segment	# Inbound Stops	Inbound--Ons	Outbound--Offs
Spring Hill - Union Sq.	3	154	16
Union Sq.	4	22	8
Union Sq. - Kendall/MIT	9	37	36
TOTAL -- ALL SEGMENTS	16	241	60

Table 5-9. Ridership Breakdown of Route 85

This analysis considers combining Routes 85 and CT2 into a new (rerouted) CT2 service. Both routes currently run only on weekdays and a combined route may be able to operate on improved headways. Re-routing CT2 through Spring Hill would increase the frequency of service for its residents (as was suggested strongly in Scenario 3), and only a handful of passengers would have to walk further. The additional benefits of a combined route would be to add additional north-south cross-town service in the heart of Somerville in advance of the Green Line opening and to provide another connection to the Orange Line at Sullivan Square (or Assembly Square in the future) for Spring Hill residents.

The ridership summary for Route CT2 is shown in Table 5-10. If Route CT2 was re-routed to serve the Spring Hill neighborhood, the only current CT2 stops that would be eliminated are the stops at Myrtle St. and McGrath Highway on Washington St., which are between Sullivan Square and Union Square. However, these two stops generate a total of only 74 inbound passenger trips. Moreover, these two stops are also served by Routes 86 and 91, which provide connections to the Red Line at Harvard Square and Central Square, respectively and which run on a significantly higher combined frequency (every 9 to 10 minutes) than the current Route CT2 (every 20 minutes).

Route CT2 Segment	**# Inbound Stops**	**Inbound--Ons**	**Outbound--Offs**
Sullivan Sq.	1	167	96
Sullivan Sq. - Union Sq.	2	74	22
Union Sq.	1	106	47
Union Sq. - Kendall/MIT	3	211	173
Kendall/MIT - Ruggles	10	166	147
TOTAL -- ALL SEGMENTS	17	724	485

Table 5-10. Ridership Breakdown of Route CT2

There are several routing possibilities for a revised Route CT2. The re-route options going from the Spring Hill neighborhood to Sullivan Square are:

- Central St. (no current service) to Broadway (Route 89). This is shown as "851" in Figure 5-3.
- Prescott St. to Highland Ave. to Cross St. to Broadway (largely follows Route 90). This is shown as "852" in Figure 5-3.

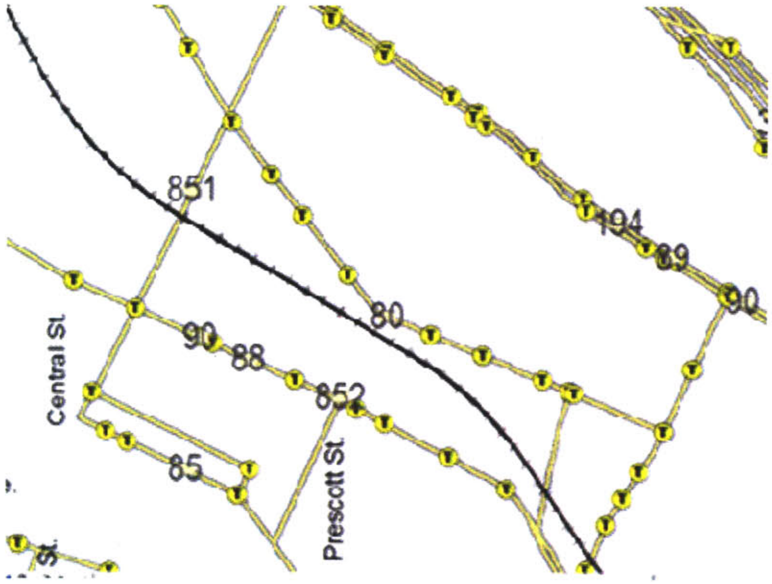


Figure 5-3. Map of Possible Modifications to Routes 85 and CT2

Internet driving directions for these routing options indicate that an additional 5 to 6 minutes outbound and 11 minutes inbound of travel time are required for Route CT2 to be rerouted through the Spring Hill neighborhood. The number of stops may increase slightly so that the Spring Hill neighborhood is better served. Thus, 7 and 12 minutes have been added to the running times of Route CT2 inbound and outbound, respectively. Also, a minute of recovery time has been added in each direction. After making these modifications, there is no change in the number of buses in the AM peak as the two buses allocated in Scenario 3 to Route 85 compensate for the longer travel times on the re-routed CT2 line through the Spring Hill neighborhood. The re-routed CT2 line would require two additional buses for the PM peak.

Recommendation: Analyze the impact of eliminating Route 85 and re-route CT2 through Spring Hill. The actual routing would be determined at a later time.

5.6.3 Route 88 Clarendon Hill – Lechmere via Highland Ave.

There are about 440 daily passengers who board Route 88 at its current Clarendon Hill terminus. This is a very high total for a non-rail station terminus in the study area. Some of these passengers would have their access times reduced if service was extended to Arlington Center. The segment from Clarendon Hill to Arlington Center is served by Route 87 and currently has 336 inbound boardings. In addition, Route 80 has 65 passengers that board at its Arlington

Center terminus. The one-way running time would need to be increased by 5 to 6 minutes (plus 1 minute of additional recovery time in each direction). When Routes 87 and 88 are coordinated, the average peak hour headway is 7.5 minutes between Arlington Center and Davis Square, which is close to the existing frequency (every 6 and 8 minutes during the AM and PM peaks, respectively) for the segment from Clarendon Hill to Davis Square. The short version of Route 88, which provides shuttle service from Davis Square to Clarendon Hill, duplicates service provided by Route 87 and the regular version of Route 88. The bus used for the AM shuttle could be moved to the extended route, but this would not quite offset the increase in cycle time (one additional bus would be required). In the PM peak, one additional bus would be required if 15-minute headways are used on both Routes 87 and 88, as in Scenario 3.

Recommendation: Extend Route 88 to Arlington Center and eliminate the AM short-turn shuttle service from Davis Square to Clarendon Hill. A frequency of every 15 minutes during the peaks should be used on Routes 87 and 88 so that they can be coordinated.

5.6.4 Route 92 Assembly Square Mall – Downtown Boston

The only portion of Route 92 in either Somerville or Medford is the short segment between Assembly Square Mall and Sullivan Square, which is in Somerville. There are 80 total boardings and alightings at Assembly Square Mall. Thus, only 10 percent of the inbound ridership comes from Assembly Square Mall, but this is partly due to the fact that peak hour buses do not serve the mall. Many of the stores do not open until after the AM peak, so there is no need to serve the mall until then. On the flip side, all stores are open during the PM peak, so adding service during that time may be beneficial, especially once the planned new Orange Line station at that location is completed. The Assembly Square Mall is served every 30 minutes by Route 90 during the PM peak, but this requires passengers coming from Route 92 (or other routes) to transfer at Sullivan Square. Modifying the schedule to remove this gap in service will increase the willingness of employees and customers to travel to the mall by public transportation. Moreover, it provides a connection from Somerville to Charlestown—a neighborhood that is transit-accessible only by bus. Based on scheduled running times during other times of the day, an additional 5 to 7 minutes of (one-way) running time would be needed during the PM peak (plus a minute of recovery time in each direction). To limit the number of buses required to serve the route, half of the trips could be extended to Assembly Square Mall and the other half could be allowed to terminate at Sullivan Square. This routing change increases the number of buses in the PM peak by one bus.

Recommendation: Analyze the impact of starting every other trip in the PM peak at Assembly Square Mall.

5.6.5 Routes 94 and 96 Medford Square – Davis Square

Routes 94 and 96 offer similar service in that they both start in Medford Square and share a common segment along Boston Ave. and College Ave., including a major stop at Davis Square. Thus, Routes 94 and 96 should be considered together in possible routing scenarios. The following three questions should be examined before providing a recommendation for the alignments of the two routes:

- Should Route 96 terminate at Davis Square (instead of Harvard Square)?
- Which roads surrounding Tufts University are most likely to generate higher ridership while supporting reliable service?
- Should both routes terminate at Medford Square?

The Northwest Corridor Study considered terminating Route 96 at Davis Square, because it would have had significant savings in buses and running time (operational costs) and a slight improvement in passenger travel time savings using the Red Line to continue to Harvard Square. The major trade-offs were that (1) some passengers would be required to walk further and (2) some passengers would be required to pay a higher fare for using the subway (this is far less significant now than in the 1980s due to fare restructuring). As shown in Table 5-11, about 88 percent of the inbound ridership is between Medford Square and the first stop after Davis Square (Elm St. at Chester St.). Only a small proportion of riders would be required to walk further if the route is truncated at Davis Square. Most riders could probably switch to other options, such as Route 77 (for stops between Porter Square and Harvard Square) or the Red Line. For the segment from Davis Square to Porter Square, all but 10 of the alightings inbound and 7 of the boardings outbound are within a 3-minute walk of either Red Line station. In addition, approximately 85 percent of inbound riders south of Porter Square are traveling to bus stops that are a short walk to the Harvard Square Red Line Station. Overall, truncating Route 96 at Davis Square would only impact about 10 percent of the current riders, most of whom could not experience any additional travel time by transferring to either the Red Line or by taking Route 77 as an alternate to Route 96. There would be no additional fare for a bus-to-bus transfer for CharlieCard users and the incremental transfer fare to the Red Line would currently be $0.45, much lower than the full subway fare that would have been required when the Red Line opened. This change would result in a savings of 23 to 25 minutes in cycle time (over the current schedule) for Route 96, or 1.2 peak period buses. This efficiency saving can be used to increase the frequency of Route 96 to every 15 minutes in the peaks.

Route 96 Segment	**Inbound**				**Outbound**			
	Ons		**Offs**		**Ons**		**Offs**	
	Total	**Percent**	**Total**	**Percent**	**Total**	**Percent**	**Total**	**Percent**
Medford Sq. - Main @ George	260	27%	4	0%	1	0%	218	26%
Main @ George - Boston @ Winthrop	219	23%	8	1%	6	1%	193	23%
Boston @ Winthrop - Powderhouse Sq.	294	31%	32	3%	18	2%	285	34%
Powderhouse Sq. - Davis Sq.	65	7%	468	49%	392	47%	41	5%
Davis Sq. - Porter Sq.	50	5%	74	8%	84	10%	55	7%
Porter Sq. - Harvard Sq.	52	5%	45	5%	49	6%	37	4%
Harvard Sq.	8	1%	318	34%	283	34%	5	1%
TOTAL -- ALL SEGMENTS	948	100%	949	100%	833	100%	834	100%

Table 5-11. Ridership Composition for Route 96

Route 94 follows a slightly more circuitous alignment than Route 96 from Medford Square to Davis Square. Daily ridership for Route 94 is shown in Table 5-12. As for Route 96 (and, to a lesser extent, Route 80), the Route 94 segment between Boston Ave. at Winthrop St. and Powderhouse Sq. is a high generator of trips. Furthermore, the segment along Boston Ave. from Winthrop St. to High St., which is also served by Route 80, generates about 46 percent of the inbound trips for the route. In addition, the Route 96 segment along George St. and Winthrop St. is high ridership. All future routing scenarios should serve these three segments with both Routes 94 and 96.

Route 94 Segment	Inbound				Outbound			
	Ons		Offs		Ons		Offs	
	Total	Percent	Total	Percent	Total	Percent	Total	Percent
Medford Sq. - Boston @ High	174	30.1%	6	1.0%	19	2.5%	247	32.6%
Boston @ High - Boston @ Winthrop	264	45.6%	32	5.5%	75	9.9%	366	48.3%
Boston @ Winthrop - Powderhouse Sq.	130	22.5%	40	6.9%	24	3.2%	140	18.5%
Powderhouse Sq. - Davis Sq.	11	1.9%	501	86.5%	639	84.4%	4	0.5%
TOTAL -- ALL SEGMENTS	579	100%	579	100%	757	100%	757	100%

Table 5-12. Ridership Composition for Route 94

The running time distribution for each segment between Medford Square and Davis Square is shown in Table 5-13. The last row for Route 96 shows an approximation of the total running times if the route terminated at Davis Square, thus using the Davis Square Busway inbound (it already does this outbound). It takes a bus 5 to 8 minutes, on average, to travel the loop from the current Route 96 stop at Davis Square to the stop on the busway. Overall, Route 94 requires 4 to 8 minutes more than Route 96 to travel between Davis Square and Medford Square.

Rt.	Route Segment		AM Peak				PM Peak			
	Begin	End	Inbound		Outbound		Inbound		Outbound	
			50th	95th	50th	95th	50th	95th	50th	95th
94	Medford Sq.	High @ Rural	4	8	4	9	4	11	5	11
	High @ Rural	Boston @ High	4	7	4	11	4	6	4	6
	Boston @ High	Boston @ North	4	6	3	6	3	4	4	5
	Boston @ North	Powderhouse Sq.	4	7	4	5	5	8	5	7
	Powderhouse Sq.	Davis Sq./Busway	6	10	1	2	8	12	2	2
	ALL 5 SEGMENTS		**26**	**36**	**18**	**24**	**25**	**31**	**23**	**27**
96	Medford Sq.	Main @ George	5	8	3	8	4	7	4	7
	Main @ George	Boston @ Winthrop	4	5	2	3	3	4	4	5
	Boston @ Winthrop	Powderhouse Sq.	2	4	3	4	3	4	3	4
	Powderhouse Sq.	Davis Sq.	2	4	1	2	2	4	2	2
	ALL 4 SEGMENTS		**16**	**21**	**12**	**21**	**14**	**19**	**15**	**21**
	ALL 4 SEGMENTS (including Busway)		**21**	**28**	**12**	**21**	**21**	**27**	**15**	**21**

Table 5-13. Running Time Distribution for Routes 94 & 96 between Medford Sq. & Davis Sq.

An additional factor to consider is that the Green Line will terminate near the intersection of Boston Ave. and College Ave. The College Avenue Station will be the main rapid transit station for Medford residents, so at least one of the routes needs to serve the station. The College Avenue Station Plan shows a bus stop on Boston Ave. near the station plaza.

Even with all of these constraints, there are several routing options to consider for Routes 94 and 96:

- Move one route from College Ave./Boston Ave. to Holland St./Curtis St. The dense residential area west of Tufts is currently not served by buses. This may improve running times (by 1 to 2 minutes) due to congestion on College Ave. However, Curtis St. is a one-way street away from Broadway, so the bus would have to make a few additional turns inbound unless the City of Somerville opts to change the street back to a two-way street. Additionally, there is a moderate crest on Curtis St., which may be too steep for MBTA buses on snowy days. This routing is shown as "941" in Figure 5-4.
- Another way to serve the population west of Tufts is to use North St. (near the Mystic River) instead of Curtis St. North St. is relatively narrow, so buses may create problems for other drivers. This routing is shown as "942" in Figure 5-4.
- Have a route continue north on College Ave. at the intersection with Boston Ave, then west along George St, north along Winthrop St. and finally east on High St. to Medford Square. The portion of College Ave. north of Boston Ave. is not currently served by bus routes. This routing is labeled as "961" in Figure 5-4.
- Retain existing routing on both routes. The City of Somerville should strongly consider adding a southbound bus lane along College Ave. close to Davis Square, especially for this option, to reduce running times for the route. Depending on the length, this would remove at least five parking spots. On-street parking can still be provided on the northbound side of College Ave.

Finally, it may be possible to extend a route into an underserved area of Medford, especially if the terminus of Route 96 is moved from Harvard Square to Davis Square. Lawrence Memorial Hospital is currently served only by Private Route 710, but it may be difficult to have an MBTA route serve the hospital due to steep grades.

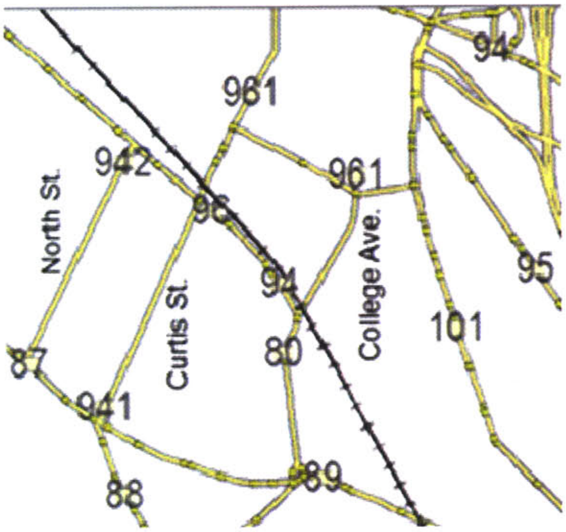


Figure 5-4. Map of Possible Modifications to Routes 94 and 96

Recommendation: Terminate Route 96 at Davis Square. The exact routings of Route 94 and 96 into Davis Square can be determined at a later time after further consultation with both the cities of Somerville and Medford. Route 96 is the likely candidate for some re-routing, because it has a shorter cycle time. For Scenario 4, the half-cycle time of Route 96 between Medford Square and Davis Square are set at the 95th percentile running time (busway included) shown in Table 5-13; the running time is set at the 50th percentile. In addition, 2 minutes of running time is added to all Route 96 trips to account for modifications to routing. The routing changes subtract a bus during the PM peak (no change in the AM peak). If the frequency of Route 96 is increased to every 15 minutes, these numbers would increase by one vehicle.

5.7 Summary of Potential Changes

The project area routes plus Routes 64, 68, and 69 currently use 77 buses in the AM peak. Scenario 1, which regularizes the headway and uses interlining (where possible), requires 73 buses. However, this is for the existing schedule that has several inefficiencies. The newly analyzed peak period running times and layover times proposed in Section 4.3 served as inputs into Scenario 2. These changes will improve the reliability of the buses, and they add only one bus to the minimum required fleet. For Scenario 3, service frequencies were increased one-at-a-time based on headways calculated using the square-root rule, which takes into account demand, cycle times, operator costs, and passenger value-of-time. There were significant passenger wait time and scheduled delay savings estimated from the increased frequencies. Finally, significant routing modifications were tested on several of the study area routes, which can be implemented with only minor changes in required resources. Although some of them can be implemented right away (like the re-routing of Route 83), others, such as changes to Routes 94 and 96 (except, perhaps, to terminate Route 96 at Davis Square and improve its headway), should be analyzed further.

6 Summary and Conclusions

This thesis demonstrated how automatically-collected data can be used in the bus service planning process for a transit agency. Performance and demand were analyzed using automatically-collected data, where available, for a case study consisting of 18 bus routes operating the cities of Somerville and Medford, Massachusetts.

The results of the service analysis were used as inputs into the timetable development and vehicle scheduling steps of the planning process. The timetable started with the existing bus schedule and was initially modified only slightly with even headways, allowing for trip time shifting whenever efficiencies could be achieved and interlining. Next, current running times and layover times for most routes were adjusted based on a detailed analysis of archived AVL data using industry standard practice to improve reliability. The last two service change scenarios modified frequencies based on demand, synchronized routes that serve the same route segments, and incorporated selected changes in routing. The number of buses required to serve each timetable scenario was the primary output of interest.

The first section of this chapter will summarize the work presented in this thesis. The second section will present a set of recommendations. Future work following on from this thesis will be presented in the third section. The chapter finishes with conclusions.

6.1 MBTA Bus Service and Operations Planning Case Study

A number of ridership and service performance analyses were conducted using ADCS on the routes in the selected MBTA study area. The results of these analyses of existing conditions were used as input for a series of service planning scenarios developed using the HASTUS NetPlan scheduling tool.

Transit agencies generally set their bus schedule running times to achieve a minimum threshold of reliability subject to the constraint of available buses. For an agency that schedules to a standard of 85 percent reliability, it was shown that the incremental cost of providing additional reliability (i.e. 90-95 percent) may be low if there are offsetting efficiencies from trip shifting and interlining.

The bus service planning portion of this thesis focused on timetabling with consideration to other steps in the process—network design, frequencies setting, and vehicle blocking. The motivation for the bus service planning scenarios used in Chapter 5 was to see to what extent improved service could be provided within a specific network of routes with approximately the same vehicle resources as used currently.

This research is useful for transit agencies that are looking to increase service but are constrained by the size of their bus fleet and available operator resources. NetPlan performs thousands of trip shifting iterations, which would be impractical to perform manually, to minimize the number of vehicles required for a given timetable. The trip shifting also considers interlining opportunities that may reduce the total amount of excess layover time in the network. Most transit agencies currently use only a limited amount of interlining, although it may be very beneficial in bus networks that are well-connected (i.e. multiple routes that serve the same terminal). Thus, it may be desirable in some cases to extend routes to a terminal served by other routes in order to maximize the possibilities of interlining. Additionally, interlining can improve the optimal vehicle blocking solution significantly if there are several routes for which the cycle time is not a multiple of the headway. For Scenario 1, regular headways and close-to-maximum running times and recovery times were used as inputs. The vehicle savings from trip shifting and interlining more than offset the conservative inputs in the AM peak but did not offset them in the PM peak. Cycle times were increased by an average of 4 to 5 minutes in Scenario 2 to provide additional reliability. After making these changes, the optimized vehicle blocking solution for the resource-constraining AM still had a net scheduling efficiency of three buses relative to the MBTA existing schedule. In Scenario 3, frequencies were increased incrementally based on equitable headway calculations. From the Scenario 3 AM peak base scenario, there were seven frequency increases (including two that were reduced for the base case) possible when 77 vehicles were used in the AM peak (as in the current MBTA schedule). From the Scenario 3 PM peak base scenario, there were five frequency changes (including one that was reduced for the base case) that were made at the initial operator-to-passenger cost ratio (8.5). The net expected passenger wait time and scheduled delay savings were 89 and 76 hours in the AM and PM peaks, respectively. Scenario 4 demonstrated that the impact of bus routing modifications on a timetable can also be easily estimated using NetPlan.

6.2 Recommendations

This thesis recommends that automatically-collected data be used more in the service planning process. AVL data provide large sample sets for running time analyses, and the outputs of these analyses should be used to revise the scheduled cycle and running times. The running time analysis in Chapter 4 was for weekday trips with a particular focus on the running times used in the AM and PM peaks. An extension to this work would be to perform running time analyses for other time periods including Saturdays, Sundays, weekdays when school is not in session, and holidays. Automatically-collected data and automated scheduling tools make it easier for transit agencies to have different timetables for each season of the year and, in addition, to refine those schedules each year. However, changing the running times may affect vehicle and crew requirements. Thus, it is desirable to determine the minimum number of buses required using an automated sketch planning scheduling tool before decisions are made to modify full production schedules.

Similarly, ridership data from APCs or AFCs should be used to adjust the service frequencies on bus routes and the thesis suggests a specific methodology (see section 5.5) to prioritize such frequency changes so that maximum wait time and scheduled delay savings can be achieved. Also, it is recommended that transit agencies use regular, clock-face headways, because these are easier for customers to remember, understand, and use. In general, the case study discussed here has shown that changing headways to the nearest clock-face will not significantly alter the number of vehicles required to provide service.

A major recommendation of this thesis is to consider the use of automated sketch service planning tools, such as NetPlan, to quickly evaluate a range of service plan modifications. In particular, vehicle blocks should be automatically generated to examine interlining options in as many instances as possible, because this will reduce the work required for schedulers to manually adjust the start times or running times of trips to investigate potential service plan efficiencies. In a network where almost all bus routes share a terminus with other routes, there are many possible interlinings and thus, many opportunities for improving the efficiency of the timetable and vehicle blocking. In fact, 72 percent of the peak hour vehicle blocks in Scenario 4 had at least one instance of interlining. NetPlan makes it easy for the user to modify inputs, which allows a transit agency to work towards a different goal in each service planning study.

For example, an agency may try to reduce its fleet size in one study, increase frequencies in a second, introduce new routes or routing modifications in a third, or some combination of these in a fourth. In addition, transit agencies should consider using the savings from trip shifting and interlining to improve bus reliability while retaining current service frequencies.

6.3 Future Work

There are several opportunities for research to extend this work in the bus service and operations planning process. Some of these research topics are context specific to the Somerville-Medford Green Line Extension Project. Potential research opportunities include:

- **Analyze the bus service changes required for after the Green Line Extension opens.** The modifications to the bus network and timetable tested in this thesis are for the short-term. Thus, additional analysis will need to be performed for the bus service planning after the Green Line Extension to College Avenue and Union Square is opened. In general, the demand for the bus routes will change in the project area, so these new ridership numbers and bus feeder movements need to be estimated. The methodology for estimating these differences should be similar to the one developed for the Northwest Corridor Study, but ADCS have the potential to add more precision to these estimations and tools such as HASTUS-NetPlan will allow researchers to analyze far more options in a given time.
- **Create stop-level O-D matrices.** Ridership numbers presented in the Case Study were taken largely from APC and AFC data. AFC can be linked to an AVL dataset to estimate an origin-destination matrix, as discussed in Wang (2010). O-D matrices, one for each day of the week and/or time period, that are detailed to the route segment or even stop level would provide additional information that could be used when setting the frequencies (see Section 5.5) and, especially, revised routing (see Section 5.6) as in NetPlan Scenarios 3 and 4, respectively.
- **Automatically select running time periods.** In this thesis, running time periods were determined primarily by visual inspection of the AVL running time distribution plots. Other techniques have been developed that are at least partially-automated, such as a “statistically-based dataset clustering algorithm” (MIT Center for Transportation & Logistics, 2003). The newest version of the HASTUS-ATP module includes algorithms

that suggest the most appropriate time periods for a route once the available AVL data is analyzed. It would be important to study the transitions between time periods and also how transit agencies would implement the results of this automated method to adjust running and cycle times on a more frequent basis.

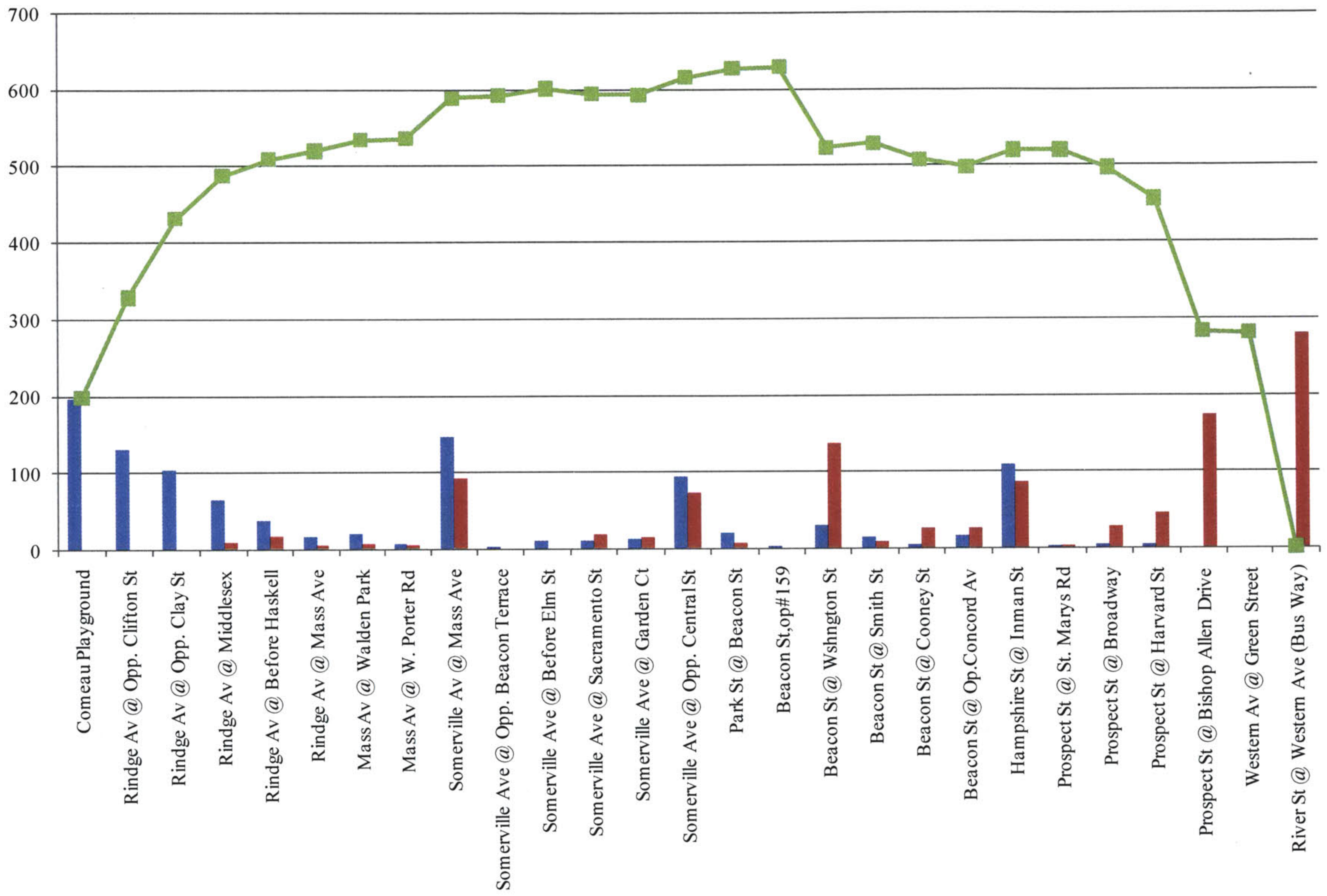
- **Set the running time between timing points based on AVL data.** The running time analysis in Chapter 4 focused on setting the end-to-end running times and terminal recovery times well. However, little attention was given as to how to set the scheduled running times between timepoints, much less how to set the running times between stops to maximize reliable passenger information and synchronization of routes along common route segments. Further research should build upon the work performed by Fattouche (2007).
- **Add additional routes to the automated timetabling scenarios.** In this thesis, the Somerville and Medford routes were studied separately from most other MBTA routes. Further work could add the excluded routes, or a subset of them, to the timetabling study. There may be interlining improvements possible, especially at terminals near the study boundary, such as Wellington Station and Sullivan Square. Passengers may benefit from interlining not only from the increased service that is made possible but potentially also when it reduces the need for them to transfer buses to reach their ultimate destination. Thus, for terminal nodes where there are many bus-to-bus transfers, synchronization factors can be applied so that some of these transfers can be accommodated by interlining. For example, one of the most frequent transfers for routes in the study area was from Route 109 (Linden Square – Sullivan Square) to Route 86. Both routes terminate at Sullivan Square, so this pair of routes would be a strong candidate for passenger-based interlining.

6.4 Conclusion

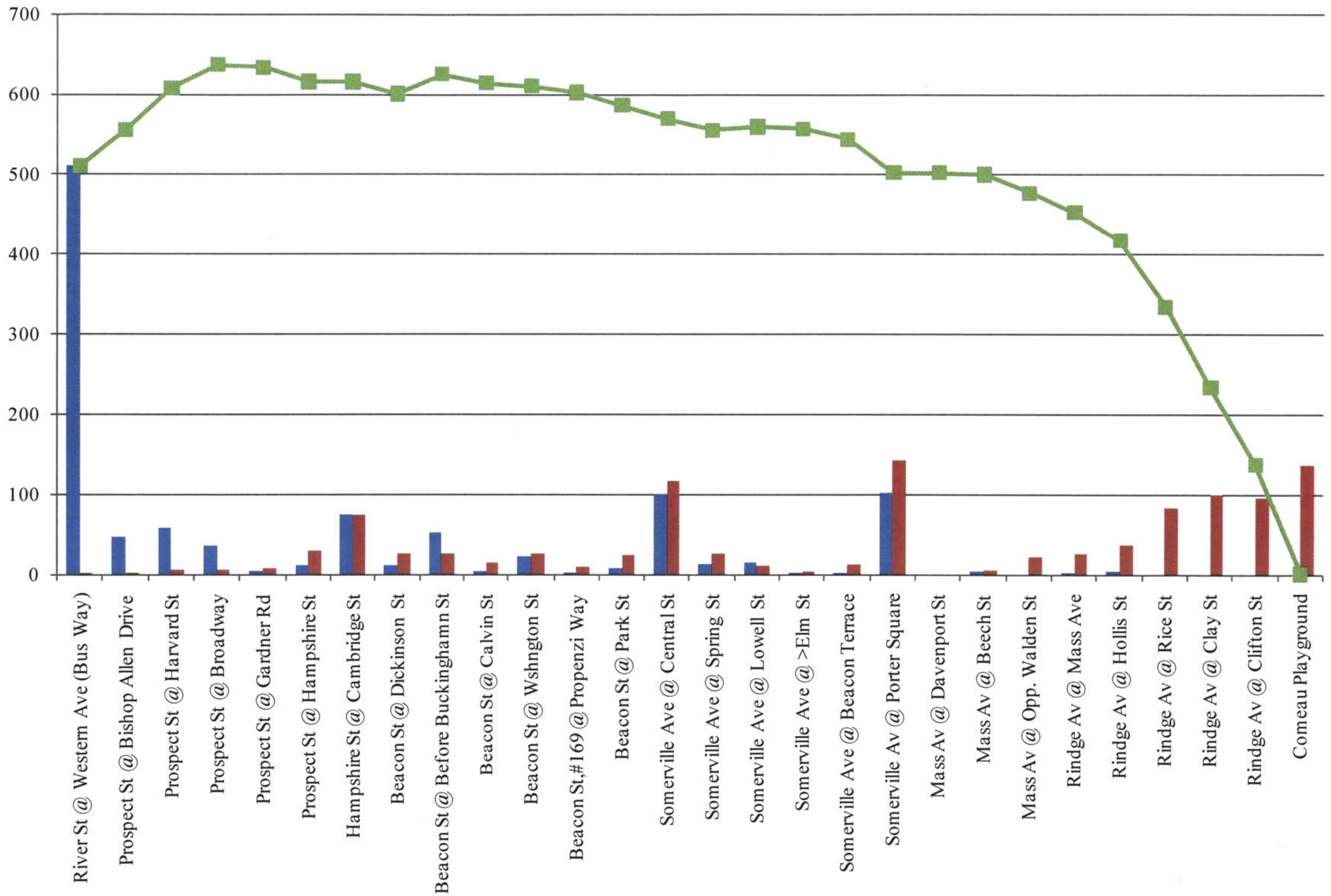
ADCS should be used more in bus service and operations planning, because they are inexpensive and, compared with manual counts, provide a much more complete picture of the demand and performance of bus routes. Some of the data may have to be discarded or adjusted (as in the case of AFC data being used for estimated ridership), but these are not significant issues due to the large quantity of data available. The automatically-collected data are useful for analyzing the demand and running times for bus routes, and the outputs of these analyses may be used as inputs into service planning scenarios. Transit agencies can improve their operating efficiency by automating the timetabling and vehicle blocking steps through the use of sketch service planning tools, such as NetPlan, that take into account all interlining possibilities. Finally, transit agencies can increase their reliability, service frequencies, and coverage areas by systematically examining and modifying the inputs into the timetable.

Appendix A. Ons, Offs, and Load Profiles

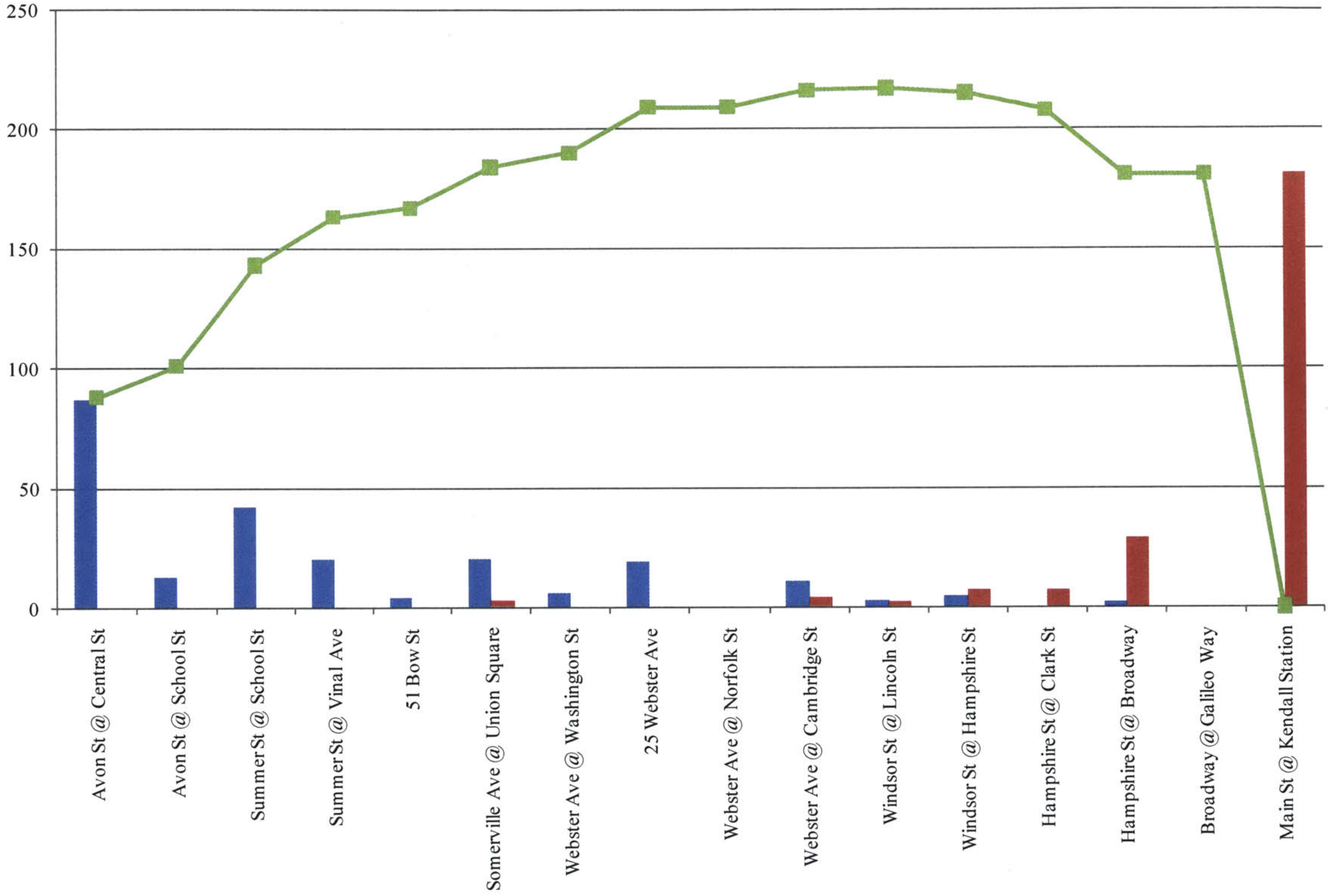
Appendix A. Route 83 Inbound--Ons,Offs, and Load



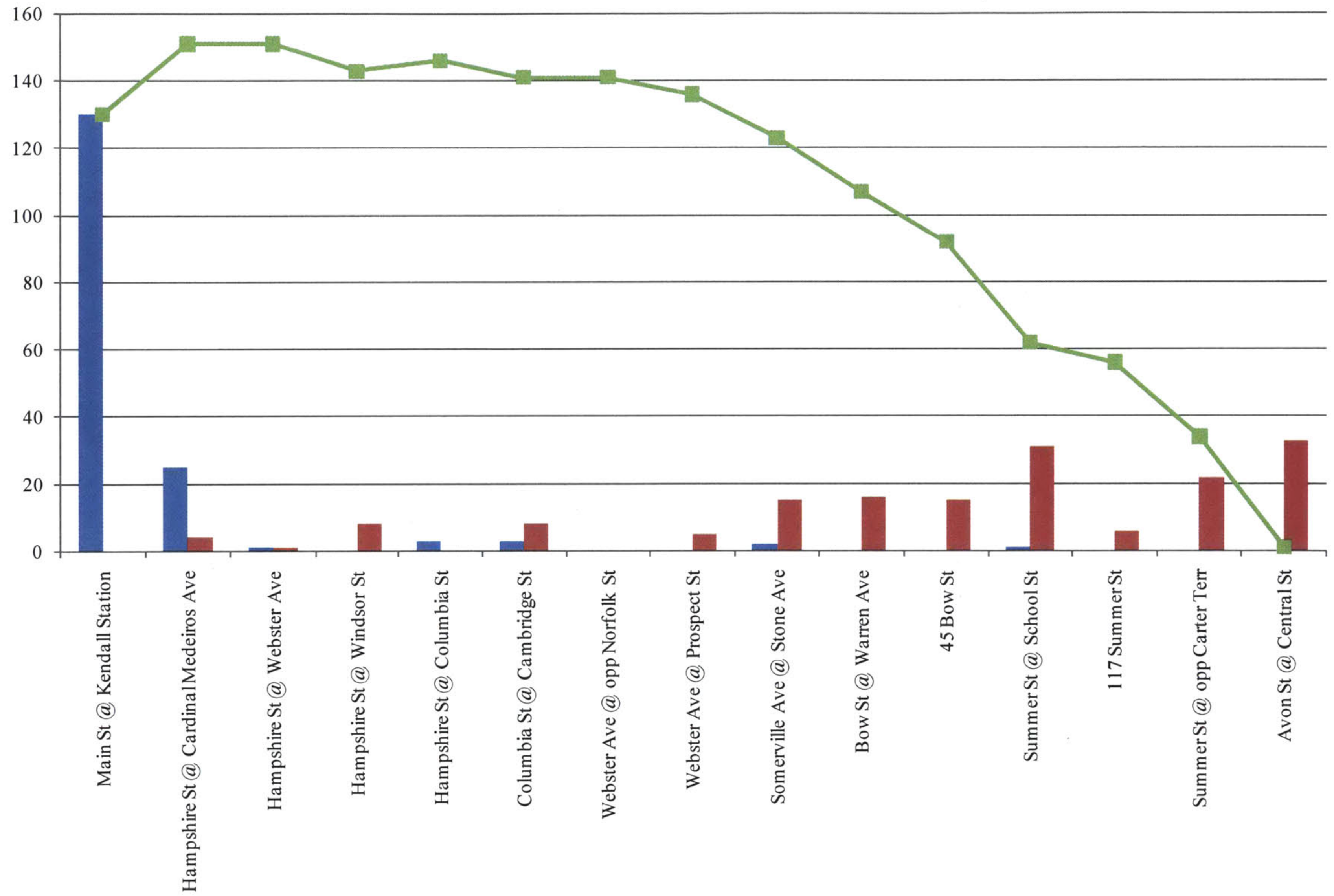
Appendix A. Route 83 Outbound--Ons, Offs, and Load



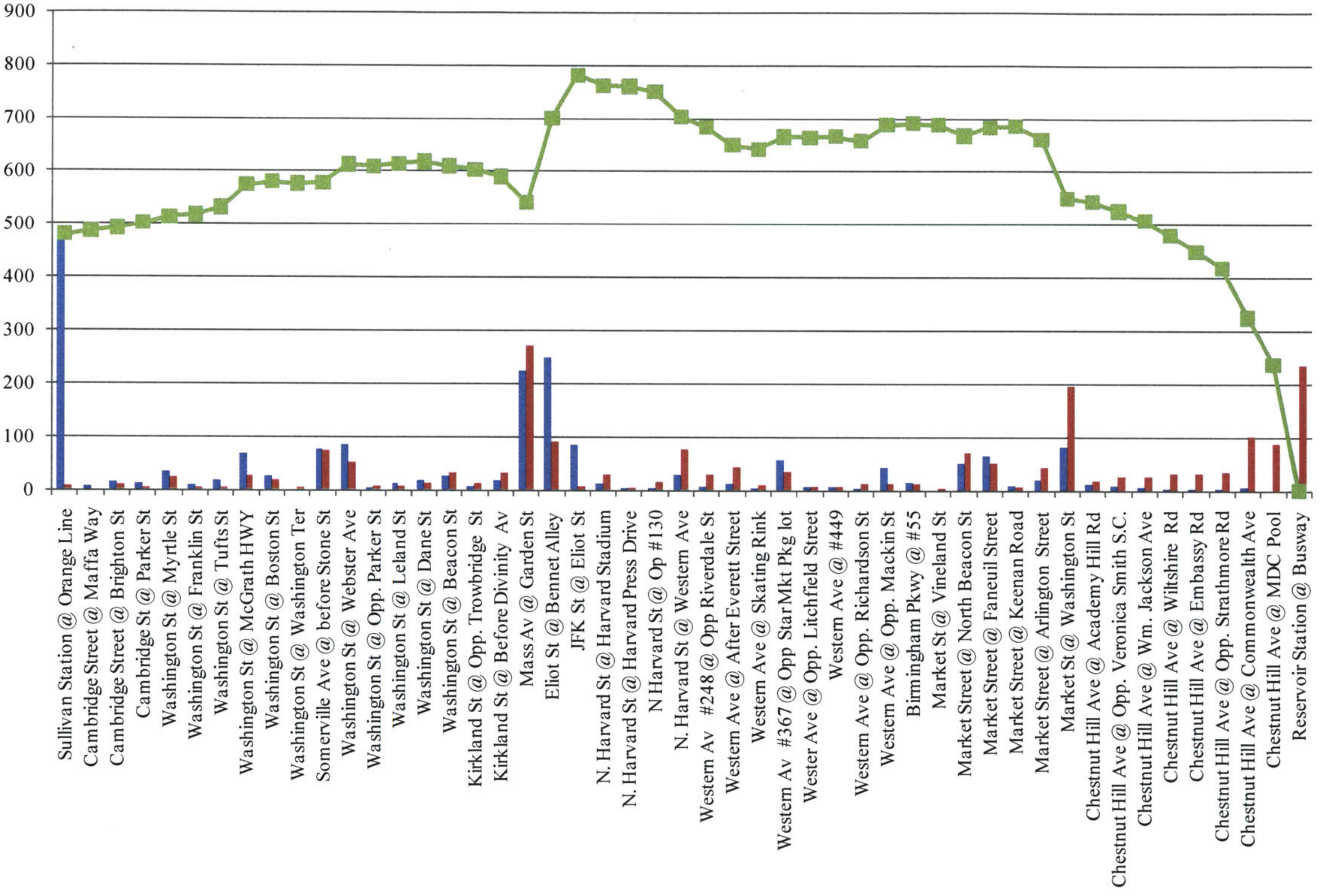
Appendix A. Route 85 Inbound--Ons, Offs, and Load



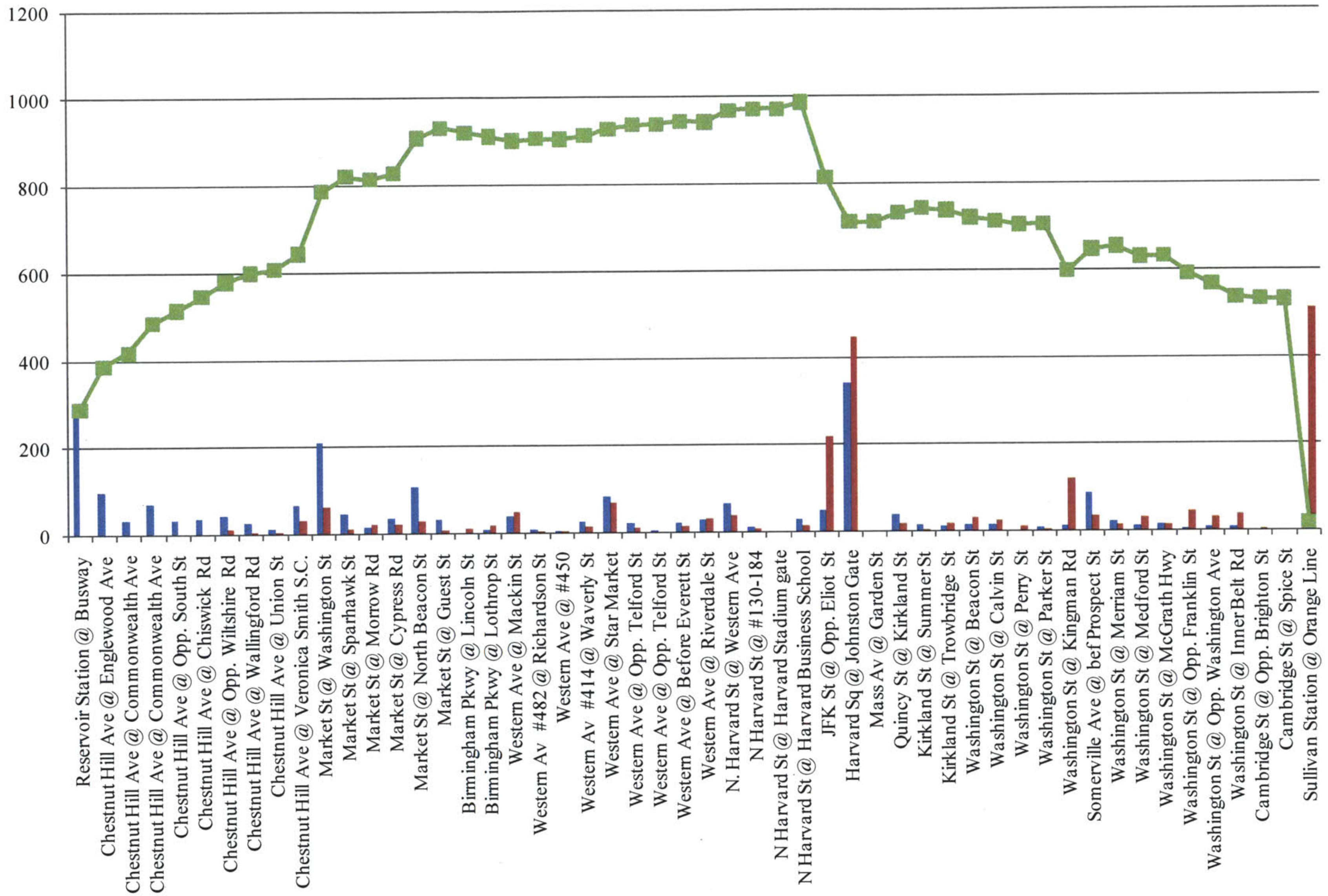
Appendix A. Route 85 Outbound--Ons, Offs, and Load



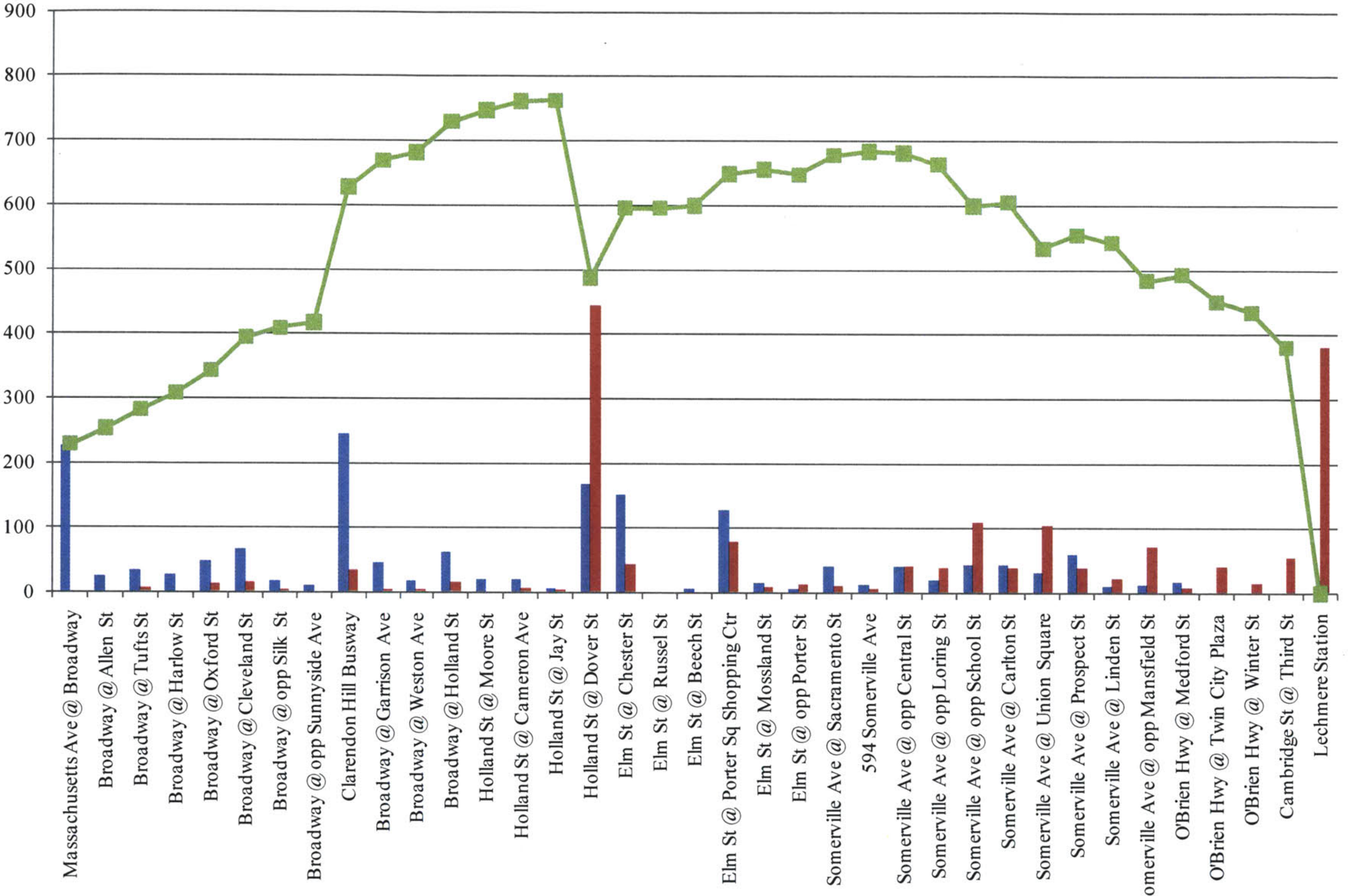
Appendix A. Route 86 Inbound--Ons, Offs, and Load



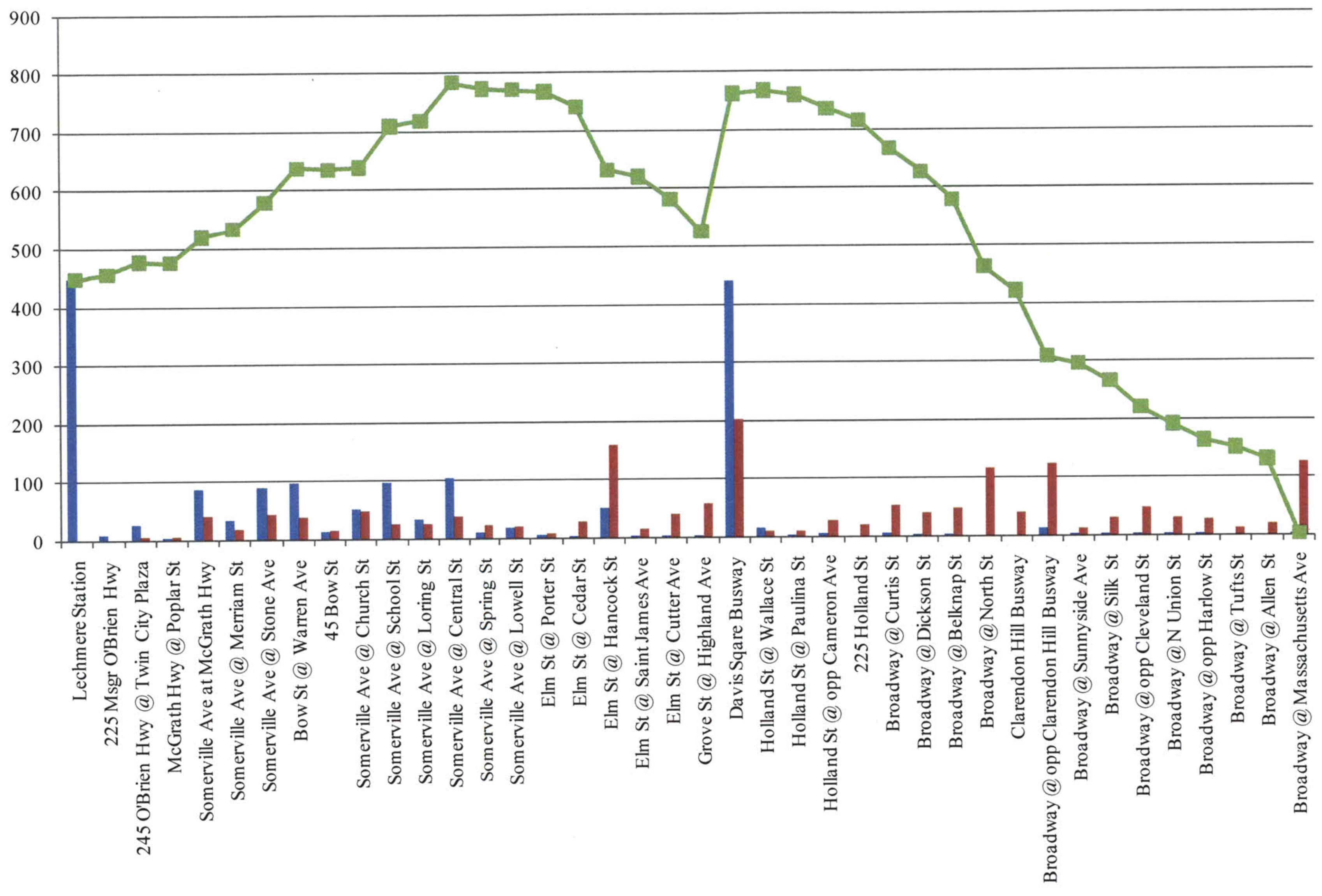
Appendix A. Route 86 Outbound--Ons, Offs, and Load



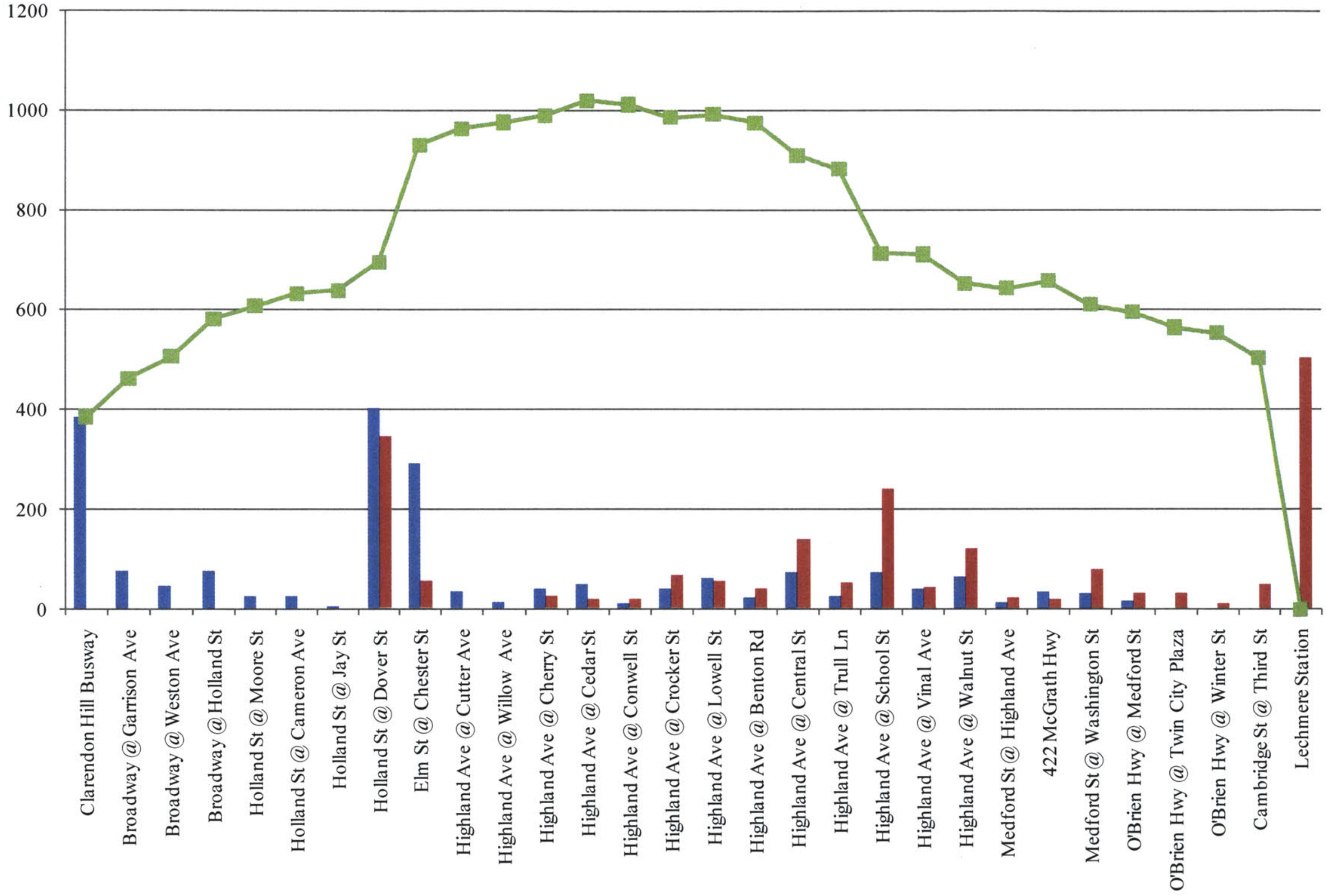
Appendix A. Route 87 Inbound--Ons, Offs, and Load



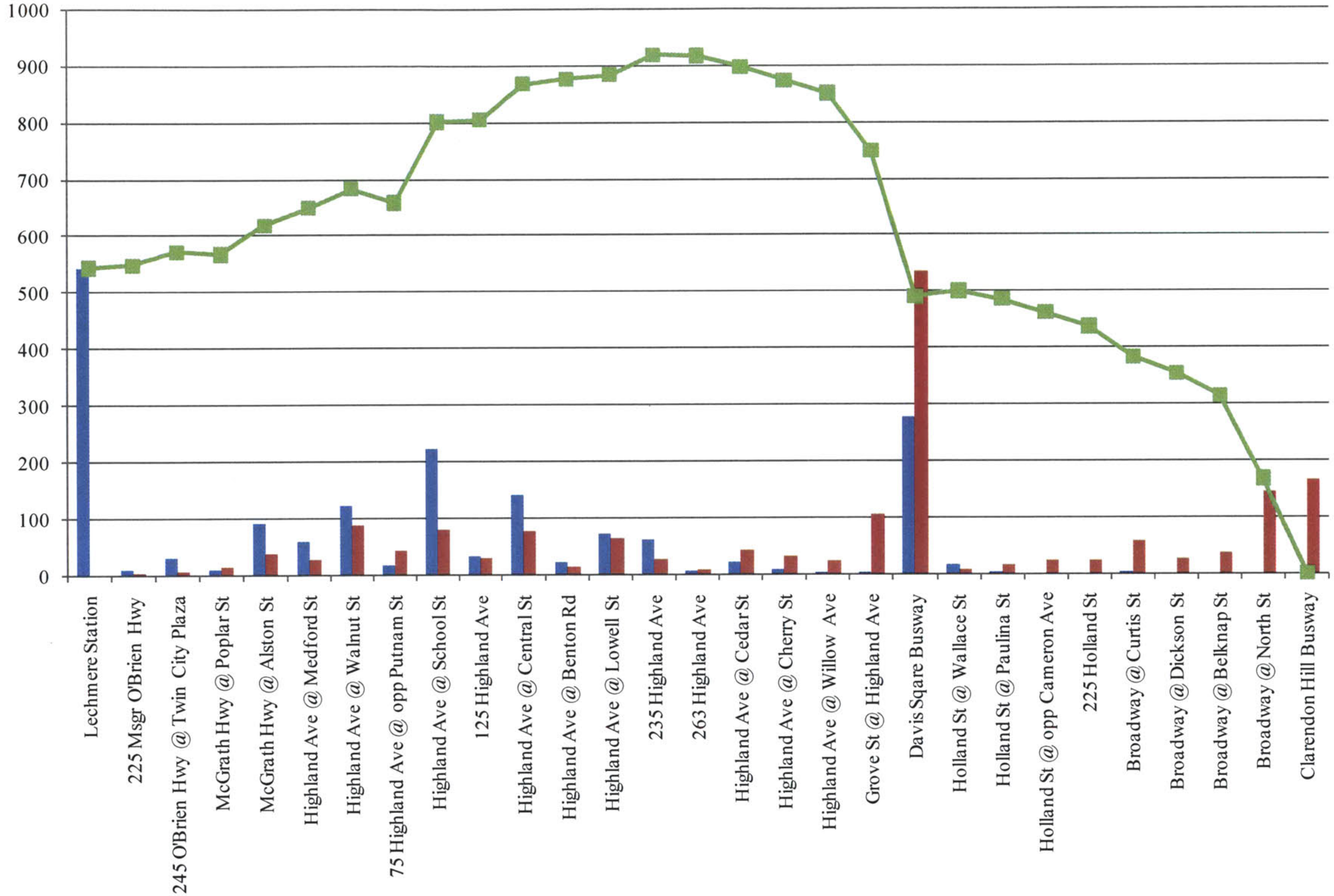
Appendix A. Route 87 Outbound--Ons, Offs, and Load



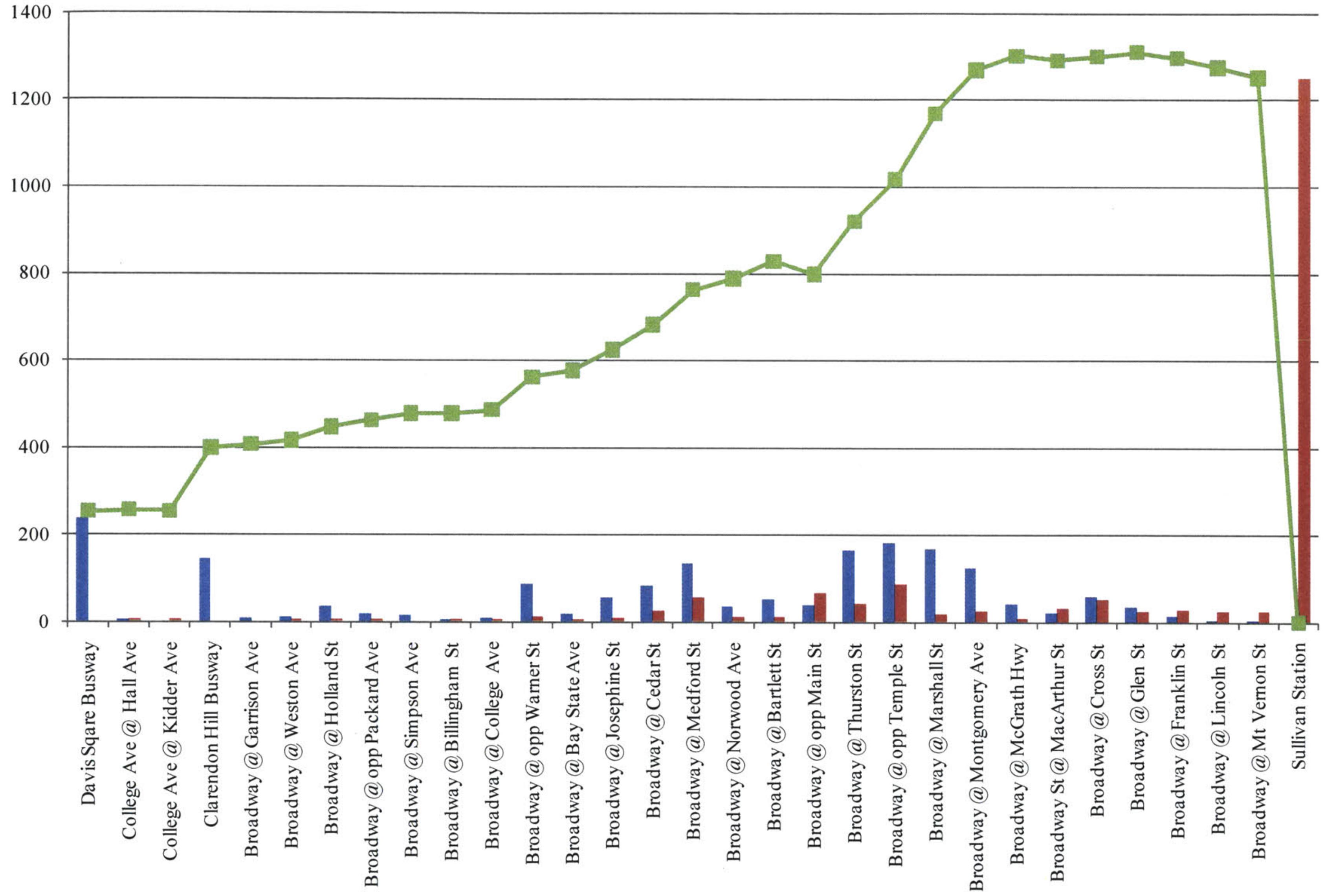
Appendix A. Route 88 Inbound--Ons, Offs, and Load



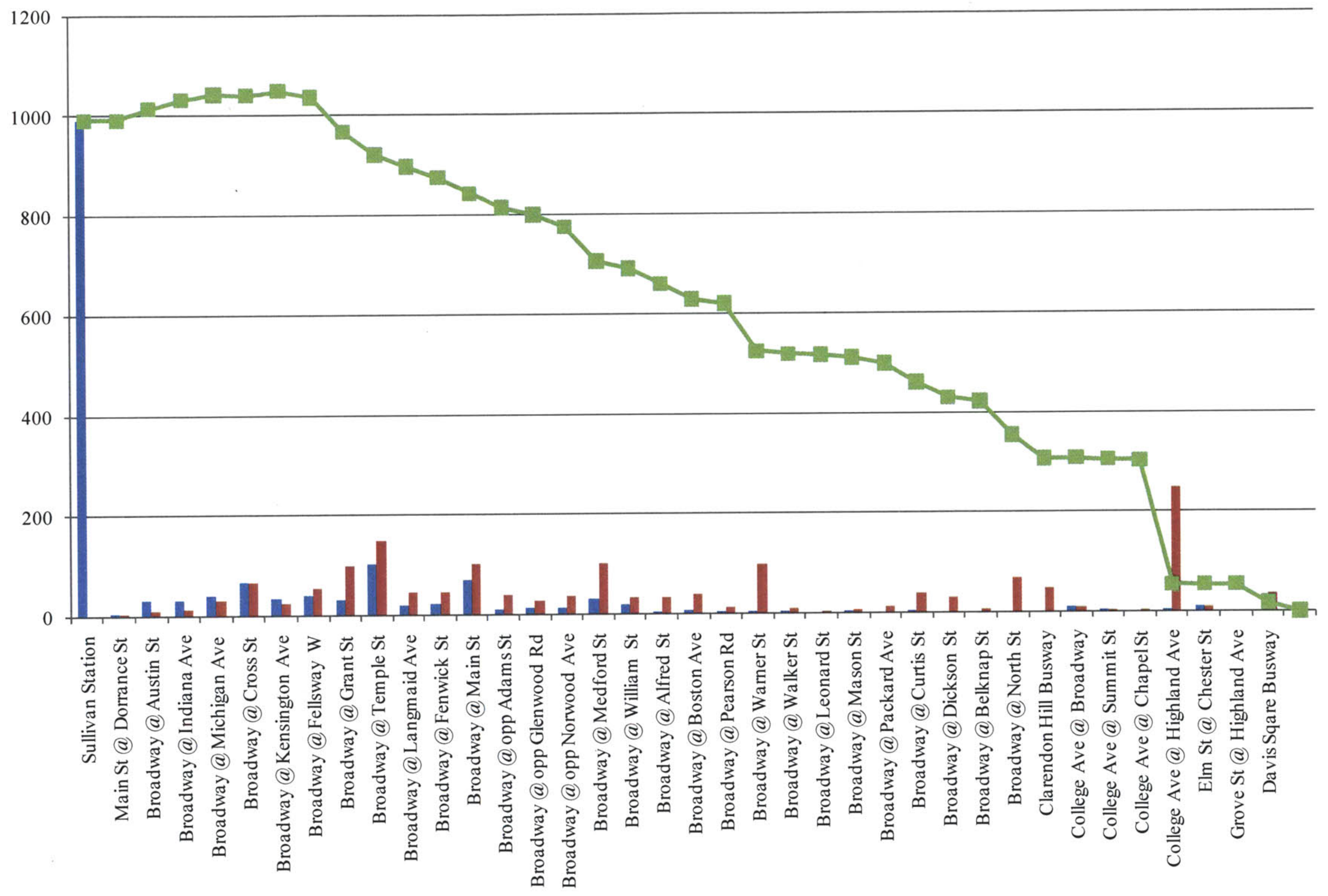
Appendix A. Route 88 Outbound--Ons, Offs, and Load



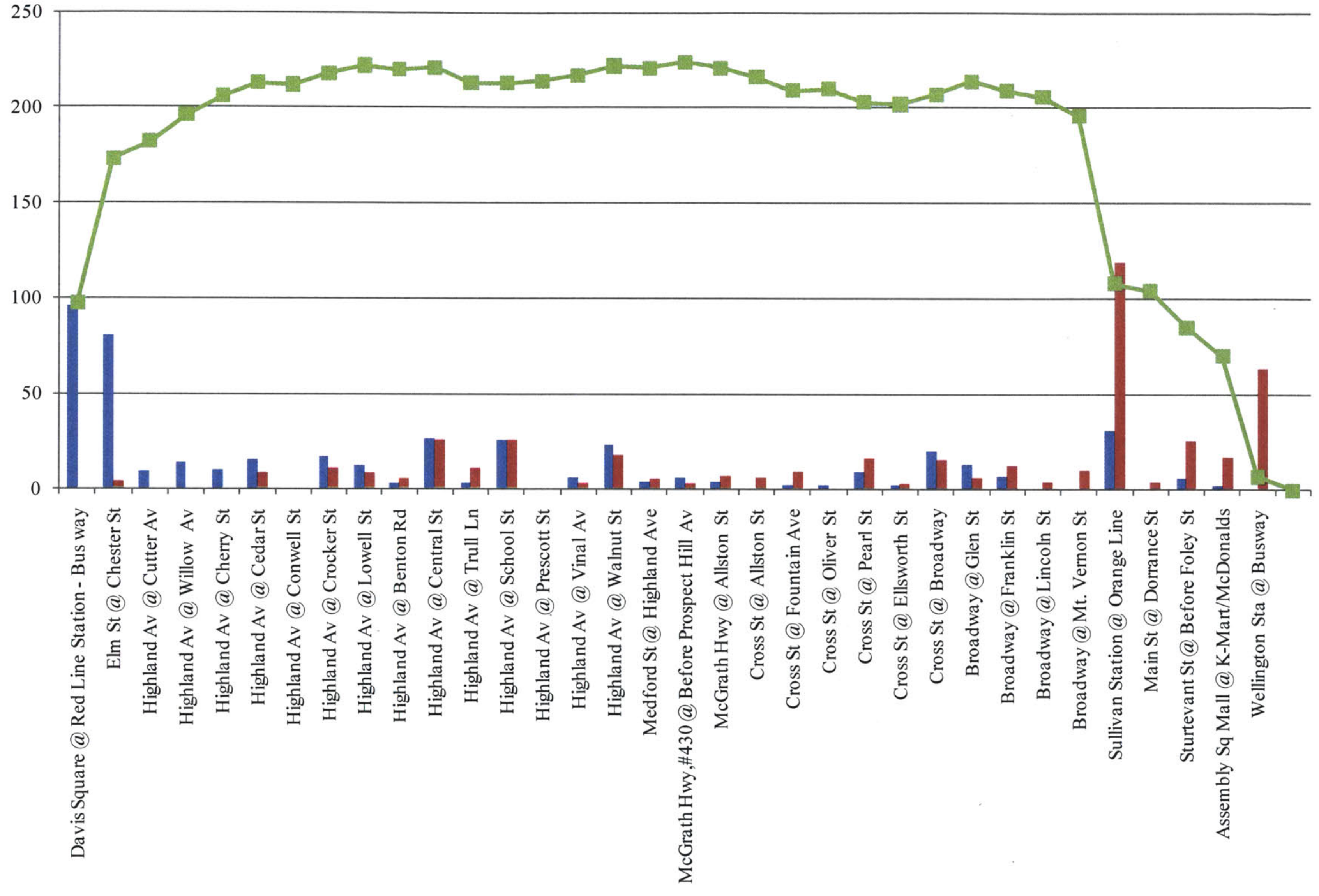
Appendix A. Route 89 Inbound--Ons, Offs, and Load



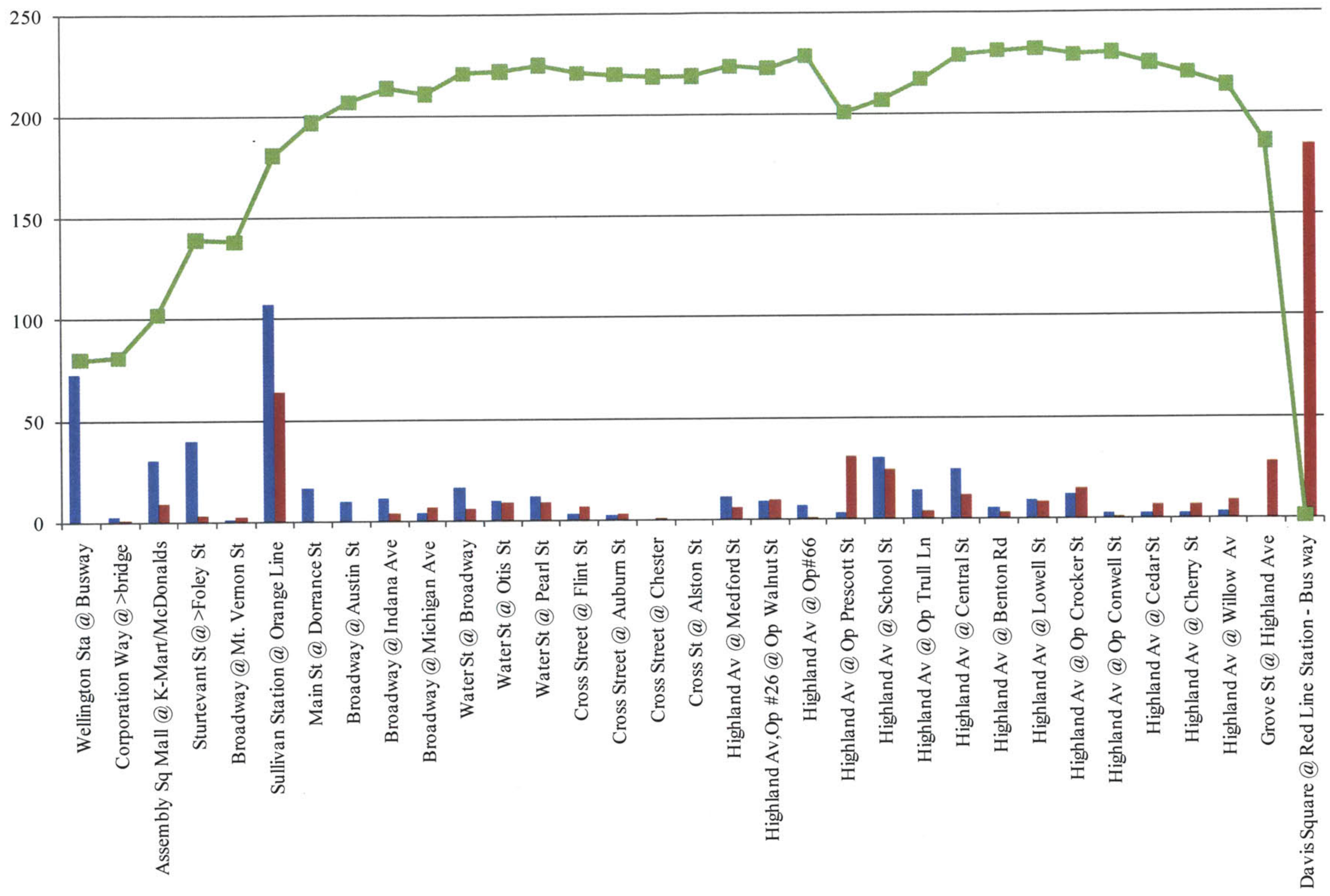
Appendix A. Route 89 Outbound--Ons, Offs, and Load



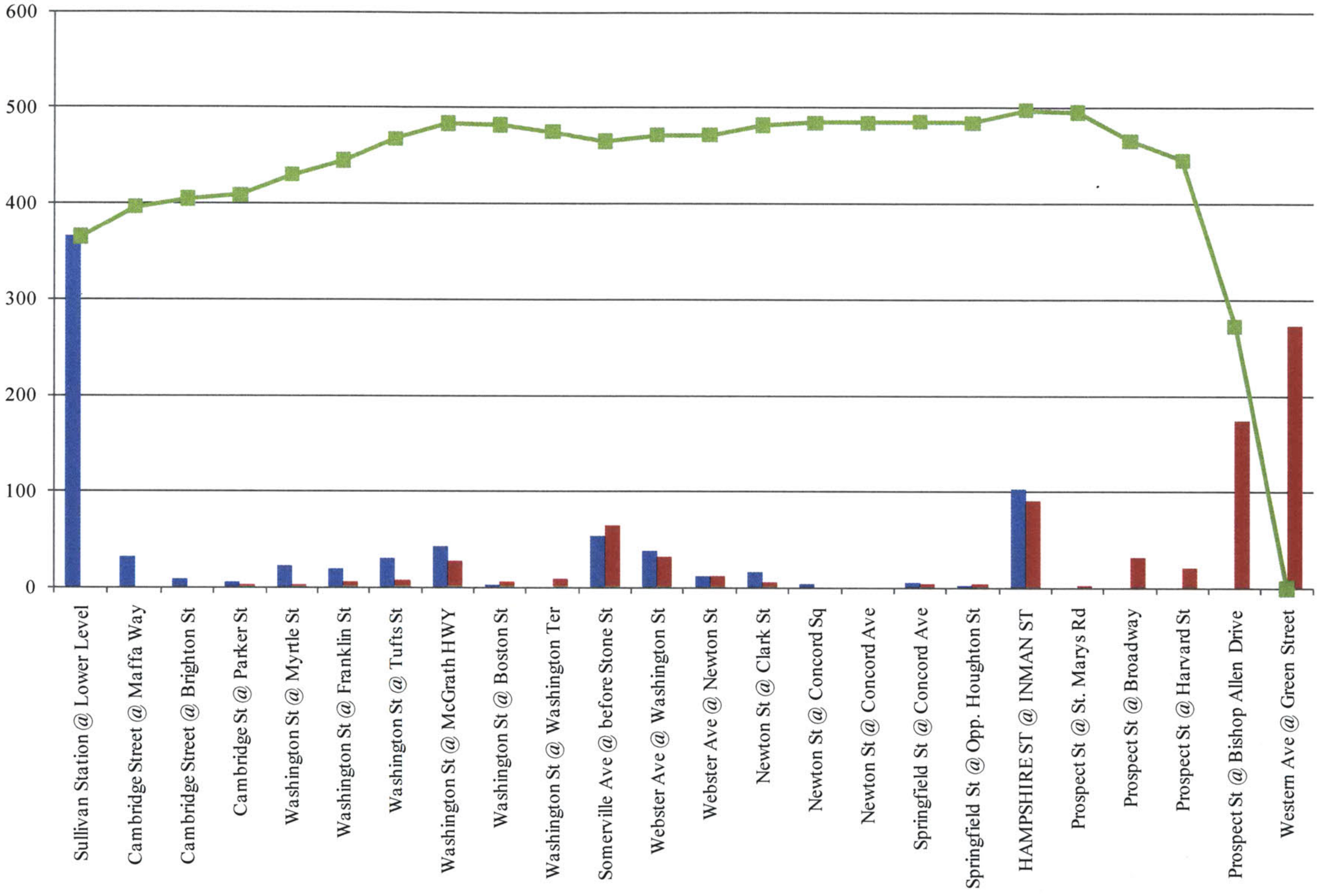
Appendix A. Route 90 Inbound--Ons, Offs, and Load



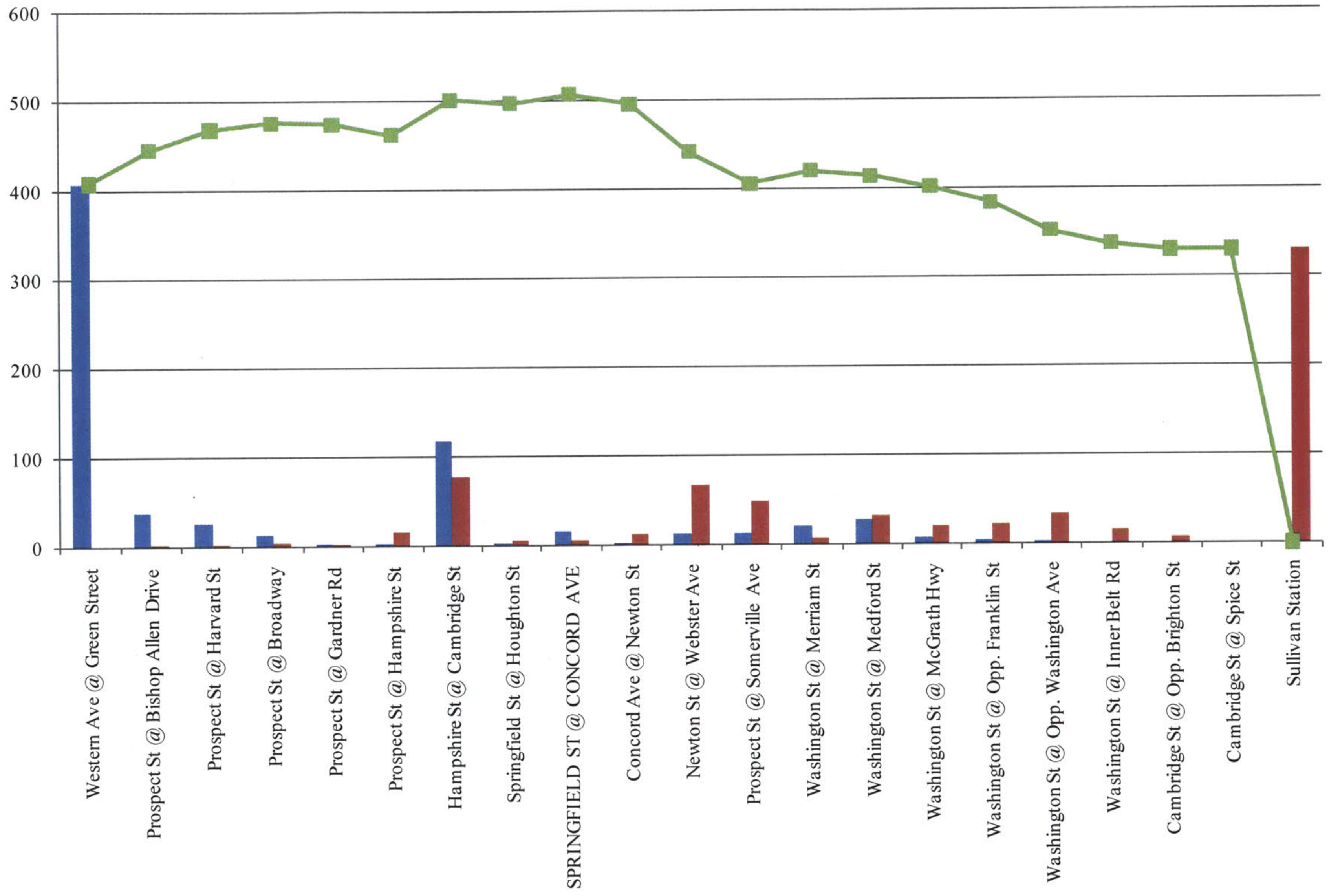
Appendix A. Route 90 Outbound--Ons, Offs, and Load



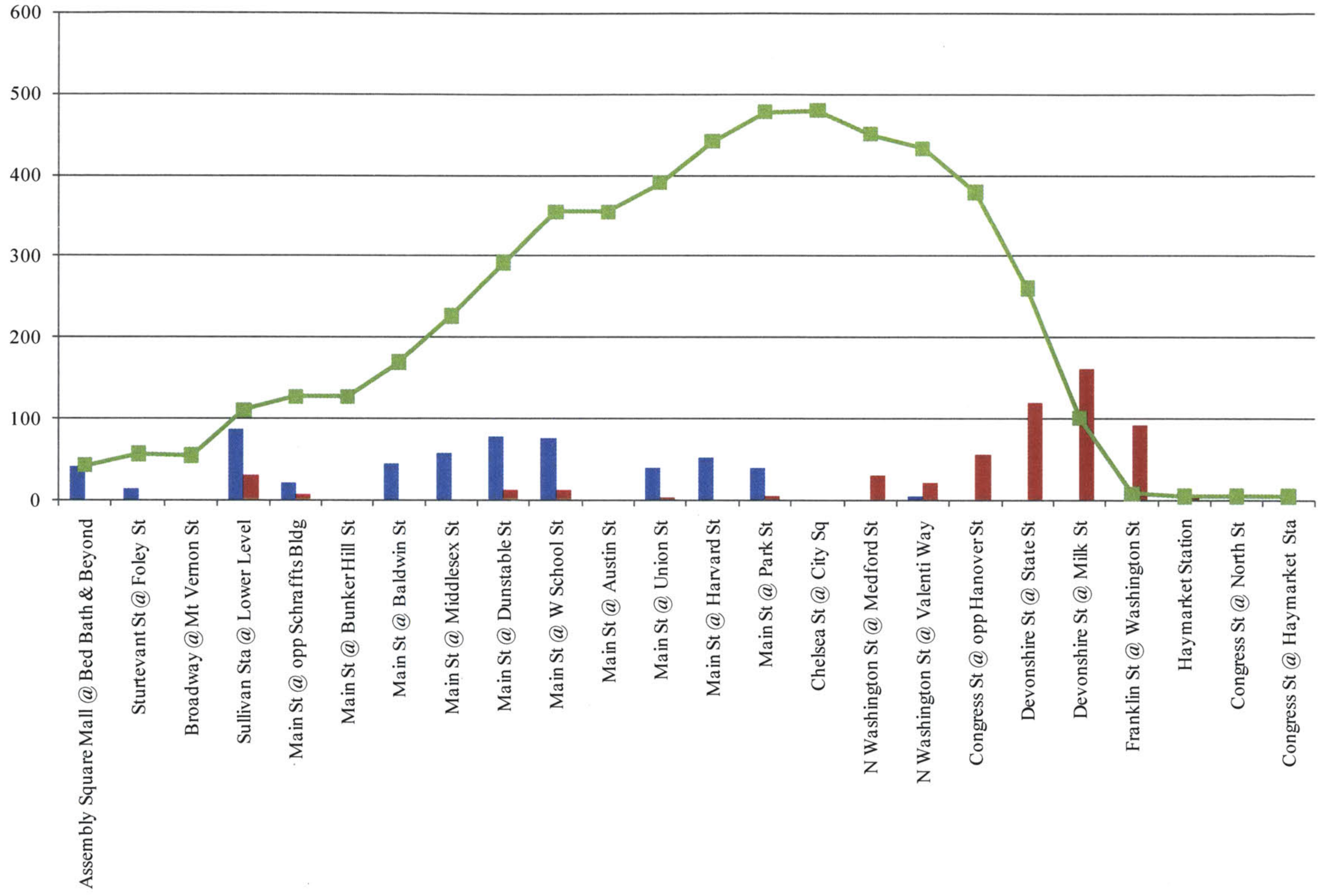
Appendix A. Route 91 Inbound--Ons, Offs, and Load



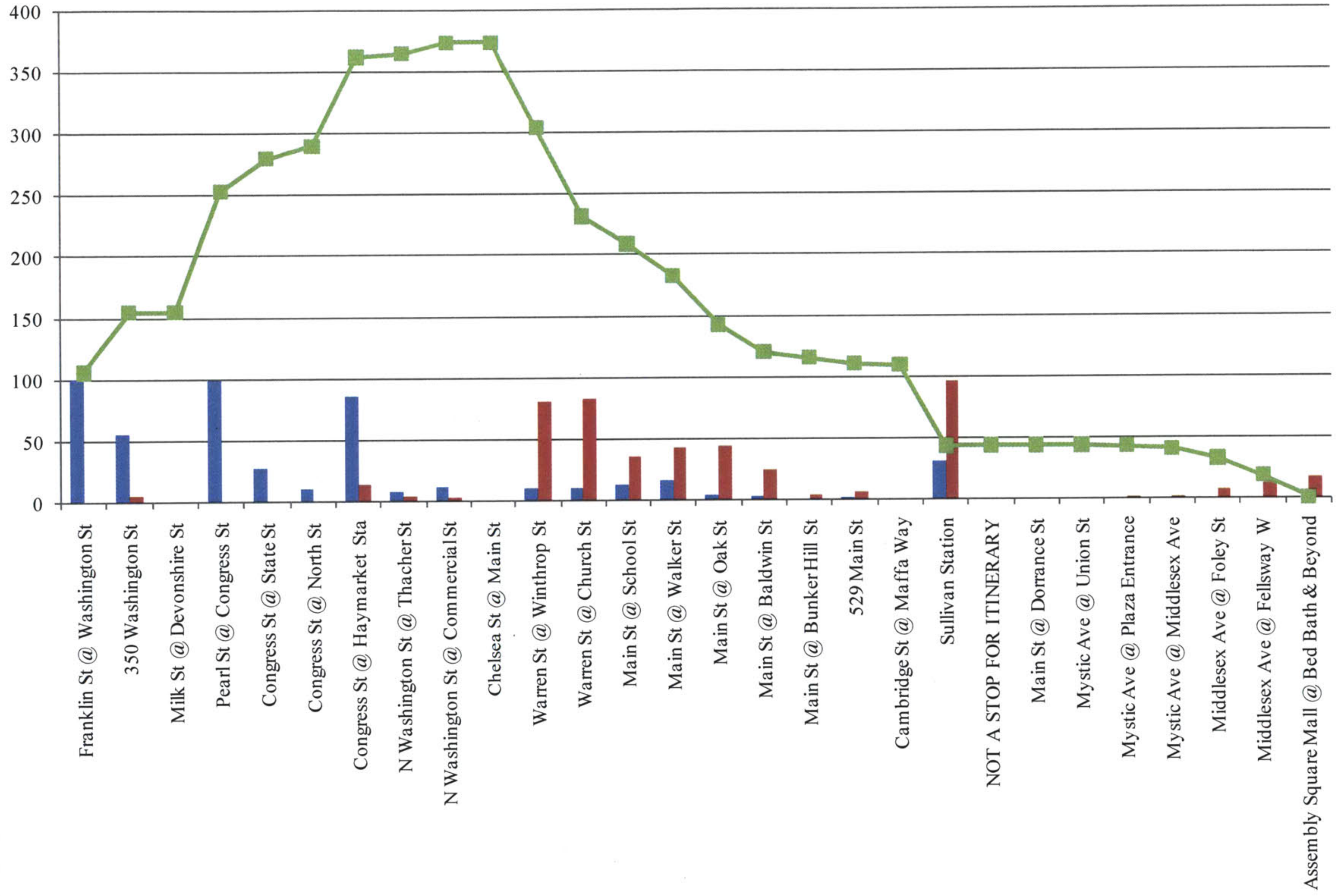
Appendix A. Route 91 Outbound--Ons, Offs, and Load



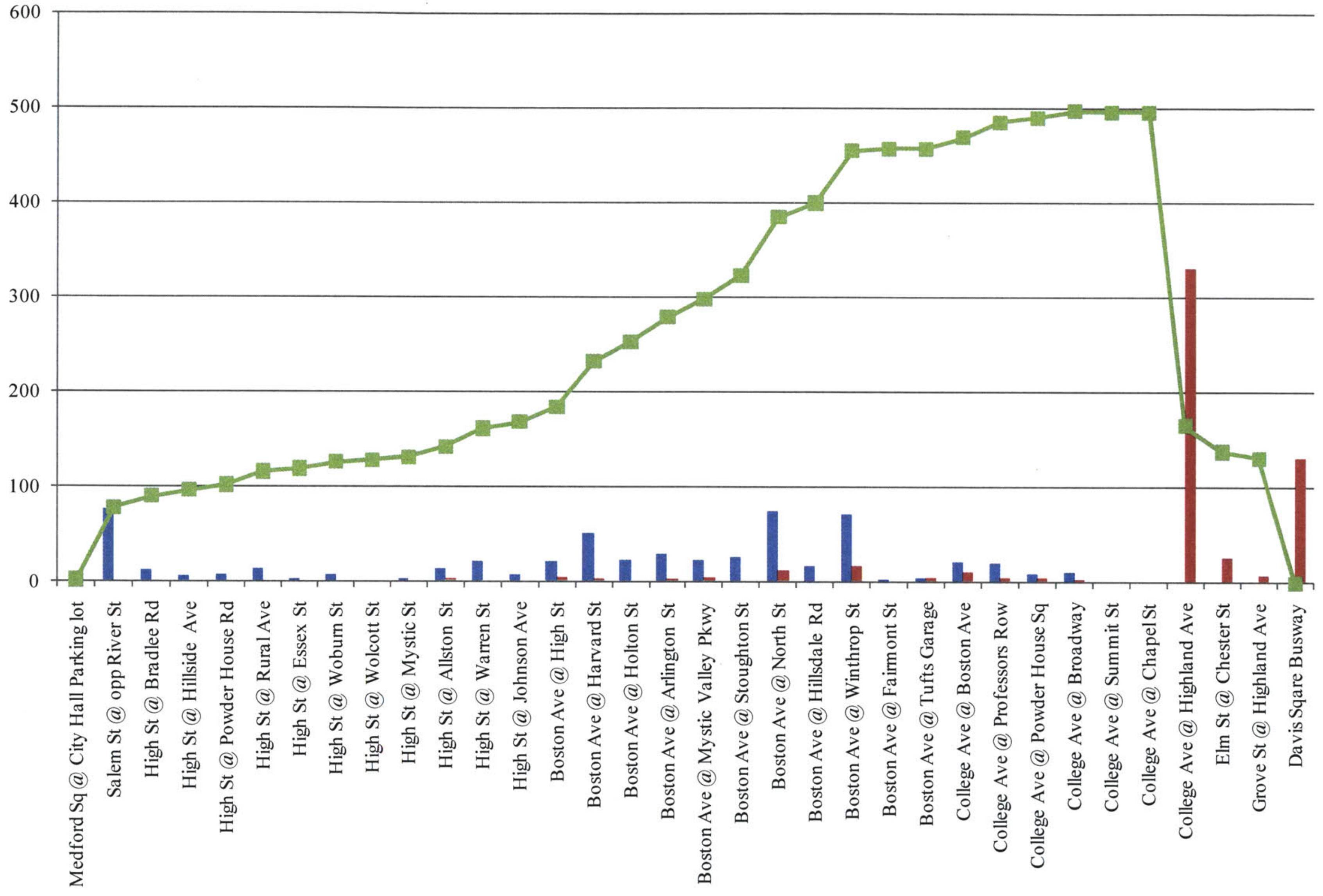
Appendix A. Route 92 Inbound--Ons, Offs, and Load



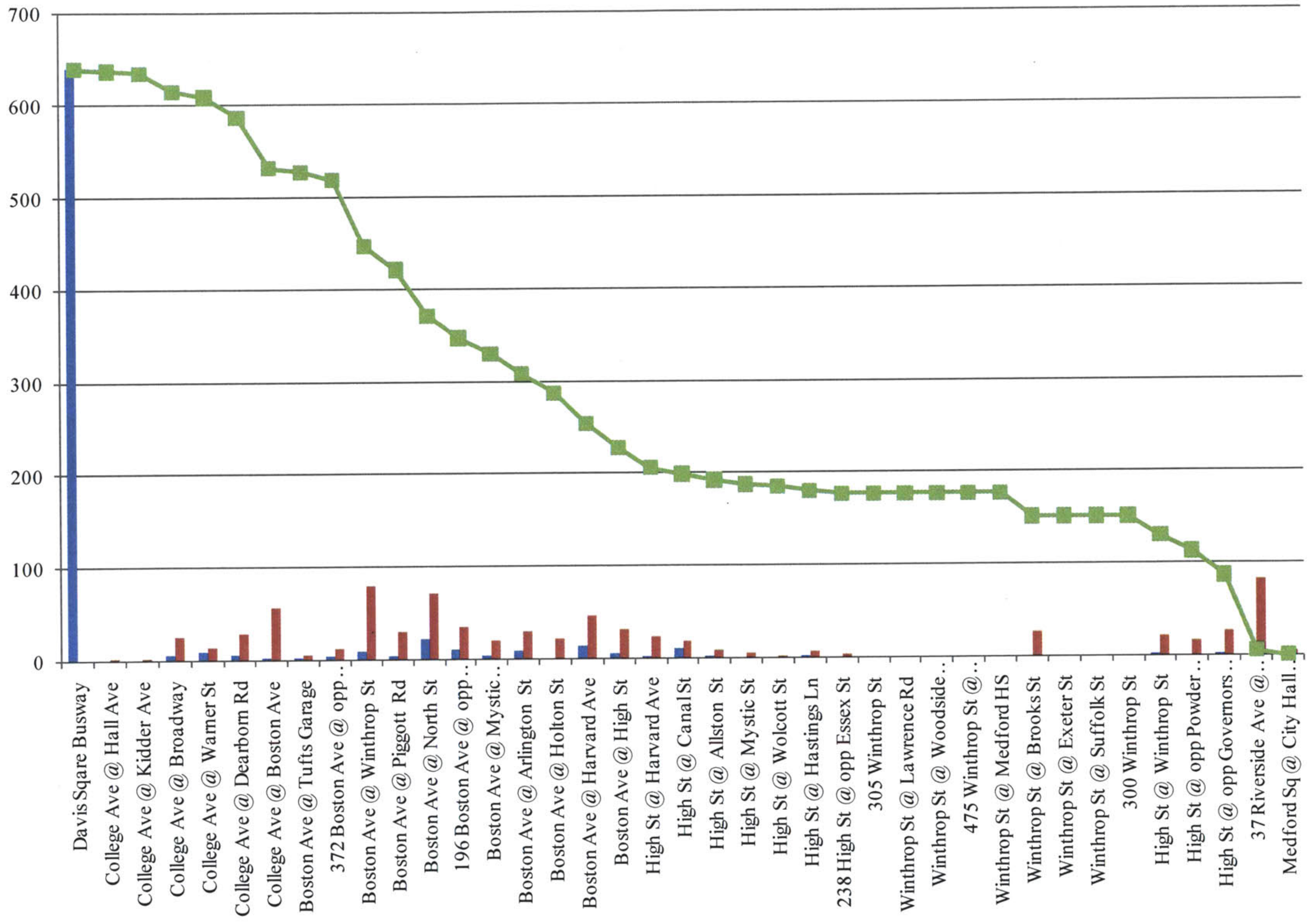
Appendix A. Route 92 Outbound--Ons, Offs, and Load



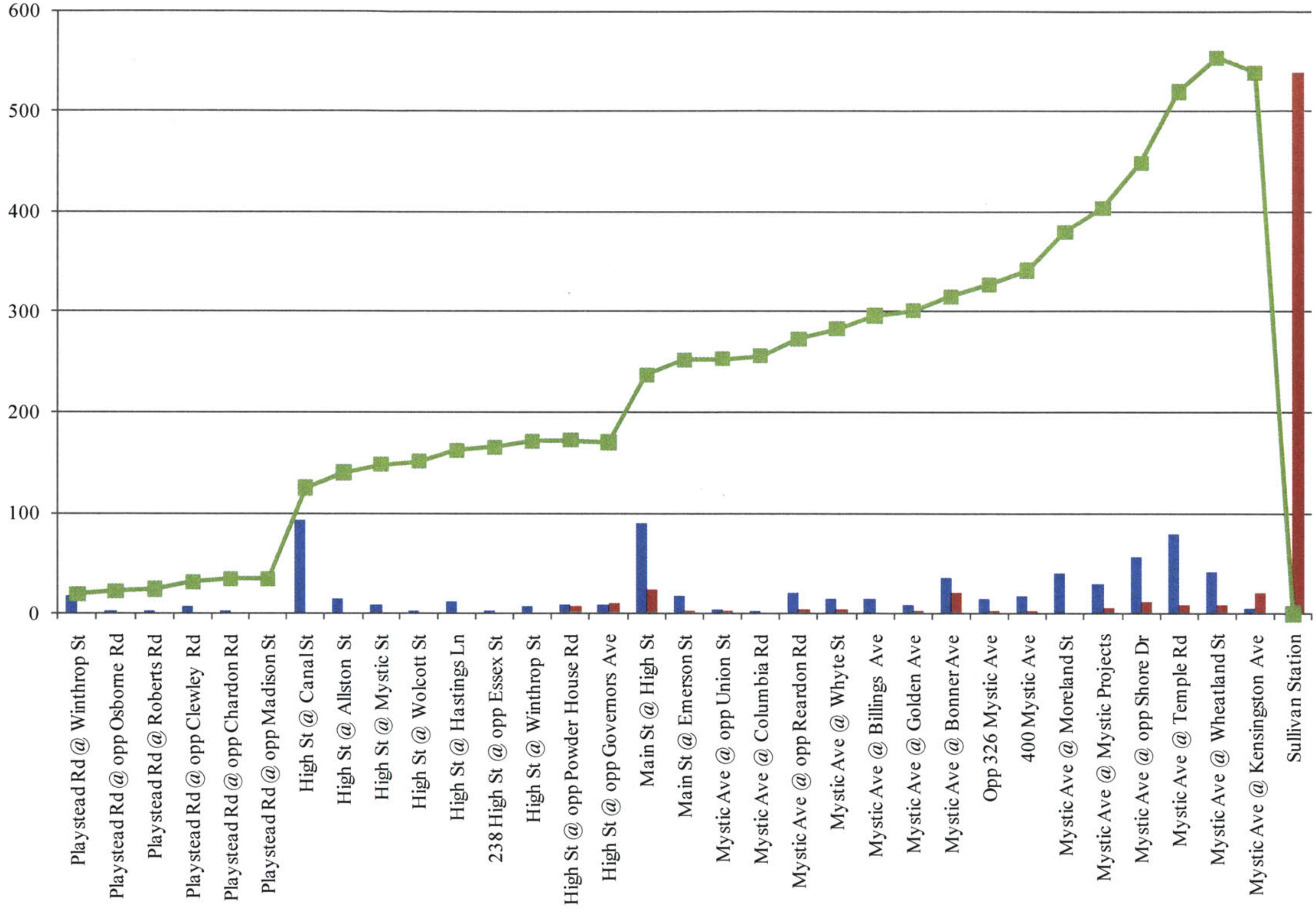
Appendix A. Route 94 Inbound--Ons, Offs, and Load



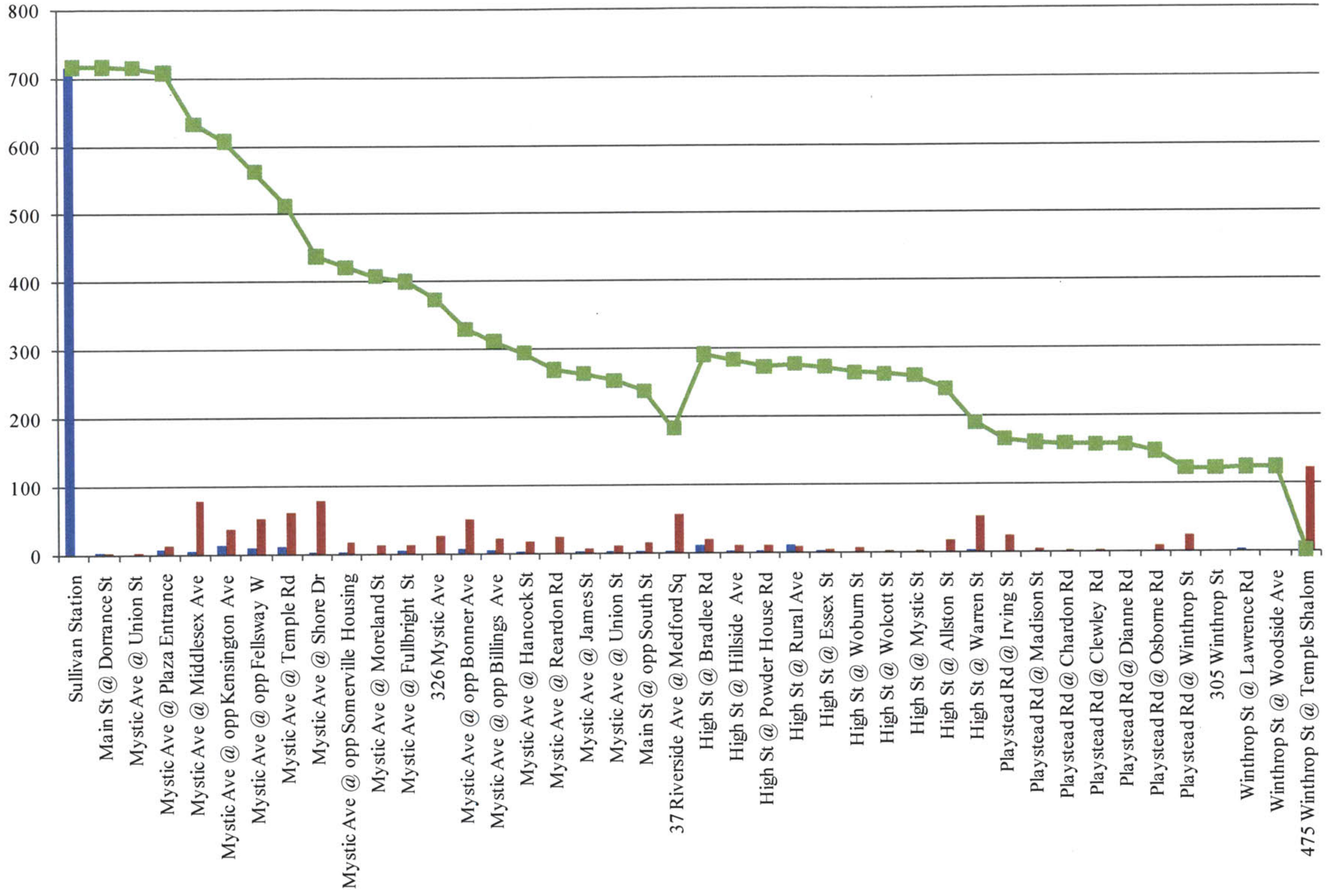
Appendix A. Route 94 Outbound--Ons, Offs, and Load



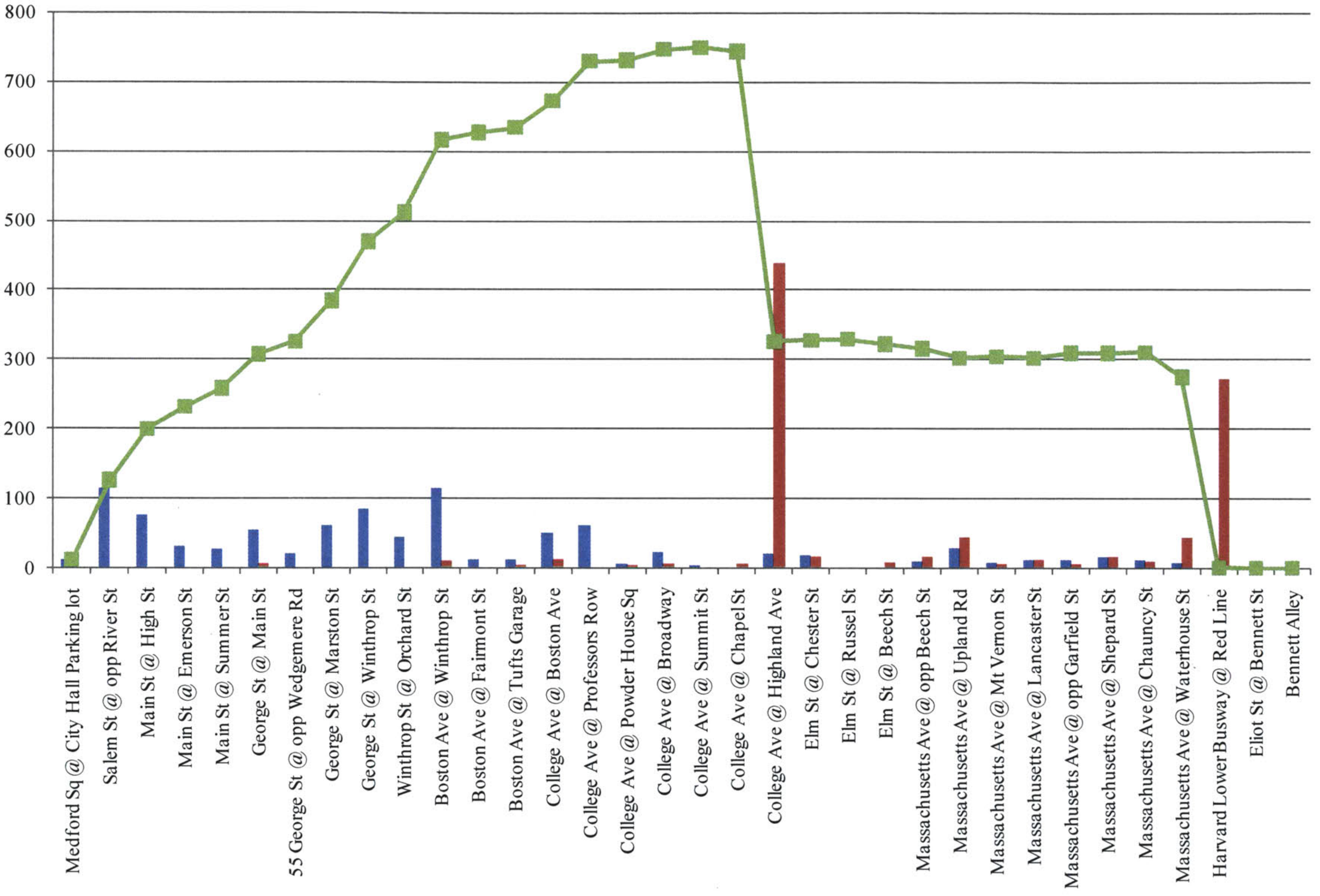
Appendix A. Route 95 Inbound--Ons, Offs, and Load



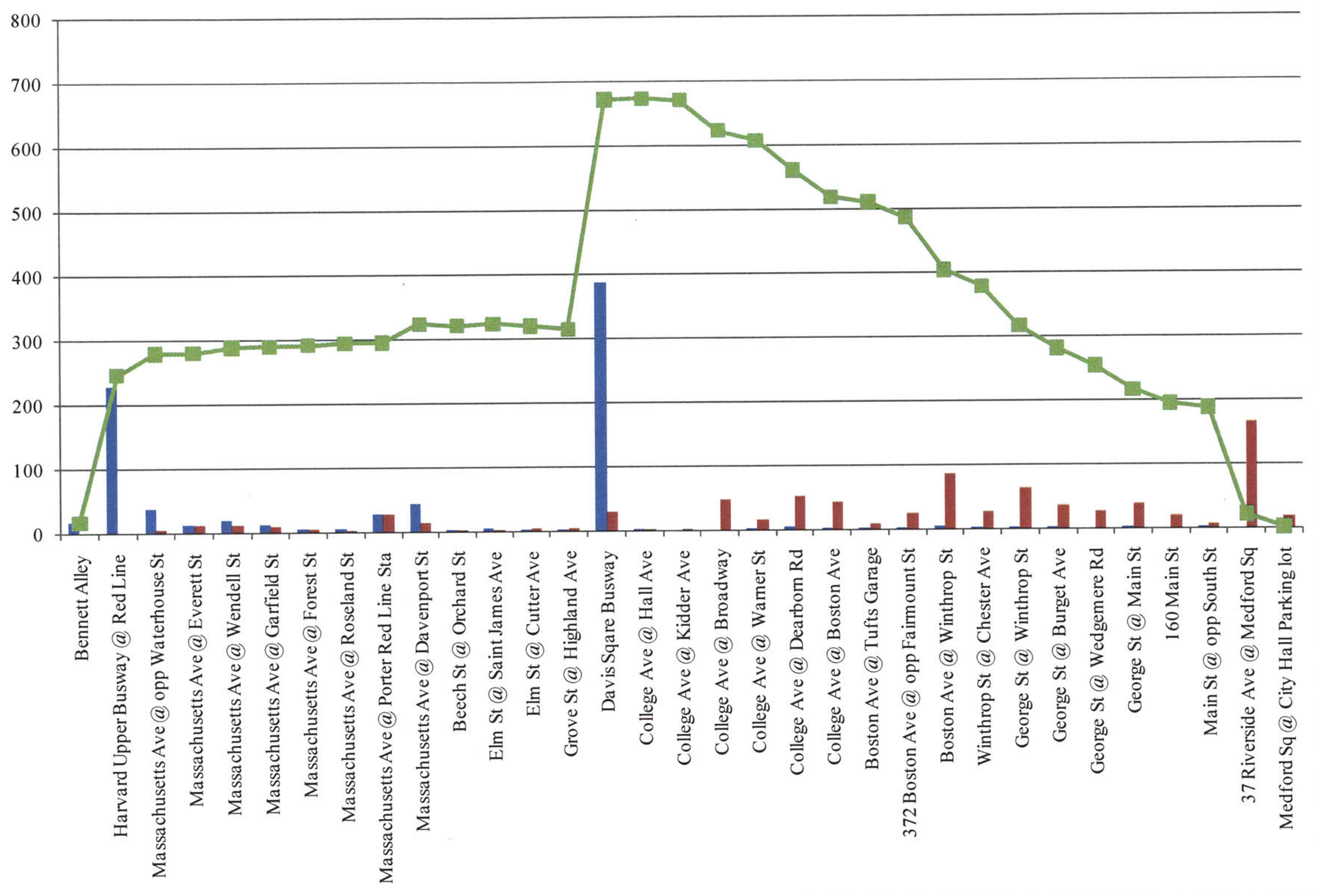
Appendix A. Route 95 Outbound--Ons, Offs, and Load



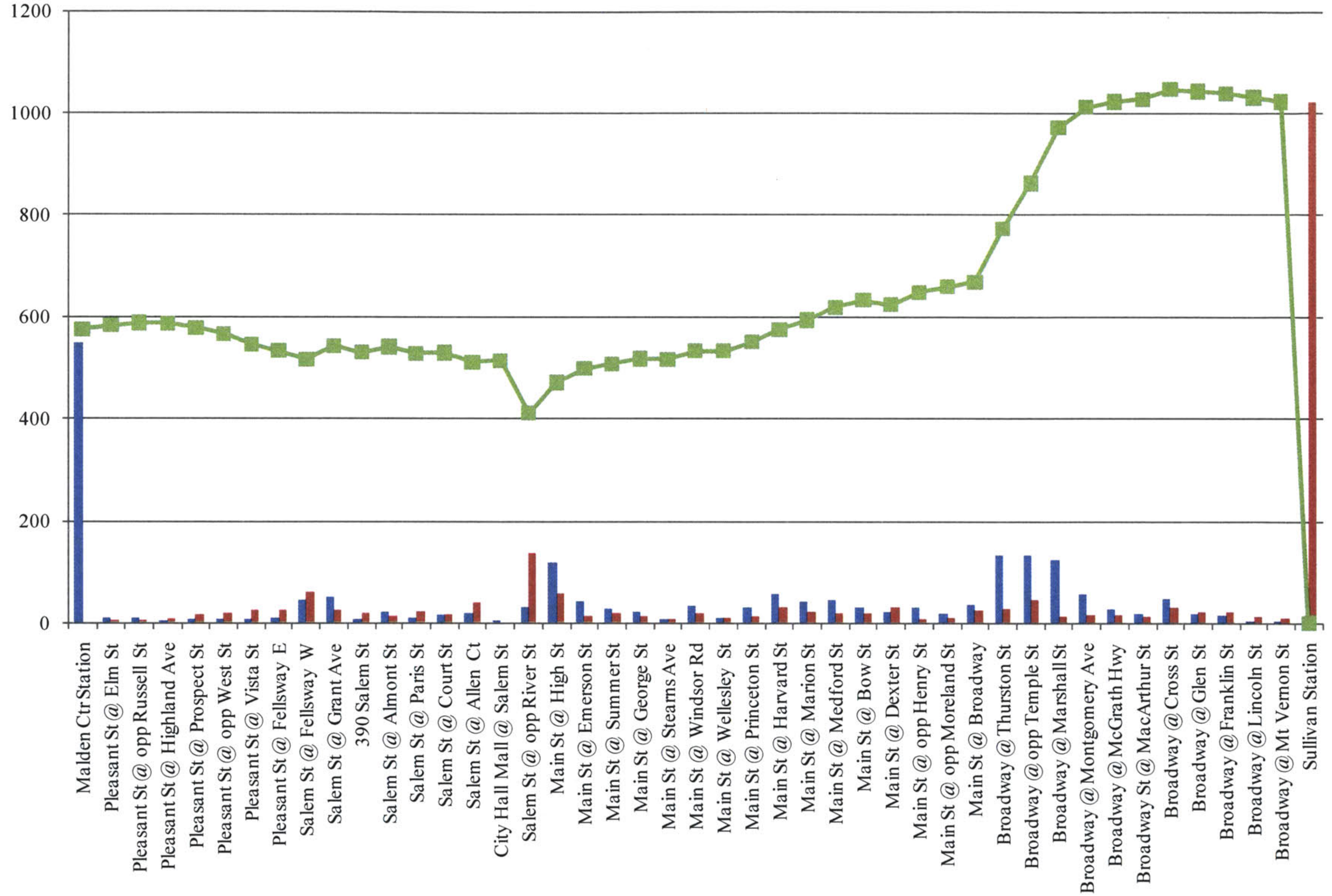
Appendix A. Route 96 Inbound--Ons, Offs, and Load



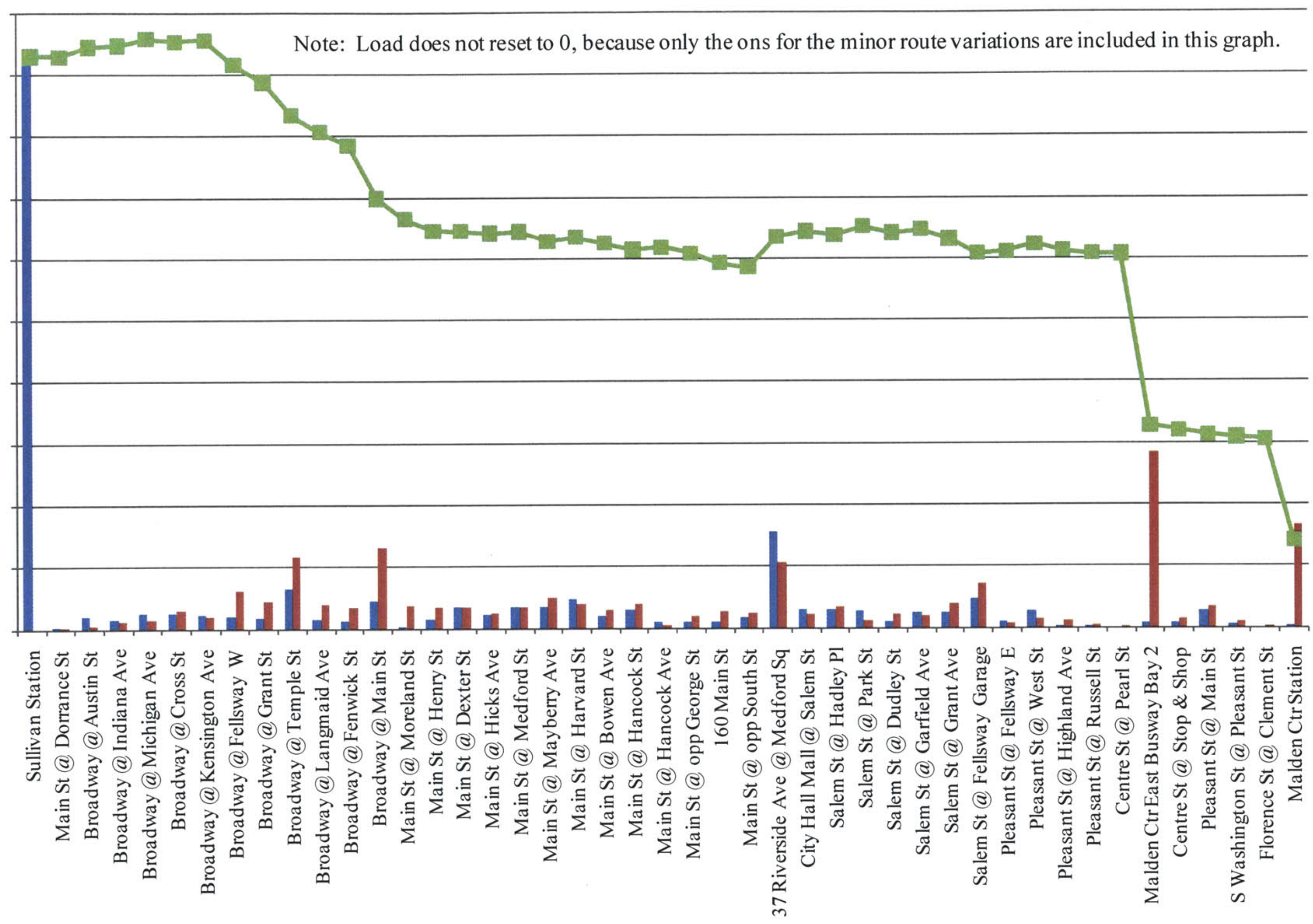
Appendix A. Route 96 Outbound--Ons, Offs, and Load



Appendix A. Route 101 Inbound--Ons, Offs, and Load

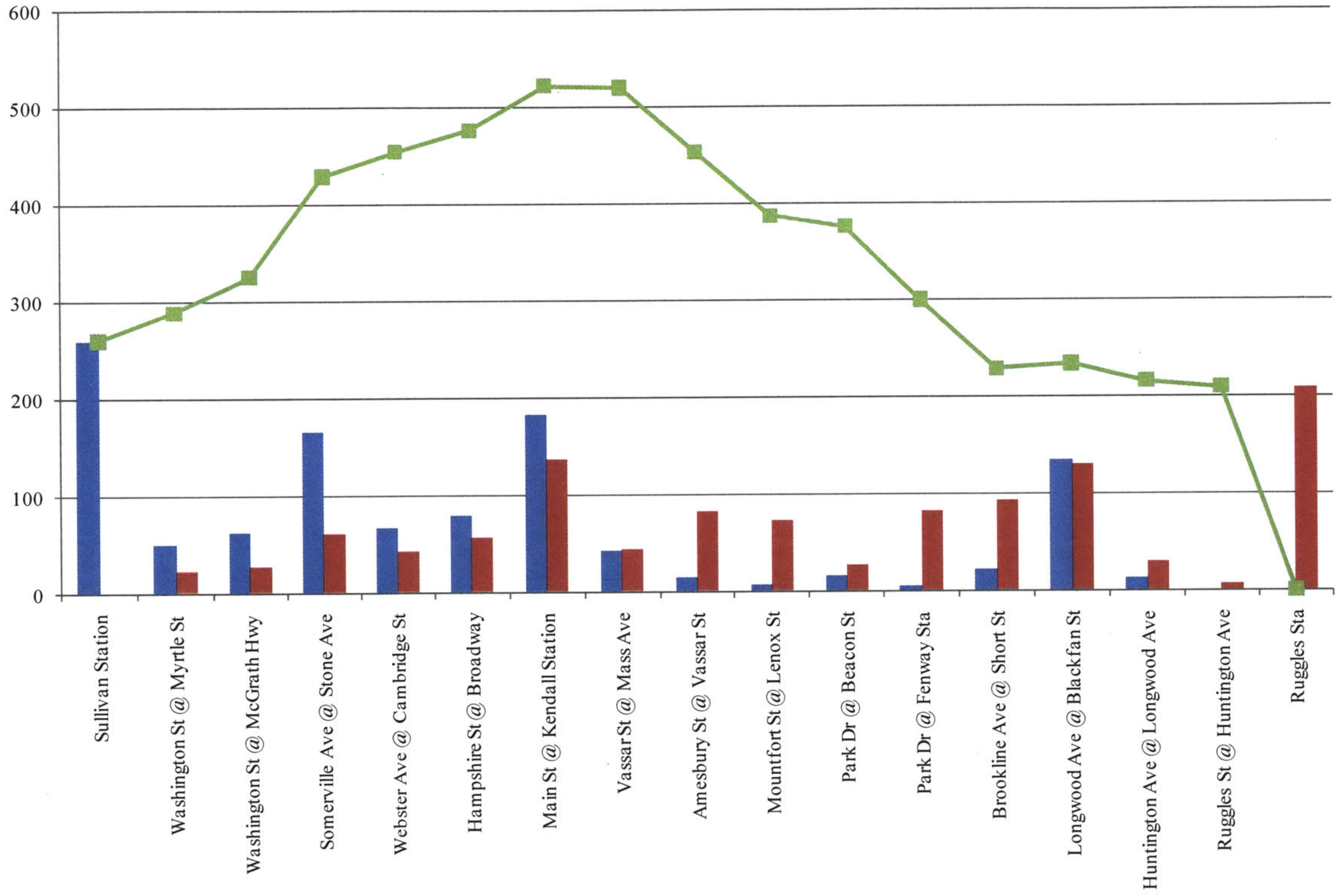


Appendix A. Route 101 Outbound--Ons, Offs, and Load

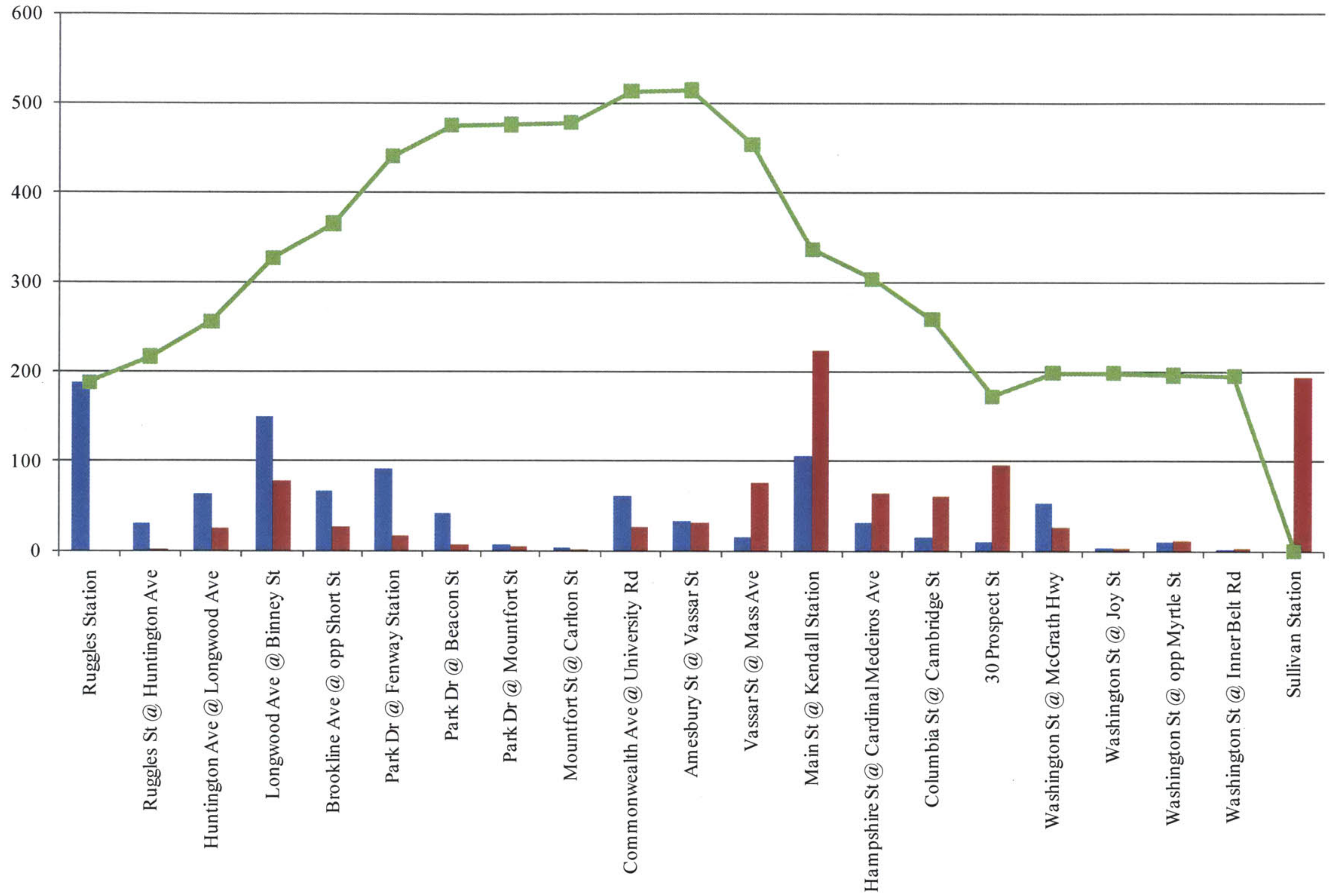


Note: Load does not reset to 0, because only the ons for the minor route variations are included in this graph.

Appendix A. Route CT2 Inbound--Ons, Offs, and Load

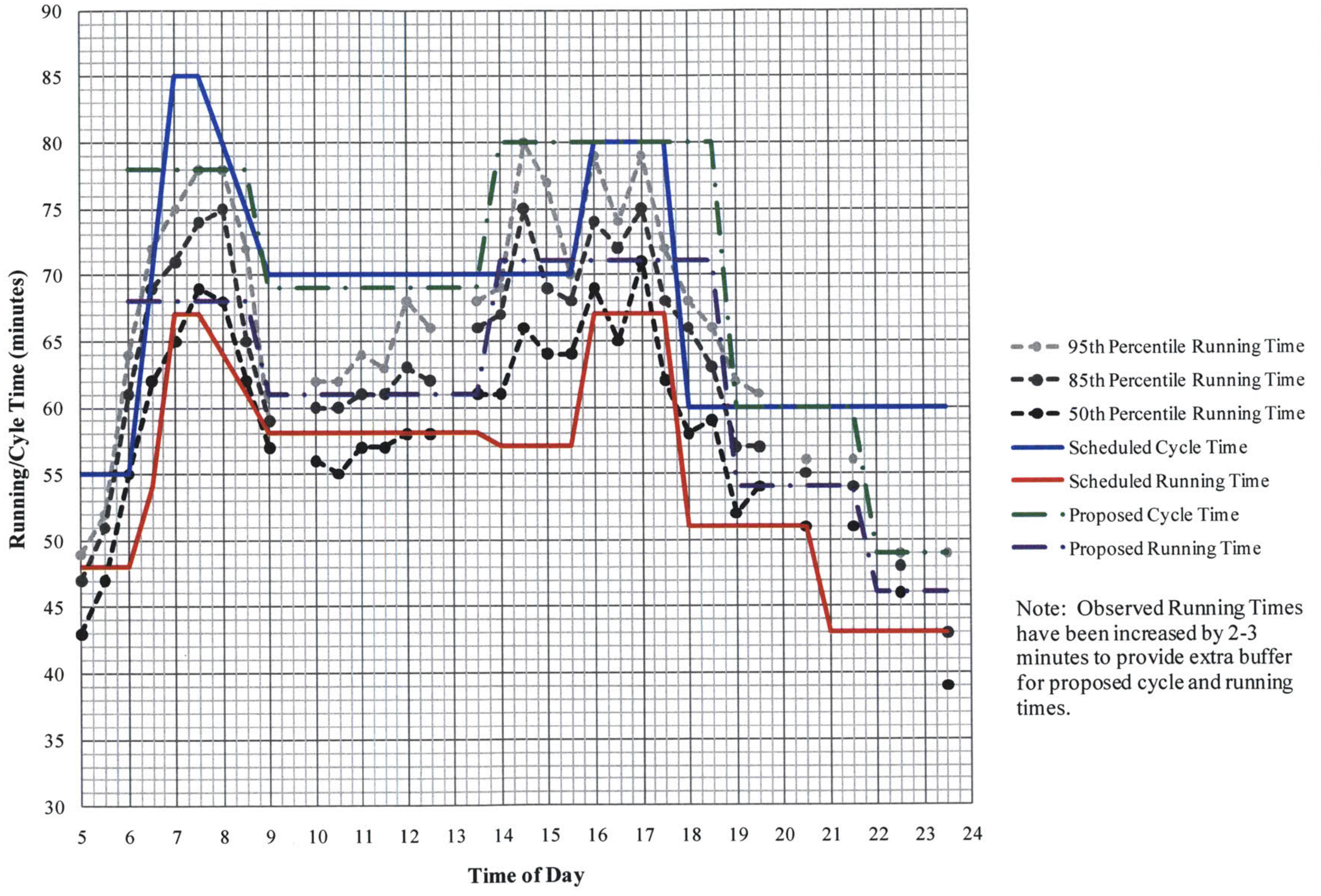


Appendix A. Route CT2 Outbound--Ons, Offs, and Load



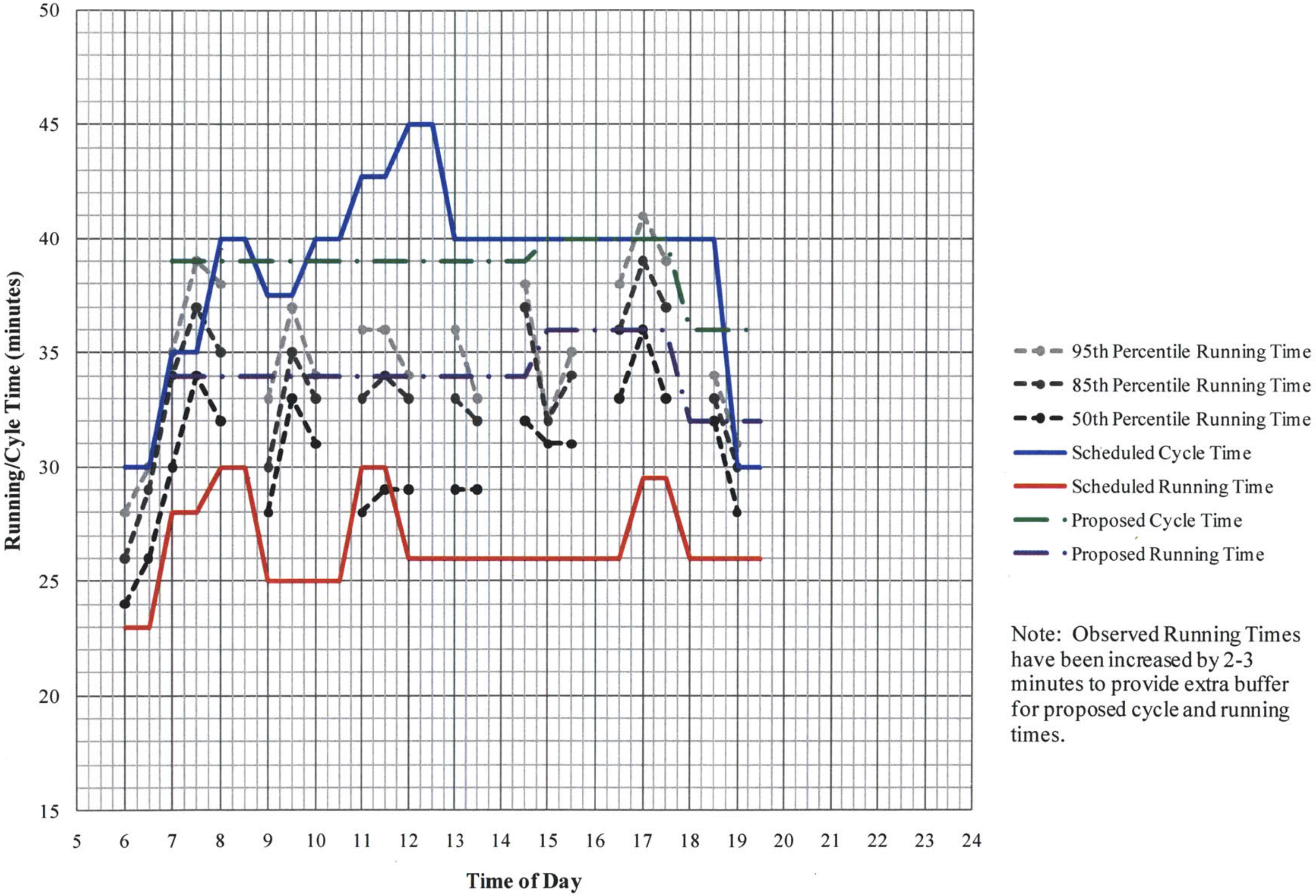
Appendix B. Running Time Analysis

Appendix B. Running Time Analysis--Route 80



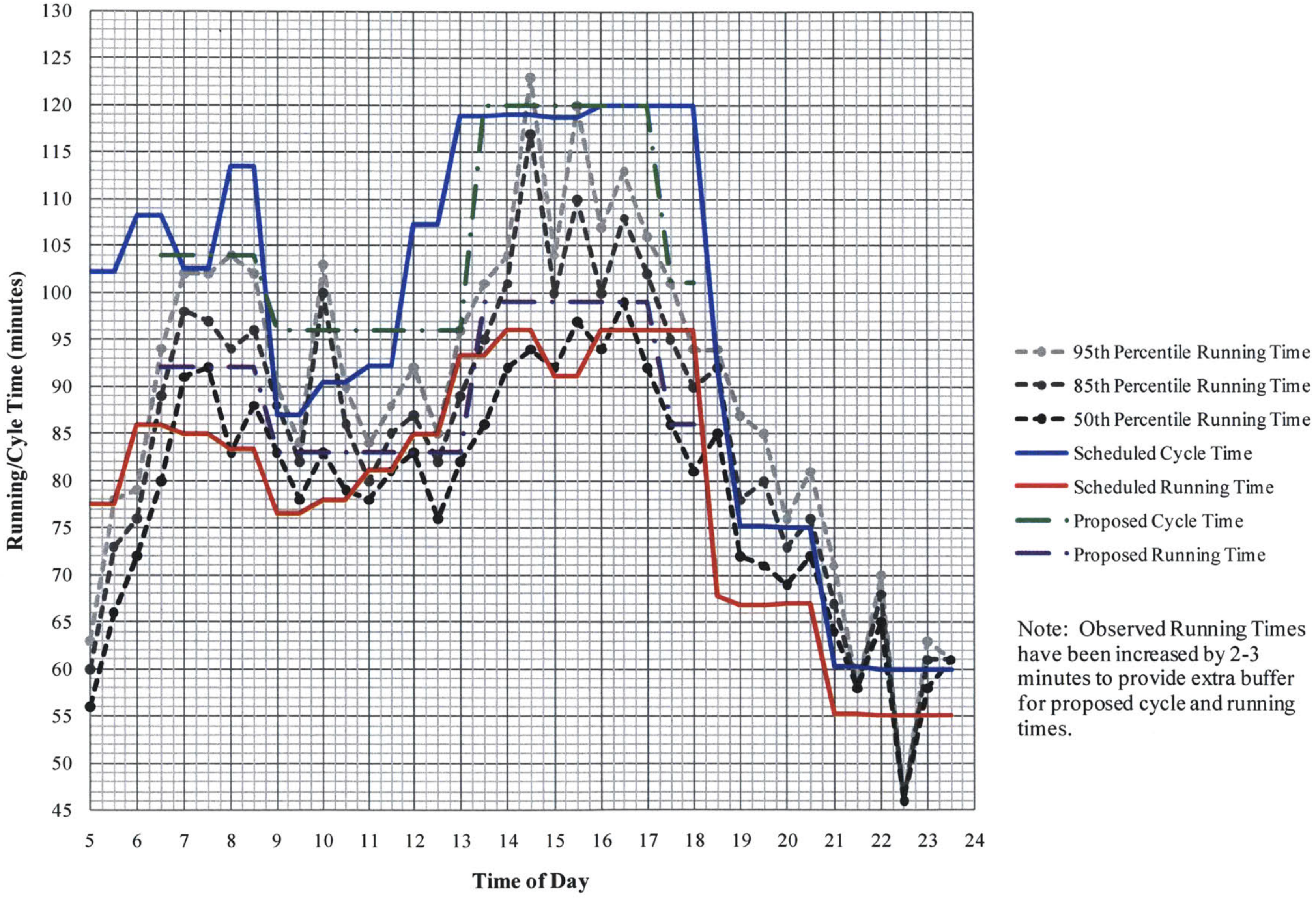
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 85



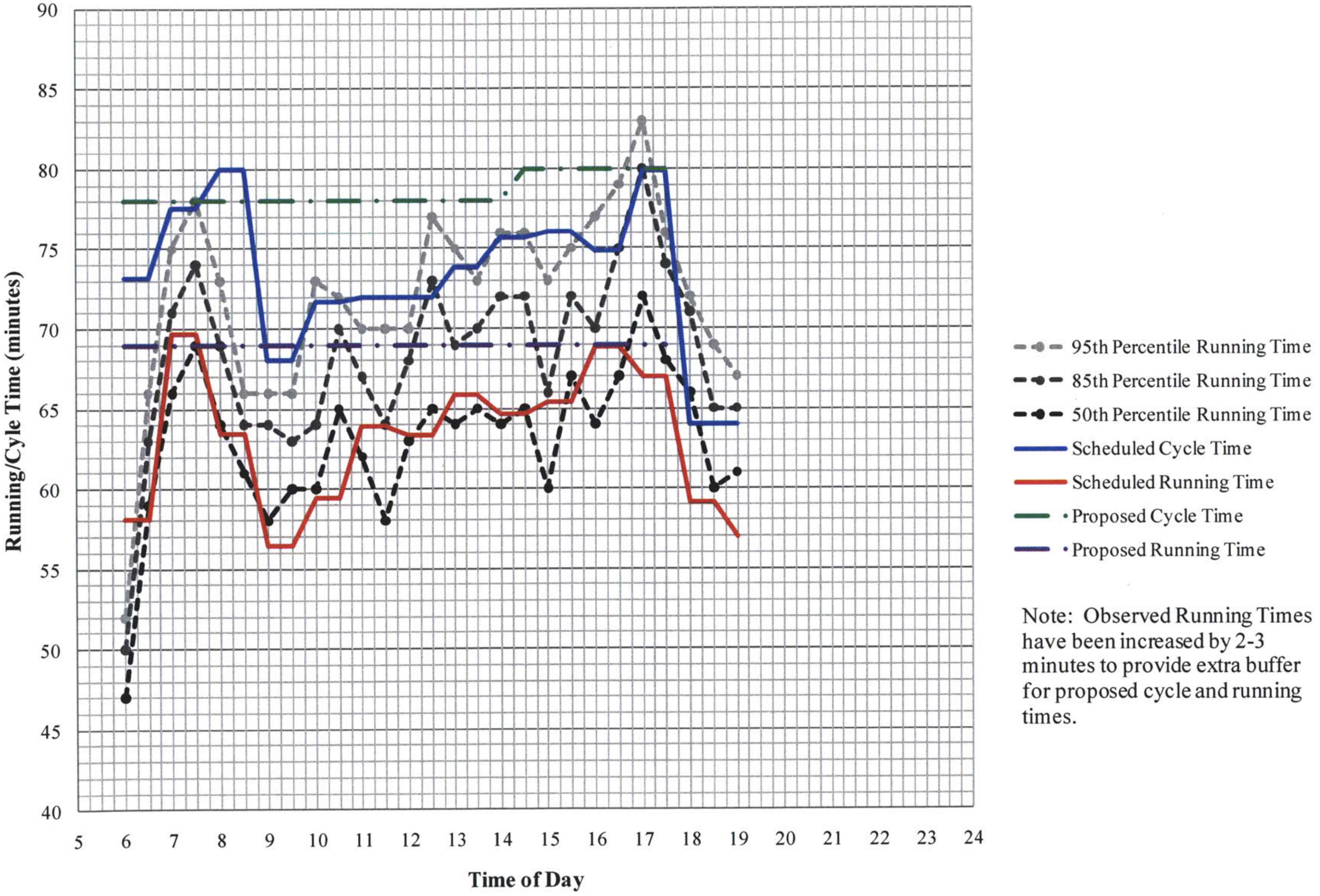
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 86



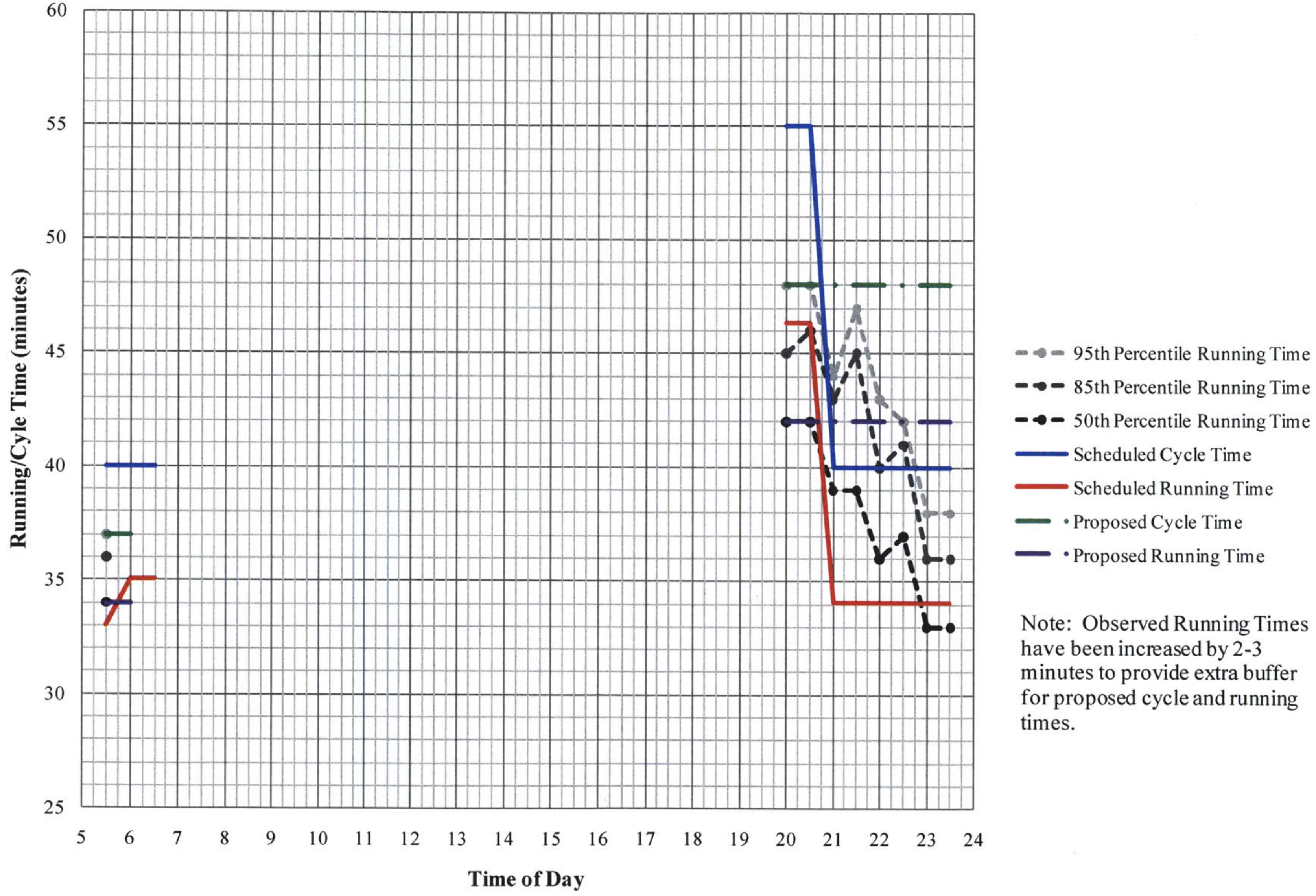
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 87 (Arlington Ctr.)



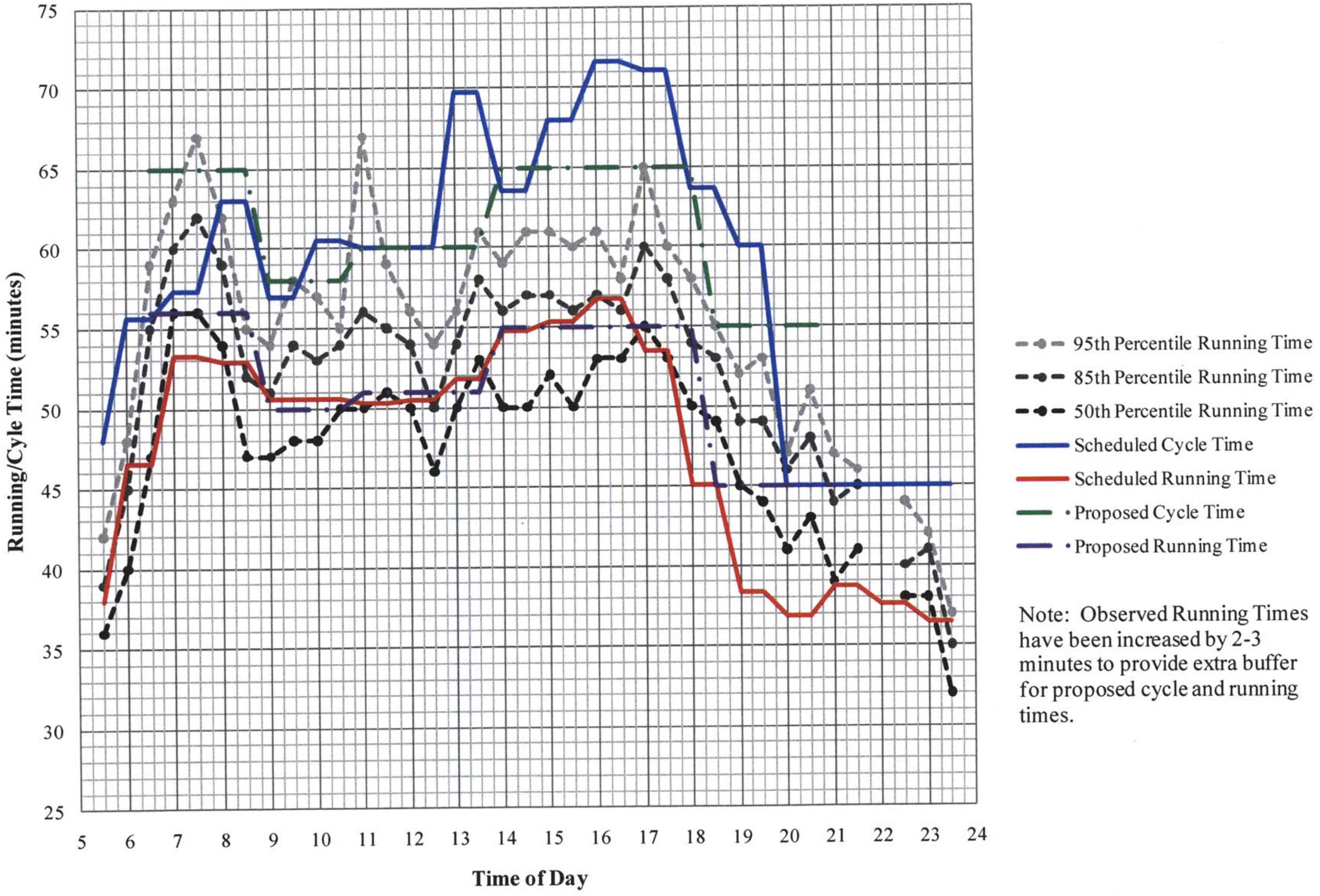
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 87 (Clarendon Hill)



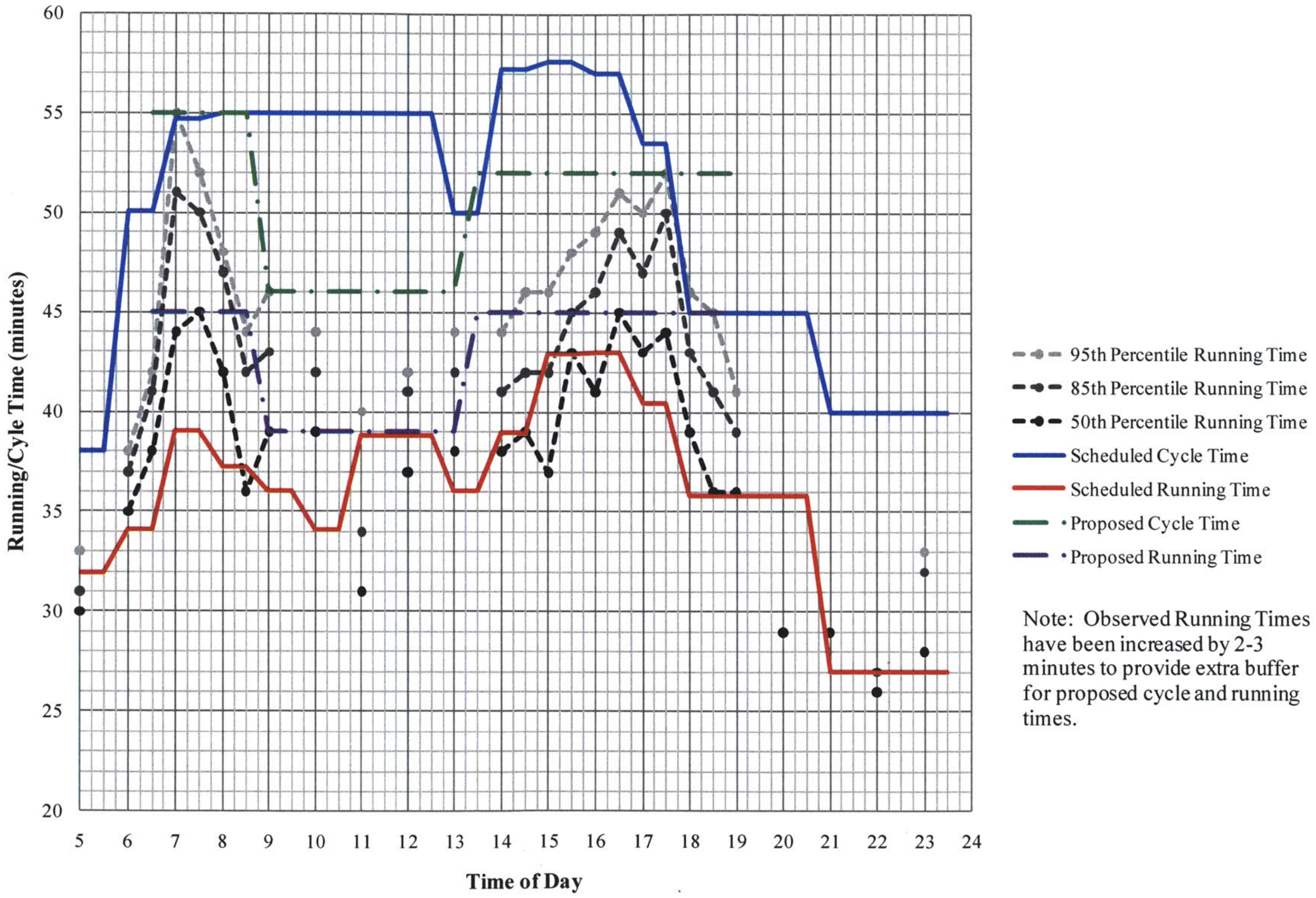
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 88



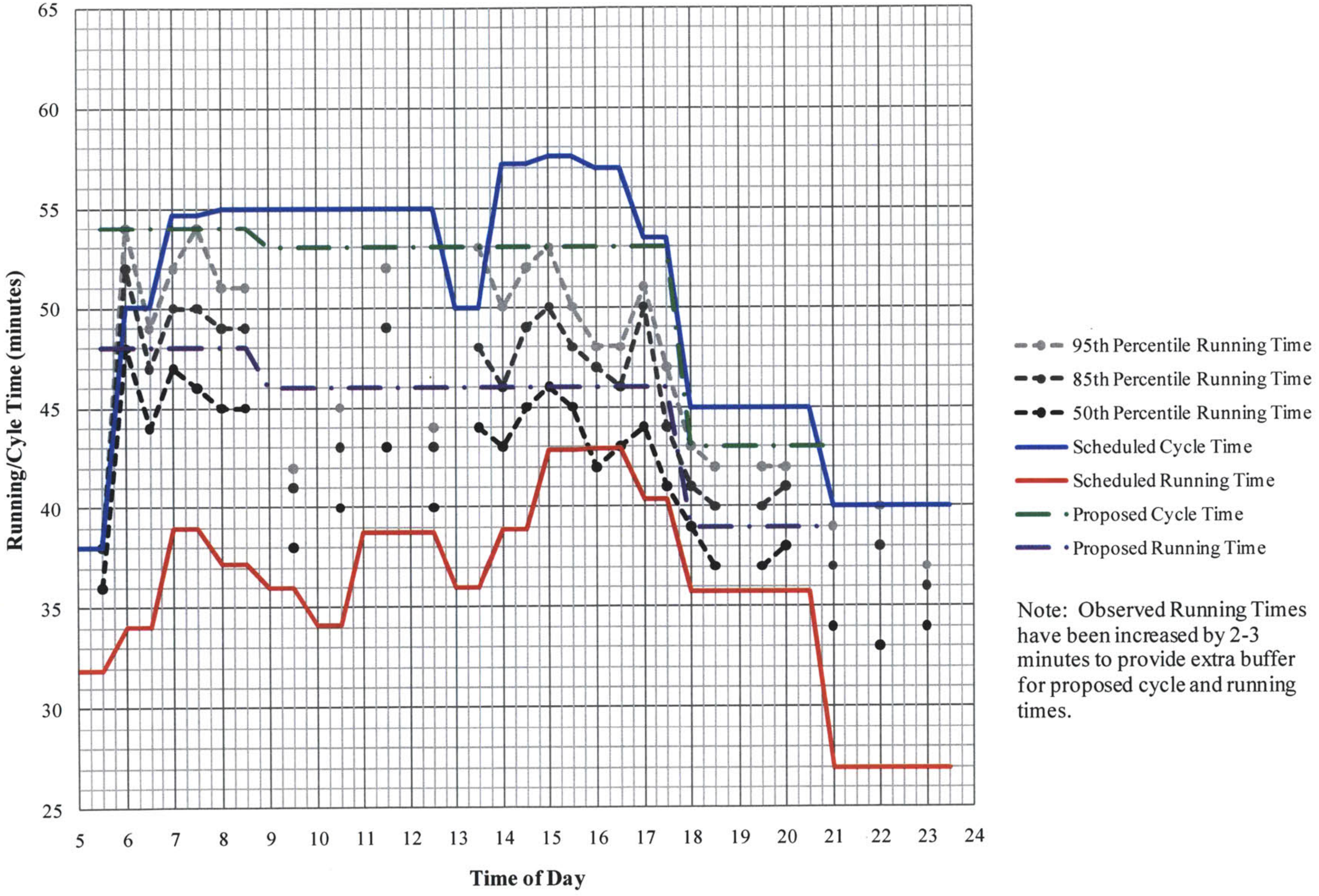
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 89 (Clarendon Hill)



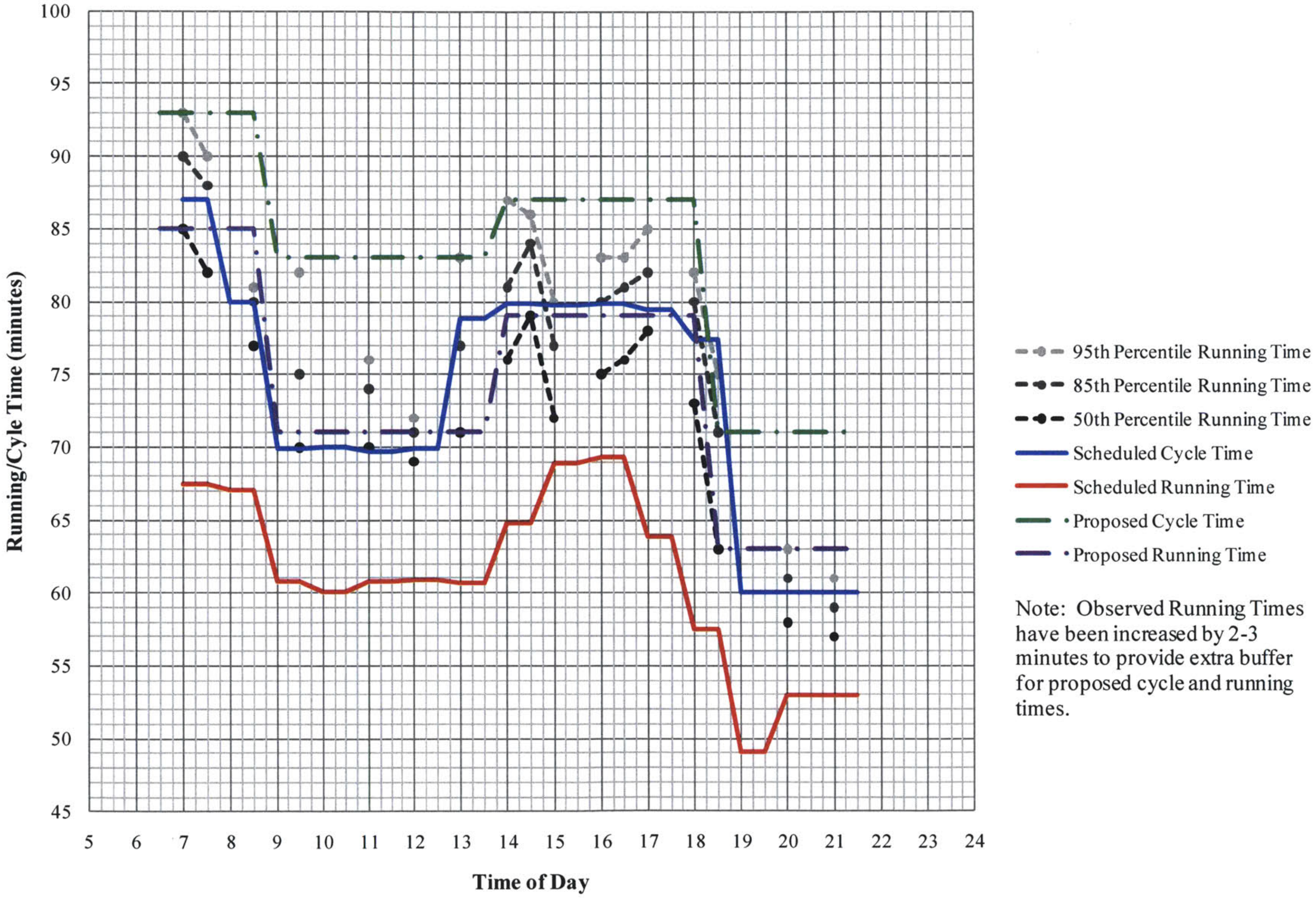
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 89 (Davis Sq.)



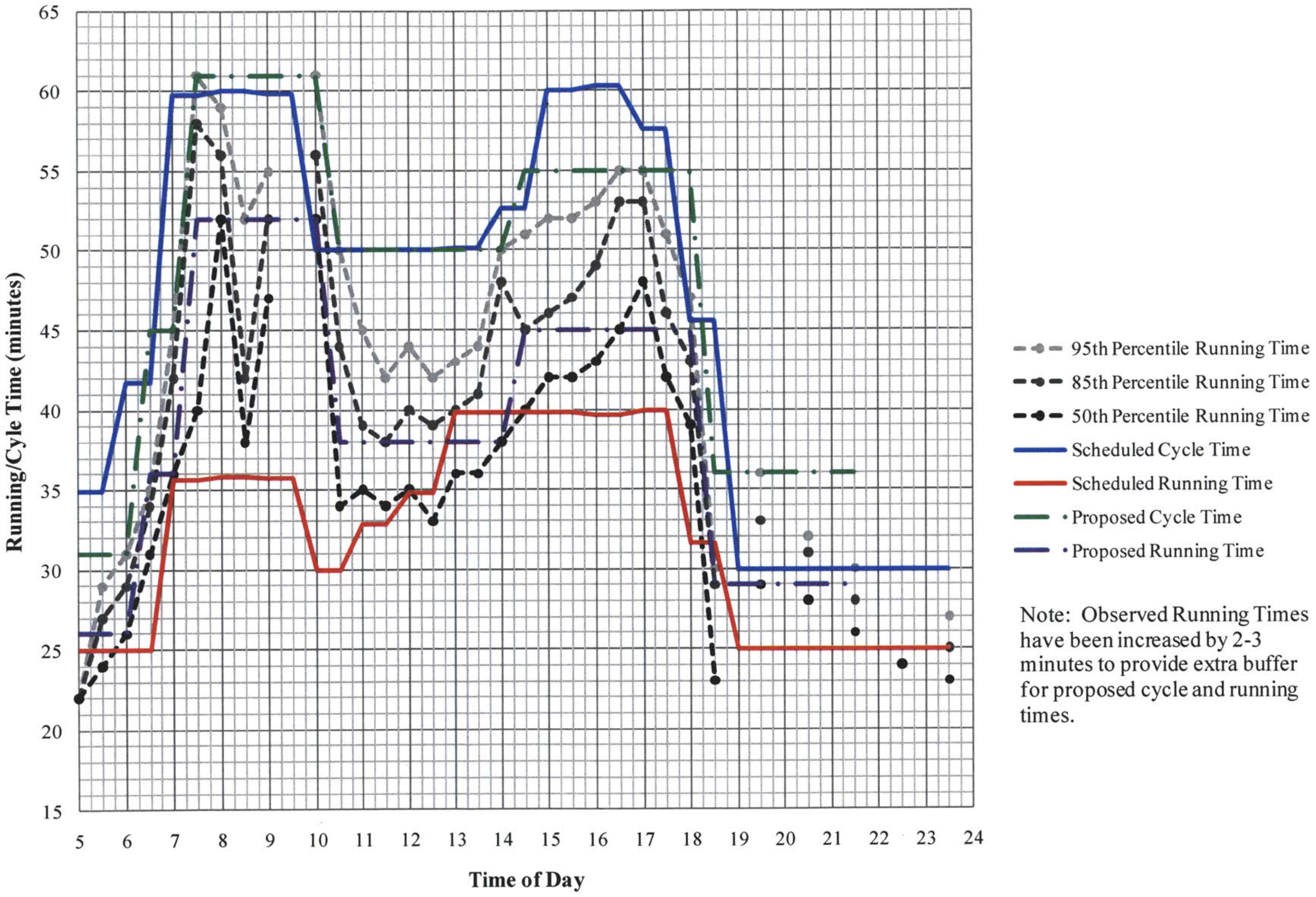
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 90



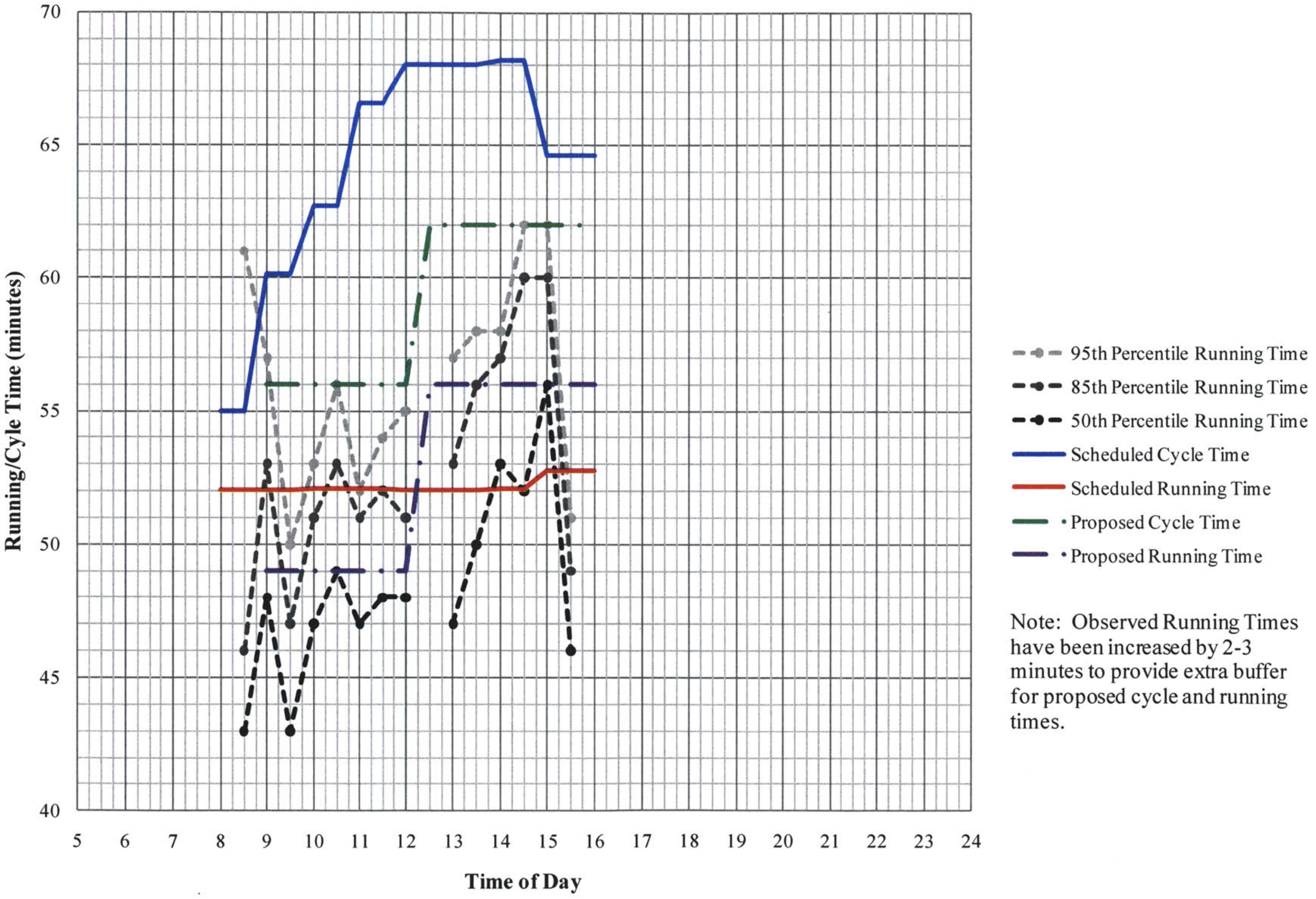
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 91



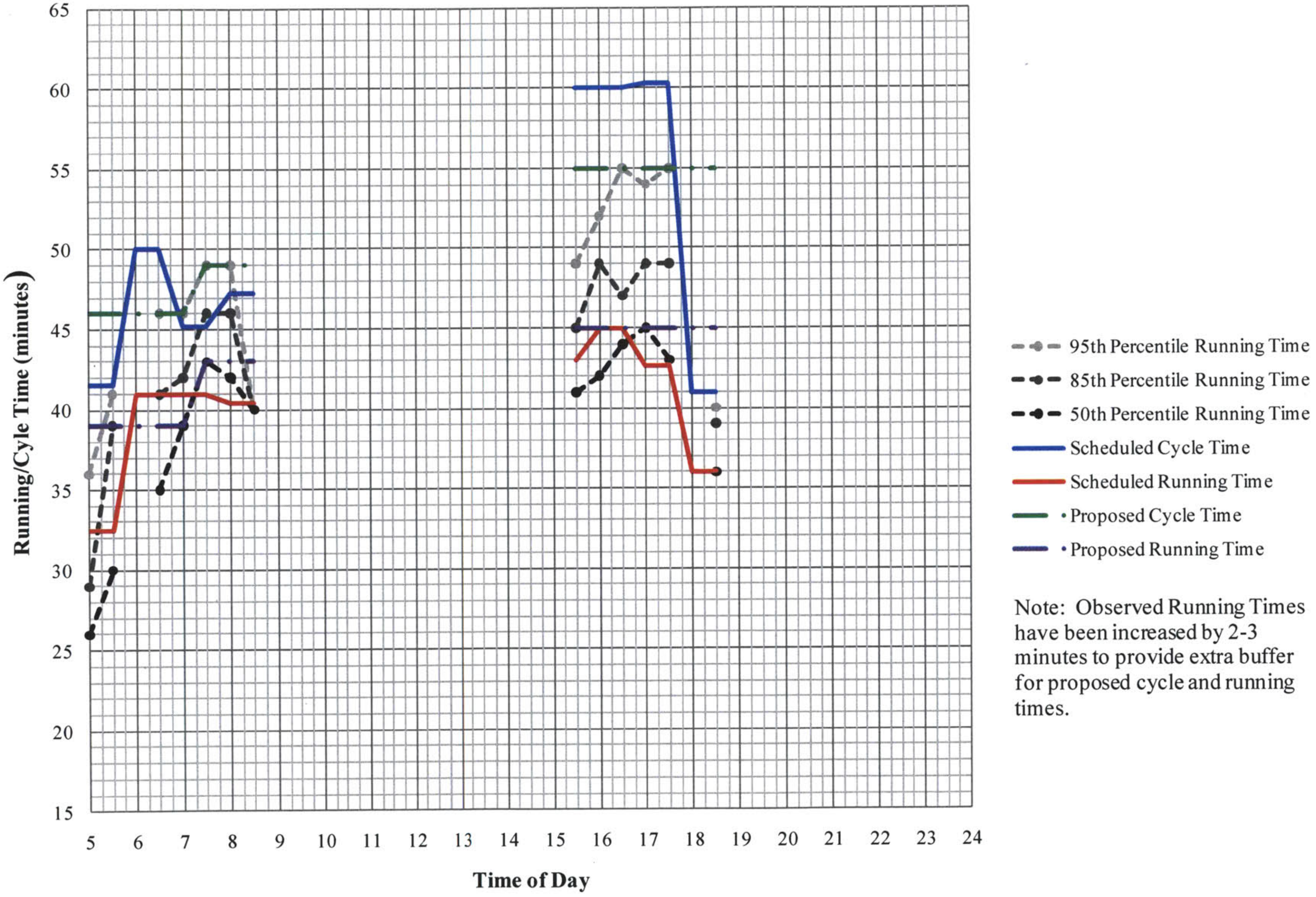
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 92 (Assembly Sq.)



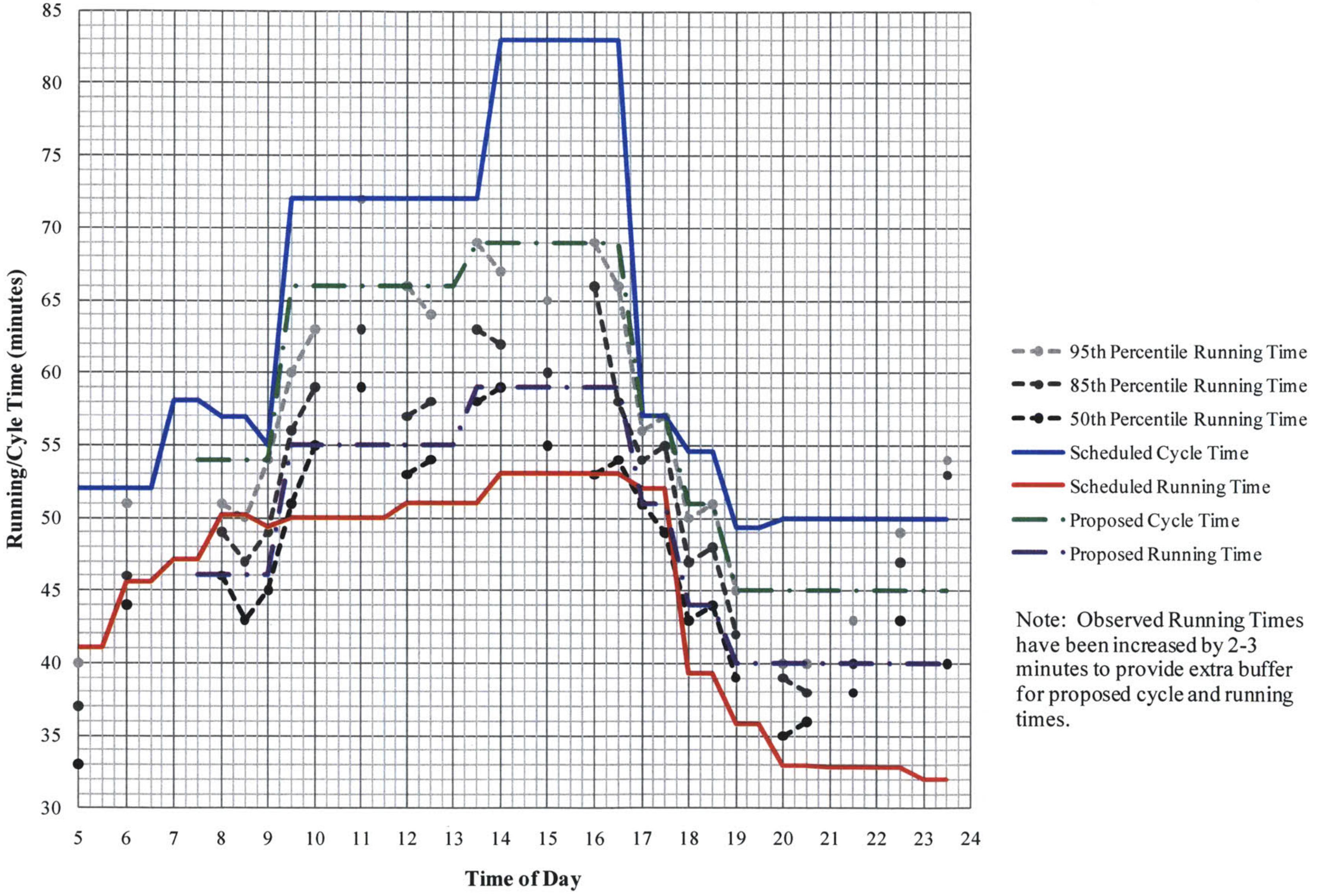
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 92 (Sullivan Sq.)



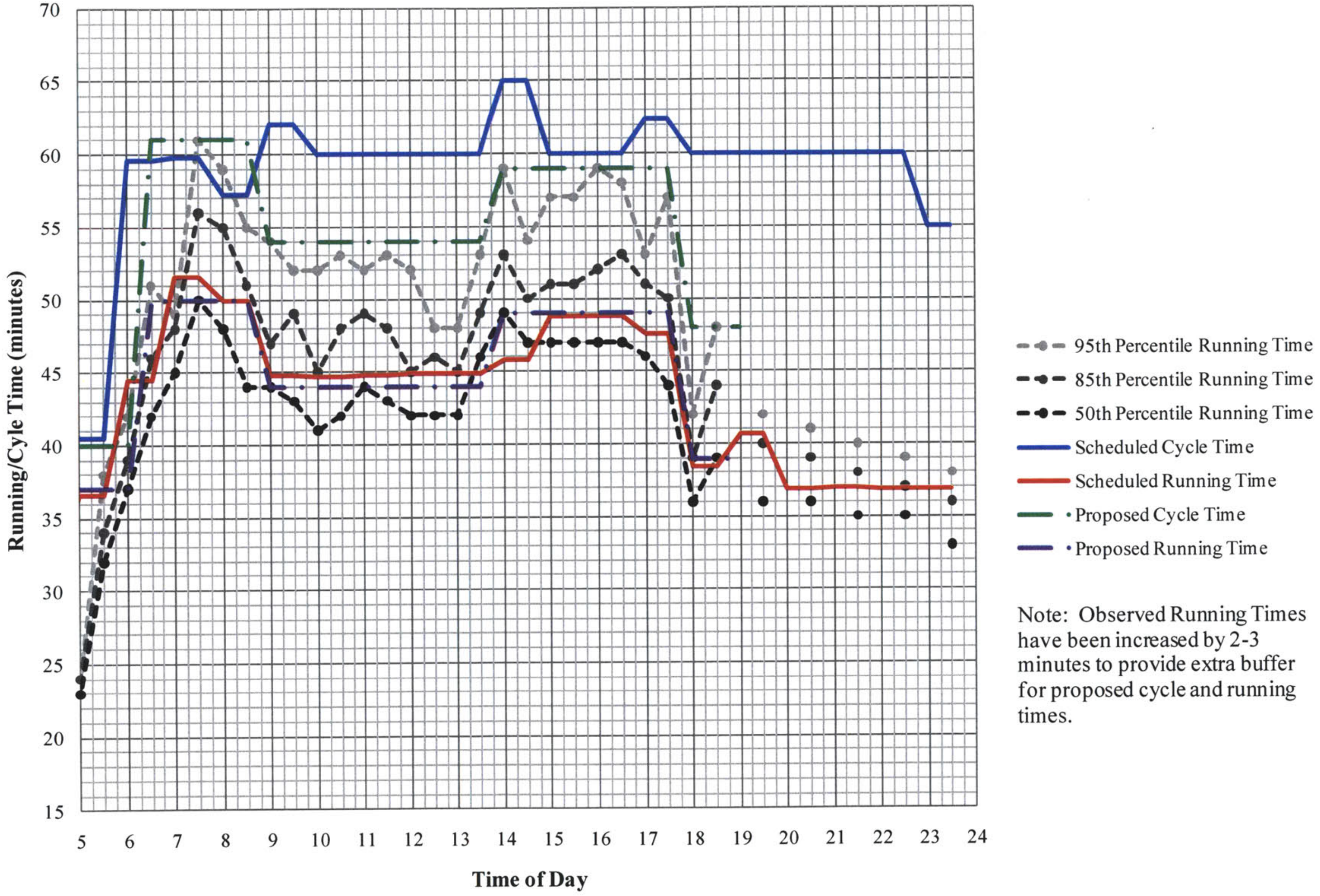
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 94



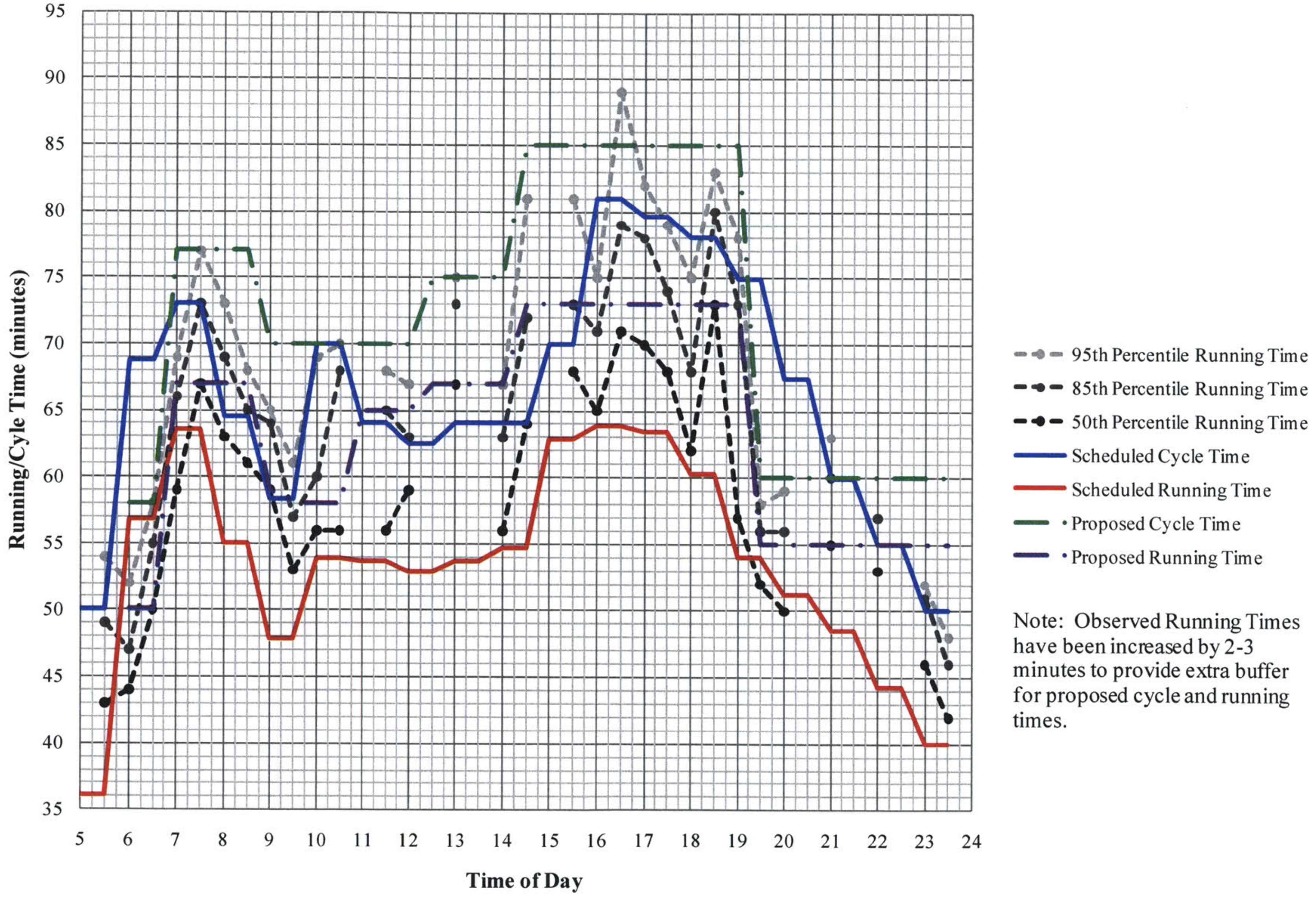
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 95



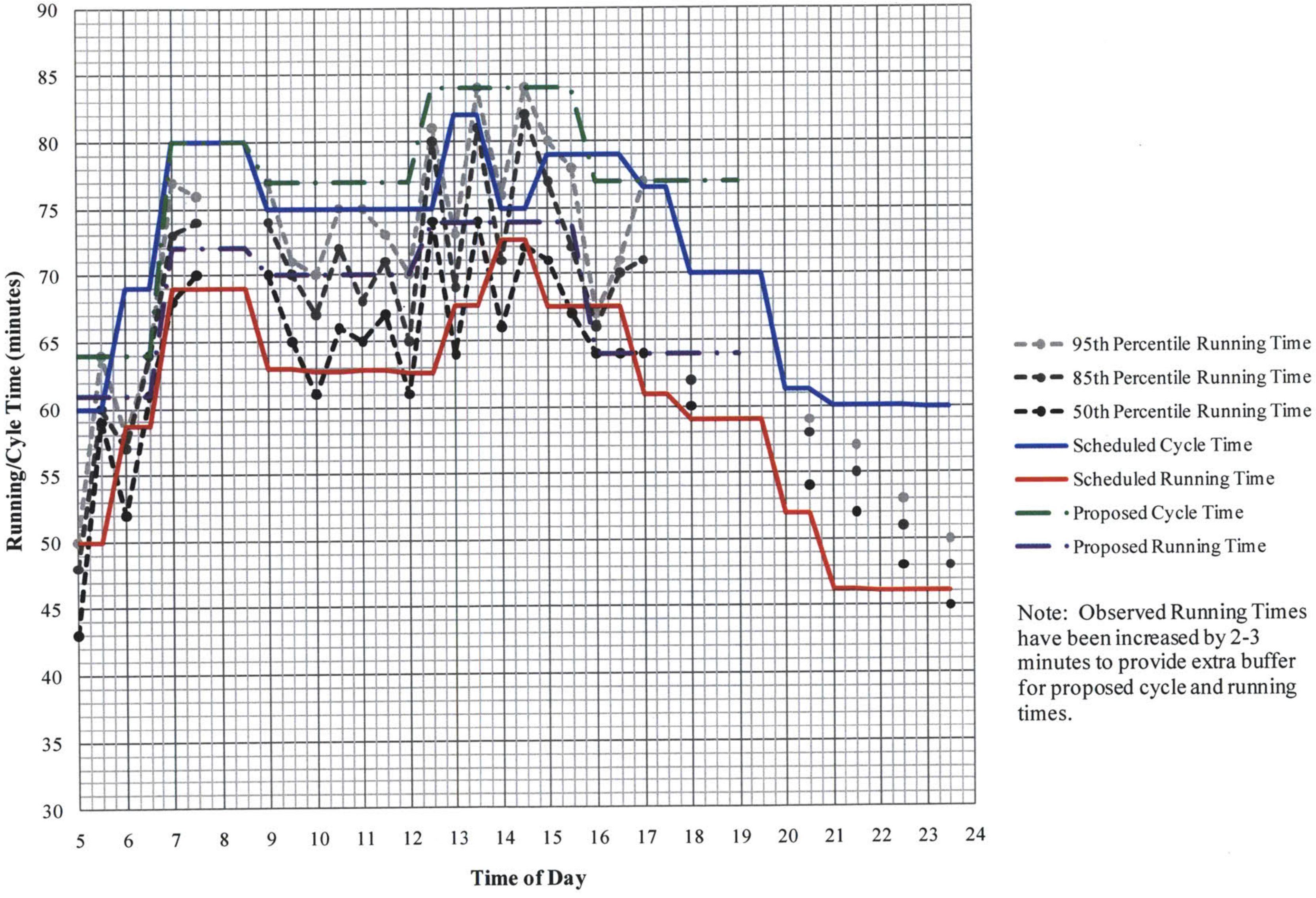
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 96



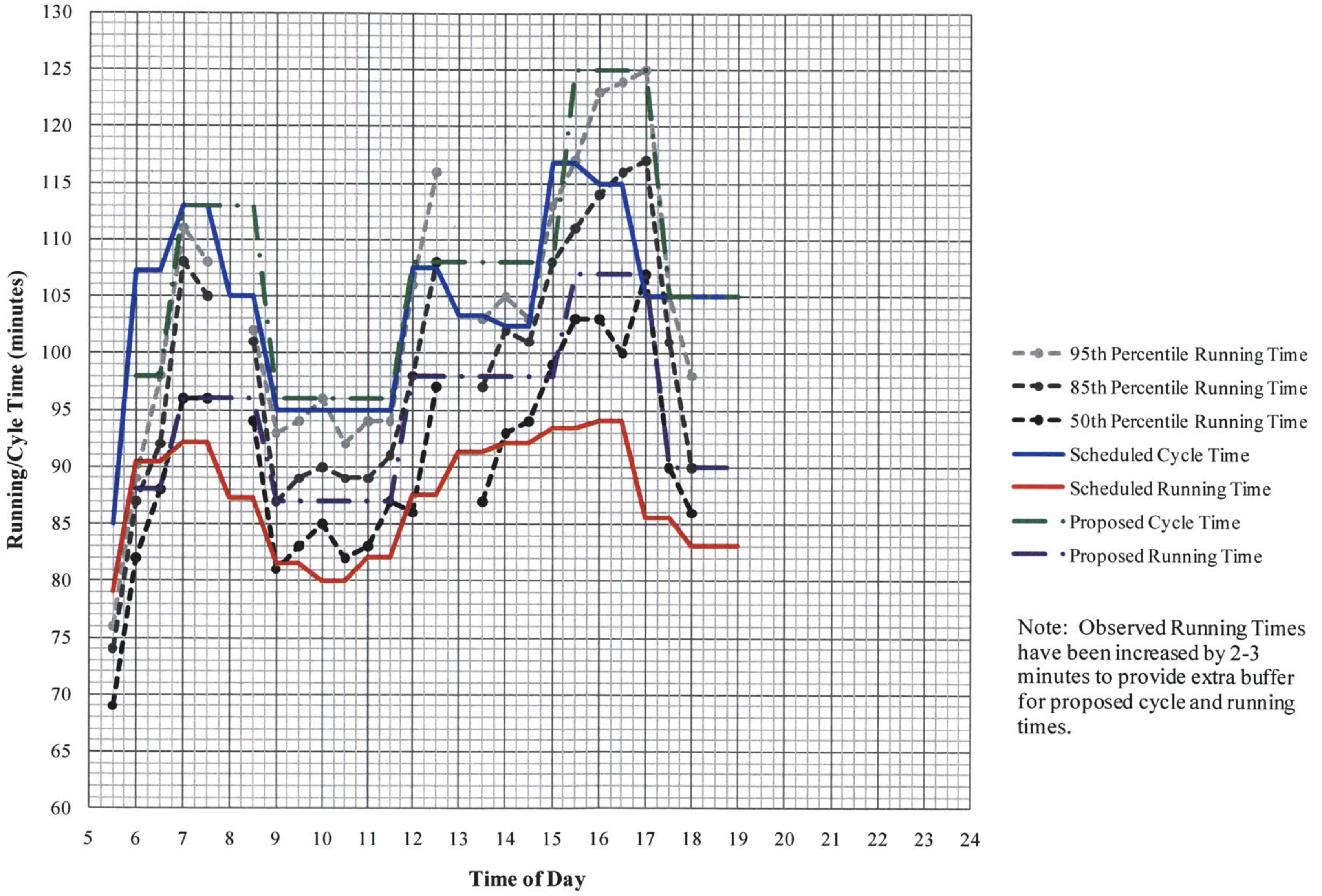
Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route 101



Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix B. Running Time Analysis--Route CT2



Note: Observed Running Times have been increased by 2-3 minutes to provide extra buffer for proposed cycle and running times.

Appendix C. Somerville Community Bus Survey

The Somerville Transportation Equity Partnership (STEP) is a community organization of Somerville residents who advocate for improved multi-modal transportation options. STEP conducted a bus passenger survey from July to October 2006 covering of routes in this study except for Route 83. The survey was handed out to passengers waiting at bus stops as well as to those attending community events. In addition, the survey was translated into Spanish, Portuguese, and French and made available on-line with links listed on websites and e-mails. A total of 245 people (90 percent of whom are Somerville residents) completed the survey (STEP, 2006).

The survey found that 38 percent of people surveyed did not own a car, although the survey did not ask about access to a car, so the actual proportion of transit dependants is likely lower than this. Half of the respondents stated that bus is their primary mode of transportation, although transfers were quite common with 69 percent of bus riders typically transferring to other modes, including rail. Only 16 percent of those surveyed rode the bus less than once a month, whereas 50 percent rode the bus every weekday. Another 31 percent rode the bus one to three times a week. The most common trip purposes for the Somerville routes are shown in Table C-1. Commuting was the most common trip purpose with 75 percent of respondents.

Purpose	% Respondents
Commuting	75
Recreation	48
Shopping	44
Appointments	43
Visiting Family & Friends	36

Note: Respondents allowed to select multiple purposes.

Table C-1. Trip Purposes for Somerville Bus Routes (STEP, 2006)

The survey also asked about satisfaction with different attributes of the bus service; the results are shown in Table C-2. The frequency of service was reported as the biggest issue with 53 percent of respondents saying that they were dissatisfied or very dissatisfied. People are generally satisfied with the location of bus stops as 61 percent of responses were satisfactory or very satisfactory.

Component of Bus Service	% Respondents				
	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
Frequency of Service	25	28	28	17	2
Cleanliness of Buses	10	17	38	32	3
Location of Bus Stops	4	9	26	42	19
Routing	8	20	31	31	10

Table C-2. Quality of Somerville Bus Service (STEP, 2006)

The survey asked the 37 people who rode buses less than once a month why they did not use Somerville buses. The responses to this question are shown in Table C-3. The most common reason, which was chosen by 51 percent of the respondents, was unreliable buses. Bus routes not serving trip destination was the second most common response with 45 percent respondents.

Reason for not using Somerville bus service	% Respondents
Unreliable service	51
Bus routes do not serve destination	45
Prefer to drive	29
Buses don't run when I need to travel	27
Prefer to walk or bike	27
Ride buses elsewhere but not in Somerville	21
Bus stops are located too far away	5
Buses are too expensive	5

Note: Respondents allowed to select multiple reasons.

Table C-3. Reasons Residents do not use Somerville Bus Service (STEP, 2006)

Appendix D. MBTA/CTPS Rider Survey Origin-Destination Matrix

The Central Transportation Planning Staff (CTPS) conducted its latest periodic systemwide ridership survey from 2008 to 2009 with bus trips surveyed from 6 a.m. to 3:30 p.m. on weekdays, which, according to CTPS estimates, covers at least one direction of 85 percent of weekday trips. The surveys returned are an estimated 5.9 percent of bus passengers during that time period and 17.1 percent of the surveys distributed (CTPS, 2010).

A weighting factor was used for each survey record to account for different sampling and response rates across routes. The ridership numbers by direction and time period were based on the trip summaries from the most recent ride checks—many of the same ride checks that were used for the ridership analysis in this thesis. In order to get reliable origin-destination (O-D) data for all O-D combinations, it would be necessary to have significantly larger sample sizes than those in this survey. Still, the surveys are useful for determining the most common travel patterns for bus riders in the area.

The MBTA system was broken down into "neighborhoods" as shown in Figure D-1. Boston has nine neighborhoods while Cambridge and Somerville have six and four neighborhoods, respectively. Medford and other towns not shown on the map have just one neighborhood. A study area O-D matrix was creating by summing the route-level O-D matrices for the study area routes. Due to space constraints, the route-level O-D matrices show only the 18 most-frequent origins and the 10 most-frequent destinations. For the 15 bus routes in the study area, there are far fewer unique destinations (35) than origins (69). There are a total of 351 O-D pairs that have at least one passenger.

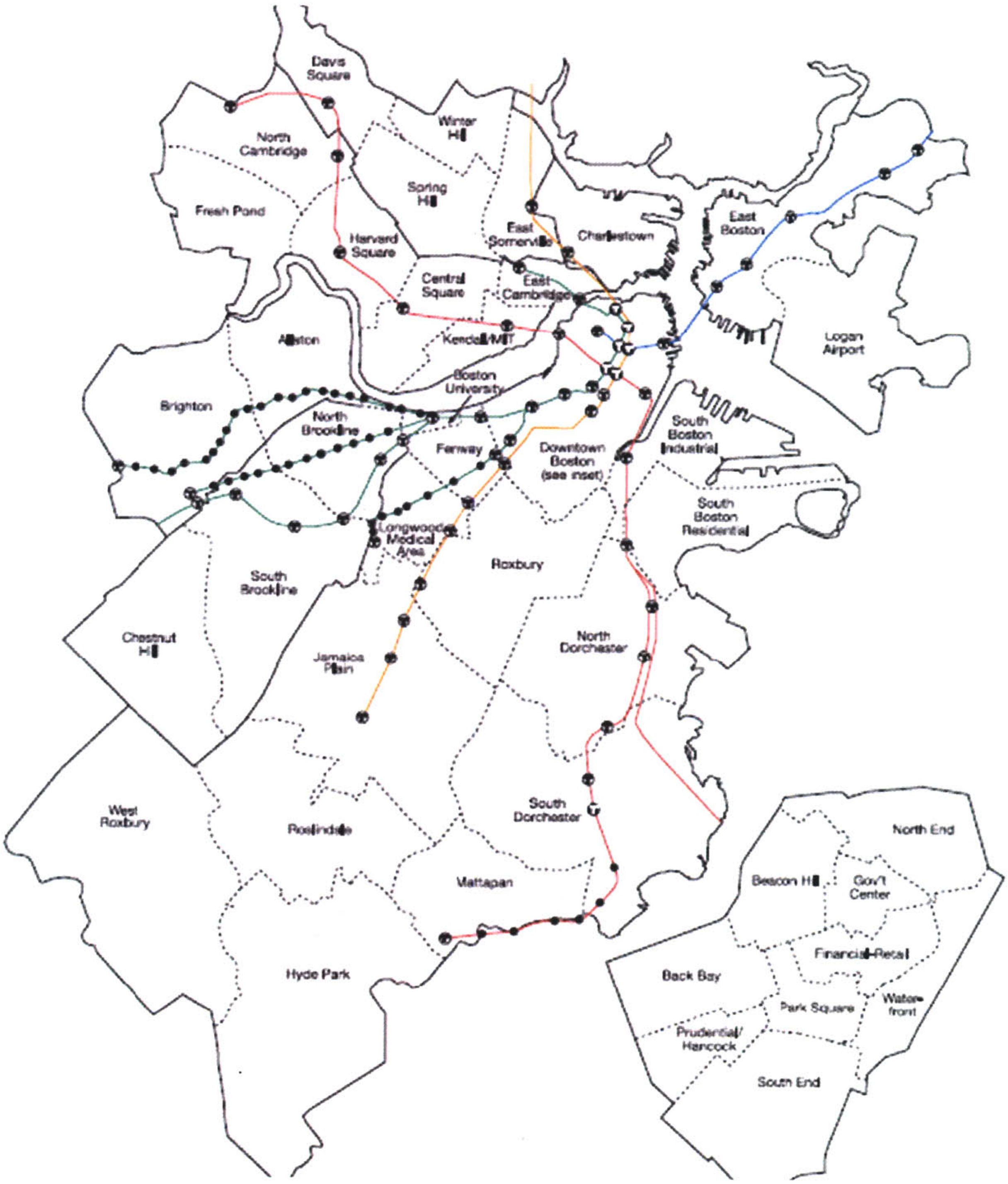


Figure D-1. CTPS Rider Survey—Neighborhood Boundaries

The O-Ds were ordered with the 12 most frequent pairs shown in Table D-1. For all but one of the top O-D pairs, there is at least one bus route that serves each O-D directly. Routes that serve an O-D pair directly are shown in Table D-1 as well as routes that are used as part of an O-D trip (shown in parentheses). The exception is from Spring Hill to Boston Financial, which is the second-ranked O-D pair. Riders to downtown from Spring Hill currently take Route 87 or another bus and transfer to either the Orange Line or Red Line.

The last column in Table D-1 describes the extent to which each trip might change after the Green Line Extension is fully operational. Travel patterns will change for most of the O-D pairs. The Spring Hill to Boston Financial O-D pair will improve the most as most passengers will then be within walking distance of a Green Line station.

Rank	Origin	Destination	Riders	Routes	GLE Importance
1	Spring Hill	Davis Square	363	87, 88, 90	Medium
2	Spring Hill	Boston Financial	361	(87), (others)	High
3	Spring Hill	Kendall/MIT	336	85, CT2, 91	Medium
4	Medford	Medford	298	101, 95, 94	Low
5	Medford	Boston Financial	270	Orange, (101)	Medium
6	Brighton	Harvard Sq.	268	86	None
7	Winter Hill	Boston Financial	215	Orange, (89)	Medium
8	Spring Hill	Harvard Sq.	212	86	Low
9	Charlestown	Boston Financial	207	92	None
10	Winter Hill	Davis Square	196	89, (101)	Medium
11	Winter Hill	Charlestown	191	89, 101	Low
12	Medford	Malden	187	101, 94	Low

Table D-1. Top 12 O-Ds from CTPS Rider Survey

Appendix E. Transfer Rates

Passengers perceive transfers as being very onerous, so they are important to note when analyzing bus service. If they do not live within walking distance of a station, passengers who use rapid transit must access it by another mode. Buses are often used as feeders to bring residents to a nearby rapid transit station. Additionally, some passengers make trips that require transfers to other bus routes.

AFC systems make it possible to understand how passengers link trips. Linked trips involve multiple legs over different routes to get to a destination, so they show up as multiple transactions with the same pass or stored-value card in the AFC dataset. For each passenger that uses one of these fare types, it is possible to combine multiple transactions from each day to create linked trips. If the second AFC transaction occurs within 60 minutes of the first AFC transaction, then it is, for the sake of this thesis, treated as a linked trip. If the transfer is more than an hour after the first AFC transaction, then it is likely that the two transactions are not linked but two separate trips. For more discussion on elapsed-time thresholds used in determining transfers in AFC datasets, the reader is referred to Seaborn (2008).

Weekday passenger transfer rates to and from each of the Somerville-Medford bus routes are shown in Table E-1. A majority (12 of 15) of the routes have higher transfer rates with rail than with bus. Route 86 has 850 daily transfers with bus, which are 220 more than any other route. Route 91 tops all routes with 54 percent of its passengers transferring to other bus routes. One explanation for the high percentage of bus transfers on Route 91 is that it has many locations to transfer. The route with the fewest number of bus transfers is Route 85, which has only 20 daily transfers. This is due to the limited bus transfer options for Route 85. Route 101 has 1000 transfers with rail (Orange Line), which leads all routes. 61 percent of Route 89 passengers transfer to rail (Red Line at Davis Square or Orange Line at Sullivan Square), which is the highest percentage for all study area routes. The route with the smallest percentage of rail transfers is Route 92, because it primarily carries people between Charlestown and downtown Boston.

Route #	Route Name	Daily Riders	Daily Transfers for Card Users	
			To/From Bus	To/From Rail
80	Arlington Ctr. - Lechmere	780	170 (21%)	250 (33%)
83	Rindge Ave. - Central Sq.	960	250 (26%)	280 (29%)
85	Spring Hill - Kendall/MIT	280	20 (8%)	100 (37%)
86	Sullivan - Reservoir	2460	850 (35%)	820 (33%)
87	Arlington Ctr./Clar. Hill - Lechmere	1400	330 (23%)	830 (52%)
88	Clar. Hill - Lechmere	1600	320 (20%)	830 (52%)
89	Clar. Hill or Davis Sq. - Sullivan	1480	450 (30%)	910 (61%)
90	Davis Sq. - Wellington	330	110 (35%)	150 (46%)
91	Sullivan - Central Sq.	510	280 (54%)	170 (33%)
92	Assembly Sq. - Downtown	410	100 (25%)	80 (19%)
94	Medford Sq. - Davis Sq.	540	150 (28%)	280 (51%)
95	West Medford - Sullivan	890	290 (32%)	450 (51%)
96	Medford Sq. - Harvard Sq.	720	250 (35%)	320 (44%)
101	Malden - Sullivan	2040	630 (31%)	1000 (49%)
CT2	Sullivan - Ruggles	1090	340 (31%)	340 (31%)

Note: Ridership and transfer numbers are for weekday AFC taps between 3 a.m. and 1 p.m.

Table E-1. Weekday Transfer Rates for Study Area Routes

Common route connections *from* the study area routes are shown in Table E-2. The number of daily transfers is shown in parentheses for the high-frequency transfers (10 or more daily transfers). The most transfers from the study area routes occur on Route 86; transfers to Routes 57, 70, 71, 30, and 66 all have at least 23 daily transfers. Routes 85, 92, 94, and CT2 do not have any significant transfers to other routes.

Similarly, the most common route connections *to* the Somerville and Medford routes are shown in Table E-3. Again Route 86 has the largest number of from other routes; Routes 109, 104, and 57 have at least 20 daily transfers to Route 86. All of the routes, except for Route 85, have at least one high or moderately-high transfer volume from another route.

FROM Route	High (10+ daily transfers)	Moderately High (5-10 daily transfers)
80	77 (11)	86, 69, 96
83	47 (14), 77 (12), 1 (12)	70, 69, 701
85		
86	57 (30), 70 (30), 71 (29), 30 (25), 66 (23), 77 (18), 93 (14)	51, 74, 1, 78, 69, 101, 87, 62, 88, 109
87	88 (15)	77, 47, 89, 86, 1
88	87 (14)	86, 71, 90, 1, 47, 111, 88
89	86 (16)	101, 109, 93, 88, 87, CT2, 91, 77, 70, 96, 73
90		88
91		70, 101
92		
94		
95		86
96		71, 66
101	86 (17), 96 (15), CT2 (13), 89 (13), 134 (13), 111 (11)	91, 95, 109, 104, 108, 93, 92, 94
CT2		

Table E-2. Common Route Connections from Study Area Routes

TO Route	High (10+ daily transfers)	Moderately High (5-10 daily transfers)
80		77
83		77, 69
85		
86	109 (31), 104 (30), 57 (20), 101 (17), 89 (16), 73 (15), 71 (14), 51 (14), 77 (12), 70 (11)	106, 95, 66, 80, 88, 87, 105, 111, 93, 110, 136
87	88 (14)	111, 89, 77, 86
88	87 (15)	89, 90, 111, 86
89	109 (16), 104 (14), 101 (13)	111, 87
90		88
91		101, 109, 104, 89
92		101
94		101
95		101, 111, 104
96	101 (15)	134, 71, 66, 89, 80
101	104 (13), 111 (12)	89, 106, 108, 91, 109, 93, 86
CT2	101 (13)	109, 23, 57, 104, 28, 15, 89, 22

Table E-3. Common Route Connections to Somerville-Medford Routes

Appendix F. Trip Rates

There are many exogenous and endogenous variables that affect transit ridership. Exogenous to the transit agency are factors such as the number of vehicles that a household owns, the access of individuals to cars, the distribution of trip generators and attractors such as employment areas, and the demographics of residents. The variables that transit agencies control include routings, service frequencies, on-time performance, fare policies, cleanliness of buses, appearance of stops or stations, and marketing. For more discussion on how transit demand, supply, and competing routes influence each other, the reader is referred to Peng, Dueker, Strathman & Hopper (1997).

For trips that use rapid transit, passengers can sometimes choose from several bus routes that serve a particular stop. This is especially true for passengers who are heading to destinations in downtown Boston or points further west or south in the MBTA system.

Trip rates measure the number of riders within walking distance of the route and the frequency of service on the route. Fijalkowski and the Chicago Transit Agency (CTA) included trip rate calculations when they were analyzing a proposed bus service along 83rd Street (labeled as Route 83) south of downtown Chicago (2009). Adding a route along 83rd Street would reduce the maximum distance required to access a bus line to a ¼ mile (½ mile between parallel bus lines) in that part of Chicago. All-day public transportation trip rates were calculated to be 0.15, 0.33, and 0.21 for the population in the catchment areas of Routes 75, 79, and 87, respectively. This means that each resident was taking, on average, 0.15 to 0.33 public transportation trips per day. These trip rates are relatively high due both to the high percentage of transit dependant riders in the area and to the high frequency of service and the connections to the Red Line subway. Route 75 was used as a proxy for the proposed Route 83 due to "population densities, development patterns, and roadway geometrics" as well as similar length, running time, and connection to the Red Line (Fijalkowski, 2009). Passengers in the catchment area of Route 83 would likely switch from Routes 79 and 87. Although the daily ridership on these two routes would decrease by about 2600, Route 83 were expected to have about 5100 daily riders for a net gain of 2500 daily riders. The trip rates for Routes 79 and 87 were predicted to increase to 0.46 and 0.26, respectively, because the residents in the Route 83 catchment area had lower-than-average trip rates when they were required to walk more than ¼ mile (Fijalkowski, 2009).

For the trip rate analysis of the MBTA routes in the study area, the population is calculated using 2000 Census data. The population within a ¼ mile (straight distance) of bus stops is determined using TransCAD. The number of trips occurring from the beginning of service to 1 p.m. was used to measure supply. The average number of boardings and alightings at each stop is calculated for each of those hours. The routes are divided into route segments at route and node interchange points and other points where services are on the same street branch. APC data was used except for Routes 94, 95, 96, and CT2 which had limited APC data. For these four routes, ride check and AFC data were both used to produce a similar breakdown of ridership throughout the day. First, the number of AFC transactions were counted and averaged for each time period. Next, these values were adjusted by the AFC undercount factor. The proportion of passengers boarding before 1 p.m. was calculated for each direction of travel, and this proportion was applied to the ride check boardings and alightings by stop. Also, the proportion of adjusted AFC counts to ride check counts was applied to the stops. Trip rates are normalized by the population (2000 Census) within a quarter mile of each route segment. Public transportation trip rates for these routes segments were calculated using Equation F-1, where r_i is the ridership of all route segment stops served by route i, n is the number of routes that provide service to the route segment, and p is the population within ¼ mile of the route segment stops.

$$Route\ Segment\ Trip\ Rate = \sum_{i=1}^{n} r_i/p \qquad \text{(Equation F-1)}$$

The inbound ons trip rates for the study area routes are shown in Table F-1, which is at the end of this section. Route 92 has only two segments, because the segment between Assembly Square Mall and Sullivan Square is the only portion of the route that is of major significance for the Green Line Extension Project. Route 80 has the most route segments (10), which is due in part to the five Green Line stations that the route will have a stop at or near.

The inbound ons trip rates for the route segments are plotted against the frequency of service in Figure F-1. The R-squared value of 0.3379 (t-stat of 5.39) indicates that the frequency of service is positively correlated with the trip rate. An increase of one inbound bus trip per hour from the beginning of the service to 1 p.m. (approximately 8 hours) will result, on average, in an increase in the trip rate by 0.0064, which is 6.4 trips per 1000 residents. Route segments typically have between 2000 and 12,000 residents, so this would be an increase of 13 to 77 trips per segment.

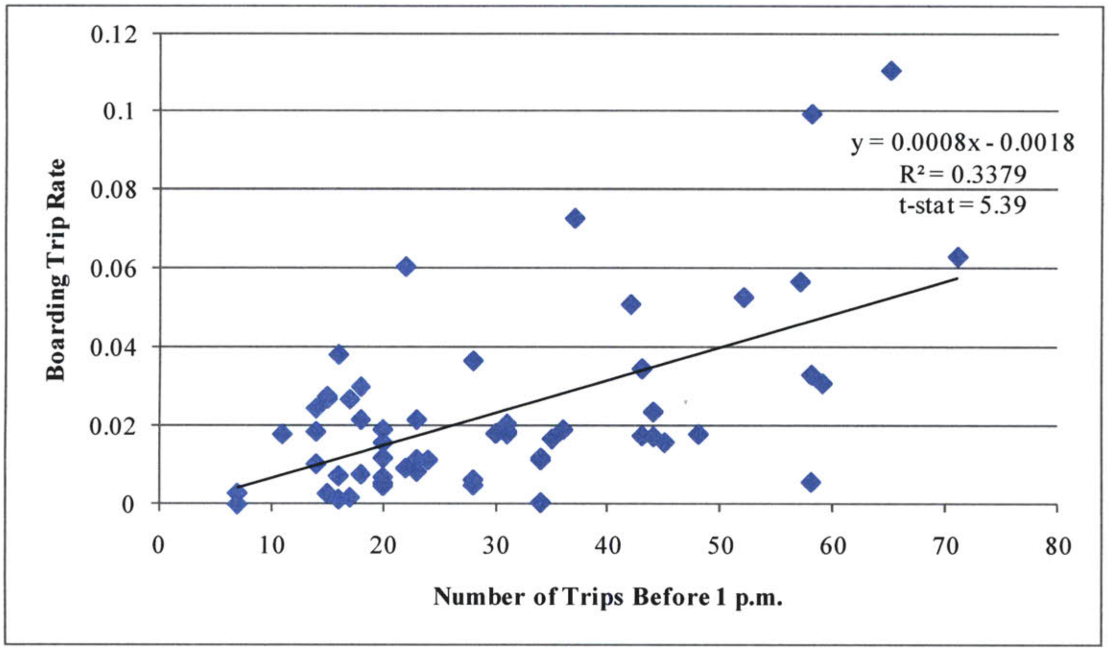


Figure F-1. Relationship between Frequency of Service and Boarding Trip Rate—Inbound

When route segments that are within walking distance of a rapid transit station are excluded, there is a stronger correlation between frequency of service and trip rate, as shown in Figure F-2. The R-squared value is now 0.4450 (t-stat of 5.34). In addition, the slope of the regression line is slightly steeper. For route segments that are not close to rapid transit nodes, increasing the number of inbound bus trips by eight will add, on average, 7.2 new transit trips per 1000 residents. This would be an increase of 14 to 86 trips per route segment.

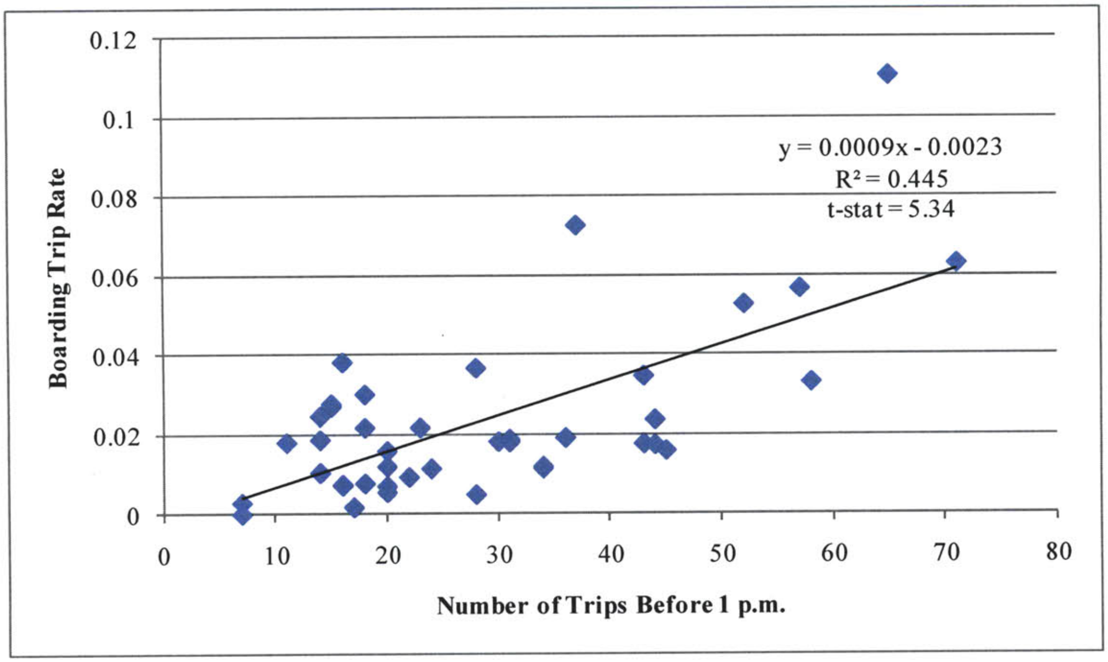


Figure F-2. Relationship between Frequency of Service and Boarding Trip Rate—Inbound (excluding route segments that are within walking distance of a rapid transit station)

Table F-1. Trip Rates for Study Area Routes

Route Segment	Bus Trips*	Inbound		
		# Stops	# Ons	Ons Rate**
80--Medford St.	14	7	96	0.019
80/94--Boston @ High	14 (28)	8	95 (276)	0.013 (0.031)
80/94/96--Boston @ Winthrop	14 (43)	3	27 (171)	0.005 (0.053)
80/94/96--N. of Powderhouse	14 (43)	3	11 (123)	0.002 (0.011)
80/89--E. of Powderhouse	14 (44)	3	31 (91)	0.006 (0.017)
80/89--Broadway @ Medford	14 (44)	2	33 (129)	0.006 (0.024)
80--Lowell Street	14	7	185	0.024
80--Pearl Street	14	8	120	0.01
80/88/90--McGrath @ Cross	14 (45)	1	34 (70)	0.008 (0.016)
80/87/88--McGrath Hwy.	14 (58)	5	4 (39)	0.001 (0.006)
83--Rindge Ave.	16	6	318	0.038
83/96--Porter Sq.	16 (31)	3	77 (103)	0.014 (0.018)
83--Elm St.	16	2	9	0.001
83/87--Somerville @ Elm	16 (36)	3	80 (132)	0.012 (0.019)
83--Beacon @ Park	16	3	42	0.007
83--Beacon @ Cambridge	16	4	54	0.007
83/91--Inman Sq.	16 (34)	3	74 (125)	0.007 (0.011)
83/91--Central Sq.	16 (34)	2	3 (4)	0 (0)
85--Summer St.	11	7	204	0.018
85/CT2--Union Sq.	11 (28)	3	21 (28)	0.004 (0.005)
85/CT2--Kendall	11 (28)	6	15 (76)	0.001 (0.006)
86/91/CT2--E. of Joy St.	23 (58)	8	516 (805)	0.064 (0.099)
86/91/CT2--W. of Joy St.	23 (58)	3	148 (267)	0.018 (0.033)
86--Washington @ Dane	23	5	210	0.022
86--Kirkland St.	23	3	71	0.008
86--W. of Harvard Sq.	23	29	331	0.012
87--Arlington Ctr.	18	9	336	0.03
87/88/89--Clarendon Hill	20 (65)	4	302 (850)	0.039 (0.111)
87/88--Holland St.	20 (48)	3	30 (156)	0.003 (0.018)
87/96--Davis Sq.	20 (35)	4	121 (124)	0.016 (0.018)
87--Elm St.	20	3	37	0.005
83/87--Somerville @ Elm	20 (36)	3	52 (132)	0.007 (0.019)
87--Union Sq.	20	6	135	0.016
87--Somerville @ McGrath	20	2	21	0.007
80/87/88--McGrath Hwy.	20 (58)	5	15 (39)	0.002 (0.006)

Note: For segments with more than one route, totals are in parentheses.

* Number of trips is the number of bus trips that serve the route segment from the start of service to 1 p.m. Most routes begin operation by 5:15 a.m.

** Trip rates are number of trips per resident in the 1/4-mile area surrounding the bus stop(s) on each route segment.

Table F-1. Trip Rates for Study Area Routes

Route Segment	Bus Trips*	Inbound		
		# Stops	# Ons	Ons Rate**
87/**88**/89--**Clarendon Hill**	28 (65)	4	444 (850)	0.058 (0.111)
87/**88**--**Holland St.**	28 (48)	4	126 (156)	0.014 (0.018)
88/90--**Highland @ Cedar**	24 (31)	7	146 (241)	0.012 (0.02)
88/90--**Highland @ Central**	24 (31)	4	115 (153)	0.013 (0.018)
88/90--**Highland @ Medford**	24 (31)	4	155 (190)	0.015 (0.019)
80/**88**/90--**McGrath @ Cross**	24 (45)	1	34 (70)	0.008 (0.016)
80/87/**88**--**McGrath Hwy.**	24 (58)	5	20	0.003 (0.006)
89/94/96--**N. of Davis Sq.**	13 (42)	3	71 (335)	0.011 (0.031)
87/88/**89**--**Clarendon Hill**	17 (65)	4	104 (850)	0.014 (0.111)
89--Teele Square	17	3	16	0 (0.097)
80/**89**--**E. of Powderhouse**	30 (44)	4	60 (91)	0.011 (0.017)
80/**89**--**Broadway @ Medford**	30 (44)	2	96 (129)	0.018 (0.024)
89--Broadway @ Norwood	30	2	58	0.018
89/**101**--**Broadway @ Main**	30 (52)	7	320 (647)	0.026 (0.053)
89/90/101--**Broadway @ Cross**	30 (59)	6	88 (179)	0.015 (0.031)
88/**90**--**Highland @ Cedar**	7 (31)	7	95 (241)	0.008 (0.02)
88/**90**--**Highland @ Central**	7 (31)	4	38 (153)	0.004 (0.018)
88/**90**--**Highland @ Medford**	7 (31)	4	35 (190)	0.003 (0.019)
80/88/**90**--**Broadway @ Cross**	7 (45)	1	2 (70)	0 (0.016)
90--Cross St.	7	6	24	0.003
89/**90**/101--**Broadway @ Cross**	7 (59)	6	34 (179)	0.006 (0.031)
90/92--**Assembly Sq. Mall**	7 (15)	3	7 (48)	0.004 (0.027)
90--Wellington Sta.	7	1	0	0
86/**91**/CT2--**E. of Joy St.**	18 (58)	6	284 (805)	0.035 (0.099)
86/**91**/CT2--**W. of Joy St.**	18 (58)	3	90 (267)	0.011 (0.033)
91--Newton St.	18	5	56	0.008
83/**91**--**Inman Sq.**	18 (34)	3	51 (125)	0.005 (0.011)
83/**91**--**Central Sq.**	18 (34)	2	1 (4)	0 (0)
90/**92**--**Assembly Sq. Mall**	8 (15)	3	41 (48)	0.023 (0.027)
92--Charlestown/Boston	18	16	381	0.022
94/95/96/101--**Medford Sq.**	14 (71)	2	53 (139)	0.024 (0.063)
94/95--**High St.**	14 (34)	11	66 (88)	0.011 (0.034)
80/**94**--**Boston @ High**	14 (28)	8	181 (276)	0.019 (0.031)
80/**94**/96--**Boston Ave.**	14 (43)	3	54 (171)	0.004 (0.053)
80/**94**/96--**College Ave.**	14 (43)	3	35 (123)	0 (0.011)
89/**94**/96--**N. of Davis Sq.**	14 (42)	3	8 (33)	0.007 (0.031)

Note: For segments with more than one route, totals are in parentheses.

* Number of trips is the number of bus trips that serve the route segment from the start of service to 1 p.m. Most routes begin operation by 5:15 a.m.

** Trip rates are number of trips per resident in the 1/4-mile area surrounding the bus stop(s) on each route segment.

Table F-1. Trip Rates for Study Area Routes

Route Segment	Bus Trips*	Inbound		
		# Stops	# Ons	Ons Rate**
95--Playstead Rd.	20	7	21	0.005
94/**95--High St.**	20 (34)	10	103 (109)	0.023 (0.034)
94/**95**/96/101**--Medford Sq.**	20 (71)	1	0 (139)	0 (0.063)
95/96/101**--Medford Sq.**	20 (57)	2	69 (141)	0.028 (0.057)
95--Mystic @ Hancock	20	6	42	0.012
95--Mystic @ McGrath	20	10	206	0.019
95/101**--Salem St.**	2 (24)	6	1 (79)	0 (0.011)
94/95/**96**/101**--Medford Sq.**	15 (71)	2	84 (139)	0.038 (0.063)
95/**96**/101**--Medford Sq.**	15 (57)	2	69 (141)	0.028 (0.057)
96/101 **Main @ George**	15 (37)	2	54 (170)	0.023 (0.073)
96--George St.	15	4	139	0.068
80/94/**96--Boston @ Winthrop**	15 (43)	3	90 (171)	0.043 (0.053)
80/94/**96--N. of Powderhouse**	15 (43)	3	77 (123)	0.009 (0.011)
89/94/**96--N. of Davis Sq.**	15 (42)	3	3 (33)	0.013 (0.031)
87/**96--Davis Sq.**	15 (35)	3	3 (124)	0.001 (0.018)
83/**96--Porter Sq.**	15 (31)	2	26 (103)	0.004 (0.018)
96--Massachusetts Ave.	15	9	45	0.003
101--Pleasant St.	22	8	418	0.06
95/**101--Salem St.**	22 (24)	6	78 (79)	0.011 (0.011)
95/96/**101--Medford Sq.**	22 (57)	2	1 (141)	0 (0.057)
94/95/96/**101--Medford Sq.**	22 (71)	1	2 (139)	0.001 (0.063)
96/**101--Main @ George**	22 (37)	1	116 (170)	0.05 (0.073)
101--Main St.	22	13	217	0.017
89/**101--Broadway @ Main**	22 (52)	7	327 (647)	0.027 (0.053)
89/90/**101--Broadway @ Cross**	22 (59)	6	57 (179)	0.01 (0.031)
86/91/**CT2--E. of Joy St.**	17 (58)	2	5 (805)	0.001 (0.099)
86/91/**CT2--W. of Joy St.**	17 (58)	2	29 (267)	0.004 (0.033)
85/**CT2--Union Sq.**	17 (28)	1	7 (28)	0.001 (0.005)
85/**CT2--Kendall**	17 (28)	2	61 (76)	0.005 (0.006)
CT2--W. of Kendall/MIT	17	12	329	0.027

Note: For segments with more than one route, totals are in parentheses.

* Number of trips is the number of bus trips that serve the route segment from the start of service to 1 p.m. Most routes begin operation by 5:15 a.m.

** Trip rates are number of trips per resident in the 1/4-mile area surrounding the bus stop(s) on each route segment.

Appendix G. On-Time Performance

Reliability is a major concern for both operators and passengers. Both passengers and the operator desire reliable service, because schedule adherence decreases loading variance among buses, ensures that buses are able to start the next trip on-time, and ensures that passengers arrive at their destinations by a set time.

The MBTA has separate reliability standards for scheduled departures and "walk-up" service considered to be scheduled headways of less than 10 minutes. Although there are a few trips for some of the study area routes that would qualify as walk-up service, it was decided that all routes would be evaluated using schedule departure standards. There are separate standards for origin, mid-route, and destination timepoints. At origins, trips must leave between 0 minutes before and 3 minutes after the scheduled time. At mid-route timepoints, trips must leave between 0 minutes before and 7 minutes after. At destinations, trips must arrive between 3 minutes before and 5 minutes after. The MBTA also has a route standard; 75 percent of all timepoints must be on-time (MBTA, 2009).

Due to the limitations of manual data collection discussed in Chapter Two, on-time performance data from CTPS ride checks are not included in this analysis. The on-time performance of the study area bus routes using AVL data is shown in Table G-1. Overall, 67 percent of the timepoints for the study area routes are on-time, which is below the route standard. Route 85, with 88 percent of its timepoints on-time, is the best performing route. Routes 89, 89-2, 91, and 95 are the other routes that meet the route standard. Route CT2 is on the other end of the spectrum with only 56 percent of its timepoints satisfying the standard.

In addition to the benefit of improved accuracy of on-time performance with AVL data, the data make it simple for analysts to customize. Standards for on-time, early, and late arrival/departure at timepoints are easily incorporated into the AVL summary tools. Table G-1 also differentiates between late and "very late" timepoints, so that there is a better accounting of the worst-performing trips. Route CT2 is the worst-performing route for on-time departures with only 54 percent of trips starting on-time. Furthermore, 23 percent of its trips start very late, or more than 6 minutes after the scheduled time. The performance of Route CT2 improves somewhat mid-route, where 23 percent of its timepoints late and only 3 percent of them very late.

Reliability is an increasing priority for many transit agencies. Ehrlich describes the following bus reliability measures that are used by Transport for London, a large transport agency that generally operates high frequency (e.g. less than ten minute headways) service throughout the day on most of its routes (2010):

- Excess Waiting Time—used for high-frequency or "walk-up" routes that assume random arrivals. Excess Waiting Time is the difference between the actual (estimated) waiting time and the scheduled waiting time.
- Percent Lost Mileage—the percentage of route miles on skipped trips caused by traffic, crew shortages, maintenance issues, and other disruptions.
- Chance of Waiting Longer than 10 Minutes
- Percentage of Long Gaps—long gaps are defined as headways greater than four times the scheduled wait time

Ehrlich describes the five components of a bus journey; access, wait, in-vehicle travel, egress, and transfer (only for multi-leg trips). Waiting time and travel time are the only two components that may be measured or inferred directly with AVL data. Ehrlich uses the term *Journey Time* to define the combined waiting time and in-vehicle travel time. If the actual Journey Time is the same as the scheduled Journey Time, the passenger will arrive at her destination at the scheduled time. However, due to variability in performance, the average (median) journey time over many days may be greater than the scheduled journey time. Furthermore, measures based on only scheduled and median journey times do not account for very unreliable trips. Ehrlich uses the following two reliability measures to assess performance (2010):

- Excess Journey Time—the difference between the median journey time and the scheduled journey time.
- Reliability Buffer Time—the difference between the 95th percentile journey time and the median journey time.

These reliability measures are not specifically applied to the Somerville and Medford bus routes; however, they may be useful for the highest frequency routes, such as Routes 86, 87, and 101.

For more discussion of reliability measures, the reader is referred to Chan (2007) and Uniman (2009).

Rt. #	Route Name	# Trips	All	Startpoints				Midpoints				Endpoints			
			On-Time	On-Time	Early	Late	Very Late	On-Time	Early	Late	Very Late	On-Time	Early	Late	Very Late
80	Arlington Center - Lechmere	5523	69%	88%	3%	4%	5%	65%	23%	8%	4%	72%	16%	8%	4%
83	Rindge Ave. - Central Sq.	6512	68%	83%	6%	5%	6%	59%	18%	15%	8%	78%	9%	8%	5%
85	Spring Hill - Kendall/MIT	2809	88%	91%	1%	4%	3%	87%	0%	10%	2%	87%	3%	9%	1%
86	Sullivan Station - Reservoir	7337	63%	73%	9%	8%	9%	62%	5%	20%	12%	62%	17%	11%	11%
87	Arlington Center - Lechmere	7372	69%	84%	2%	5%	8%	66%	6%	18%	10%	69%	19%	7%	5%
88	Clarendon Hill - Lechmere	8032	74%	83%	4%	5%	8%	71%	14%	10%	5%	73%	17%	6%	4%
89	Clarendon Hill - Sullivan	4275	75%	73%	2%	15%	10%	76%	5%	14%	5%	77%	6%	12%	5%
89-2	Davis Sq. - Sullivan	4630	75%	72%	1%	14%	13%	76%	7%	12%	5%	76%	2%	14%	9%
90	Davis Sq. - Wellington	2749	64%	77%	9%	6%	7%	61%	5%	21%	13%	63%	4%	19%	15%
91	Sullivan - Central Sq.	5545	75%	70%	5%	15%	10%	76%	8%	10%	5%	77%	5%	8%	10%
92	Assembly Sq. - Downtown	5438	66%	67%	12%	11%	10%	62%	8%	21%	9%	76%	11%	9%	4%
94	Medford Square - Davis Sq.	5041	67%	72%	11%	6%	11%	69%	13%	9%	8%	53%	15%	17%	15%
95	West Medford - Sullivan	5862	79%	76%	3%	12%	8%	81%	7%	8%	3%	78%	14%	5%	3%
96	Medford Square - Harvard	5466	66%	61%	29%	4%	6%	67%	19%	9%	5%	66%	20%	9%	5%
101	Malden - Sullivan	6554	64%	67%	5%	14%	14%	62%	2%	22%	14%	71%	7%	13%	10%
CT2	Sullivan - Ruggles	8787	56%	54%	10%	13%	23%	56%	19%	23%	3%	60%	11%	15%	14%
ALL STUDY AREA ROUTES		91932	67%	74%	7%	9%	10%	70%	12%	10%	8%	65%	11%	16%	8%

On Time startpoints are defined as departures between 0 minutes before and 3 minutes after the schedule.
On Time midpoints are defined as departures between 0 minutes before and 7 minutes after the schedule.
On Time endpoints are defined as arrivals between 3 minutes before and 5 minutes after the schedule.
Very Late startpoints are defined as departures more than 6 minutes after the schedule.
Very Late midpoints are defined as departures more than 10 minutes after the schedule.
On Time endpoints are defined as arrivals more than 10 minutes after the schedule.

Table G-1. On-Time Performance—AVL Data

Appendix H. Deadhead Matrix

Appendix H. Deadhead Matrix (times are in minutes)

Terminus	From\To	arlct	bally	clarh	cntsq	davis	kndl	lchmr	malst	medfd	plast	rindg	sprhl	sull	welst
Assembly Sq.	amall														
Arlington Ctr.	arlct			6							6				
Harvard	bally				7										
Brighton Ctr.	brctr														
Clarendon Hill	clarh	6				5									
Central Sq.	cntsq		7				7								
Davis Sq.	davis			6								4	13		
Downtown	frank														
Kendall Sq.	kndl				7			11							
Lechmere	lchmr						8								
Malden Ctr.	malst									8					11
Medford Sq.	medfd								8		7				
W. Medford	plast	8								4					
Reservoir	resbu														
Rindge Ave.	rindg					5									
Spring Hill	sprhl					9								15	
Sullivan Sq.	sull												13		11
Wellington	welst								12					9	

Appendix I. MBTA Published Schedule and NetPlan Inputs—Scenarios 1 & 2

Route	Pk. Period/ Direction	MBTA Published Schedule					NetPlan Inputs--Scenario 1				NetPlan Inputs--Scenario 2		
		Head-way	Run. Time		End Layover		Head-way	Running Time	End Layover	Half-Cycle	Running Time	End Layover	Half-Cycle
			Min.	Max.	Min.	Max.							
80	AM--Inbound	20	**36**	**36**	**4**	**4**	20	36	4	40	37	6	43
	AM--Outbound	20	**31**	**31**	**9**	**9**	20	31	9	40	31	6	37
	PM--Inbound	20	**31**	**31**	**9**	**9**	20	31	9	40	33	5	38
	PM--Outbound	20	**36**	**36**	**4**	**4**	20	36	4	40	38	6	44
83	AM--Inbound	15	23	**30**	**5**	7	15	30	5	35	30	5	35
	AM--Outbound	15	**21**	**21**	**9**	**9**	15	21	4	25	22	5	27
	PM--Inbound	20	**27**	**27**	**3**	**3**	20	27	3	30	27	5	32
	PM--Outbound	20	**26**	**26**	**4**	**4**	20	26	4	30	31	4	35
85	AM--Inbound	35	**14**	**14**	**6**	**6**	35	14	6	20	18	4	22
	AM--Outbound	35	**11**	**11**	**4**	**4**	35	11	4	15	16	3	19
	PM--Inbound	40	11	**13**	7	7	40	13	7	20	17	4	21
	PM--Outbound	40	**13**	**13**	7	7	40	13	7	20	19	2	21
86	AM--Inbound	15*	**40**	**40**	**15**	**15**	12	40	15	55	44	7	51
	AM--Outbound	9*	**46**	**46**	4	14	12	46	14	60	48	7	55
	PM--Inbound	12*	44	**47**	11	17	15	47	12	59	50	12	62
	PM--Outbound	17	47	**49**	**12**	**12**	15	49	12	61	49	11	60

* designates that Headways were calculated by dividing the current peak hour trips into 60 (Equation 5-1).

Notes: 1. The AM peak period is from 7 to 9 a.m. The PM peak period is from 4 to 6:30 p.m.

2. The AM planning period chosen is 7:30 to 8:30 a.m. The PM planning period chosen is 4:30 to 5:30 p.m.

3. The most common values in the existing MBTA published schedule are shown in bold.

3. The "Starting At" column refers to the first scheduled run in the planning period.

that route, or values that make the full-cycle time a multiple of 5.

5. The Scenario 1 inputs for running time and layover time are chosen from the typical values or the maximum non-excessive values found for that route.

6. The Scenario 2 inputs are the median (+2 minutes) observed running time as the proposed running time and a value close to the 95th percentile (+2 minutes) observed running time for the half-cycle time. The layover time is the difference between the half-cycle time and the scheduled running time.

Route	Pk. Period/ Direction	MBTA Published Schedule					NetPlan Inputs--Scenario 1				NetPlan Inputs--Scenario 2		
		Head-way	Run. Time Min.	Run. Time Max.	End Layover Min.	End Layover Max.	Head-way	Running Time	End Layover	Half-Cycle	Running Time	End Layover	Half-Cycle
87 (Arlington Center)	AM--Inbound	20*	39	**40**	4	6	20	40	4	44	38	5	43
	AM--Outbound	20*	**30**	**30**	**1**	**1**	20	30	1	31	31	6	37
	PM--Inbound	15	**32**	**32**	**3**	**3**	15	32	3	35	32	7	39
	PM--Outbound	15	**37**	**37**	**3**	**3**	15	37	3	40	37	6	43
88	AM--Inbound	15*	30	32	**2**	**2**	15	30	2	32	31	6	37
	AM--Outbound	15*	**23**	**23**	0	5	15	23	5	28	25	5	30
	PM--Inbound	18	**28**	**28**	**2**	4	18	28	4	32	27	6	33
	PM--Outbound	18	**29**	**29**	3	**13**	18	29	9	38	28	6	34
88 (AM Shuttle)	AM--Inbound	18	**6**	**6**	**0**	**0**	18	6	0	6	6	0	6
	AM--Outbound	18	**6**	**6**	**6**	**6**	18	6	6	12	6	6	12
89 (Clarendon Hill)	AM--Inbound	20*	**20**	**20**	7	9	20	20	9	29	25	7	32
	AM--Outbound	20*	**19**	**19**	**8**	**8**	20	19	8	27	20	5	25
	PM--Inbound	20*	**20**	**20**	**11**	**11**	20	20	11	31	23	5	28
	PM--Outbound	20*	**23**	**23**	3	4	20	23	4	27	22	4	26

* designates that Headways were calculated by dividing the current peak hour trips into 60 (Equation 5-1).

Notes: 1. The AM peak period is from 7 to 9 a.m. The PM peak period is from 4 to 6:30 p.m.

2. The AM planning period chosen is 7:30 to 8:30 a.m. The PM planning period chosen is 4:30 to 5:30 p.m.

3. The most common values in the existing MBTA published schedule are shown in bold.

3. The "Starting At" column refers to the first scheduled run in the planning period.

that route, or values that make the full-cycle time a multiple of 5.

5. The Scenario 1 inputs for running time and layover time are chosen from the typical values or the maximum non-excessive values found for that route.

6. The Scenario 2 inputs are the median (+2 minutes) observed running time as the proposed running time and a value close to the 95th percentile (+2 minutes) observed running time for the half-cycle time. The layover time is the difference between the half-cycle time and the scheduled running time.

Route	Pk. Period/ Direction	MBTA Published Schedule					NetPlan Inputs--Scenario 1				NetPlan Inputs--Scenario 2		
		Head-way	Run. Time		End Layover		Head-way	Running Time	End Layover	Half-Cycle	Running Time	End Layover	Half-Cycle
			Min.	Max.	Min.	Max.							
89-2 (Davis Square)	AM--Inbound	20*	**19**	**19**	**6**	**6**	20	19	6	25	21	5	26
	AM--Outbound	20*	18	19	**10**	**10**	20	19	10	29	27	3	30
	PM--Inbound	20*	**17**	**17**	**6**	**6**	20	17	6	23	19	5	24
	PM--Outbound	20*	**27**	**27**	1	6	20	27	6	33	27	4	31
90	AM--Inbound	45	**33**	**33**	5	10	45	33	5	38	43	4	47
	AM--Outbound	45	**35**	**35**	**7**	**7**	45	35	7	42	42	6	48
	PM--Inbound	40	**36**	**36**	**4**	**4**	40	36	4	40	41	5	46
	PM--Outbound	40	34	36	4	6	40	36	4	40	38	5	43
91	AM--Inbound	30	**22**	**22**	**18**	**18**	30	22	18	40	27	5	32
	AM--Outbound	30	**14**	**14**	**6**	**6**	30	14	6	20	25	6	31
	PM--Inbound	30	**19**	**19**	4	9	30	19	9	28	22	6	28
	PM--Outbound	30	**21**	**21**	**11**	**11**	30	21	11	32	23	6	29
92 (Sullivan Square)	AM--Inbound	15	**23**	**23**	**1**	**1**	15	23	1	24	23	3	26
	AM--Outbound	15	**18**	**18**	**3**	**3**	15	18	3	21	18	6	24
	PM--Inbound	15	**22**	**22**	**2**	**2**	15	22	2	24	19	5	24
	PM--Outbound	15	**23**	**23**	13	15	15	23	13	36	26	7	33

* designates that Headways were calculated by dividing the current peak hour trips into 60 (Equation 5-1).

Notes: 1. The AM peak period is from 7 to 9 a.m. The PM peak period is from 4 to 6:30 p.m.

2. The AM planning period chosen is 7:30 to 8:30 a.m. The PM planning period chosen is 4:30 to 5:30 p.m.

3. The most common values in the existing MBTA published schedule are shown in bold.

3. The "Starting At" column refers to the first scheduled run in the planning period.

that route, or values that make the full-cycle time a multiple of 5.

5. The Scenario 1 inputs for running time and layover time are chosen from the typical values or the maximum non-excessive values found for that route.

6. The Scenario 2 inputs are the median (+2 minutes) observed running time as the proposed running time and a value close to the 95th percentile (+2 minutes) observed running time for the half-cycle time. The layover time is the difference between the half-cycle time and the scheduled running time.

Route	Pk. Period/ Direction	MBTA Published Schedule					NetPlan Inputs--Scenario 1				NetPlan Inputs--Scenario 2		
		Head-way	Run. Time		End Layover		Head-way	Running Time	End Layover	Half-Cycle	Running Time	End Layover	Half-Cycle
			Min.	Max.	Min.	Max.							
94	AM--Inbound	20*	**28**	**28**	1	**3**	20	28	3	31	27	6	33
	AM--Outbound	20*	**21**	**21**	4	8	20	21	4	25	19	4	23
	PM--Inbound	20*	**23**	**23**	5	19	20	23	5	28	33	7	40
	PM--Outbound	20*	23	26	8	19	20	26	8	34	26	5	31
95	AM--Inbound	20	**27**	**27**	**3**	**3**	20	27	3	30	28	7	35
	AM--Outbound	20	**25**	**25**	**5**	**5**	20	25	5	30	22	6	28
	PM--Inbound	20*	**22**	**22**	**3**	**3**	20	22	3	25	23	7	30
	PM--Outbound	20*	**27**	**27**	**8**	**8**	20	27	8	35	24	7	31
96	AM--Inbound	20*	34	35	1	**4**	20	35	4	39	36	6	42
	AM--Outbound	20*	**30**	**30**	6	7	20	30	7	37	31	6	37
	PM--Inbound	20*	29	30	1	3	20	30	3	33	34	7	41
	PM--Outbound	20*	**36**	**36**	4	21	20	36	8	44	39	7	46
101 (Malden Center)	AM--Inbound	9*	**32**	**32**	6	14	12	32	7	39	34	5	39
	AM--Outbound	15*	36	37	**4**	**4**	12	37	4	41	38	5	43
	PM--Inbound	12*	**27**	**27**	**6**	**6**	12	27	6	33	29	7	36
	PM--Outbound	12*	34	35	3	5	12	35	5	40	35	8	43

* designates that Headways were calculated by dividing the current peak hour trips into 60 (Equation 5-1).

Notes: 1. The AM peak period is from 7 to 9 a.m. The PM peak period is from 4 to 6:30 p.m.

2. The AM planning period chosen is 7:30 to 8:30 a.m. The PM planning period chosen is 4:30 to 5:30 p.m.

3. The most common values in the existing MBTA published schedule are shown in bold.

3. The "Starting At" column refers to the first scheduled run in the planning period.

that route, or values that make the full-cycle time a multiple of 5.

5. The Scenario 1 inputs for running time and layover time are chosen from the typical values or the maximum non-excessive values found for that route.

6. The Scenario 2 inputs are the median (+2 minutes) observed running time as the proposed running time and a value close to the 95th percentile (+2 minutes) observed running time for the half-cycle time. The layover time is the difference between the half-cycle time and the scheduled running time.

Route	**Pk. Period/ Direction**	**MBTA Published Schedule**					**NetPlan Inputs--Scenario 1**				**NetPlan Inputs--Scenario 2**		
		Head-way	**Run. Time**		**End Layover**		**Head-way**	**Running Time**	**End Layover**	**Half-Cycle**	**Running Time**	**End Layover**	**Half-Cycle**
			Min.	**Max.**	**Min.**	**Max.**							
CT2	AM--Inbound	20*	**50**	**50**	**10**	**10**	20	50	10	60	52	8	60
	AM--Outbound	20*	41	44	8	12	20	44	12	56	44	9	53
	PM--Inbound	20	**47**	**47**	13	23	20	47	13	60	52	8	60
	PM--Outbound	20	**47**	**47**	**13**	**13**	20	47	13	60	55	12	67
64 (Oak Square - Kendall)	AM--Inbound	23	**42**	**42**	**6**	**6**	23	42	6	48	42	6	48
	AM--Outbound	23	**43**	**43**	**11**	**11**	23	43	11	54	43	11	54
	PM--Inbound	25	**35**	**35**	**5**	**5**	25	35	5	40	35	5	40
	PM--Outbound	25	**55**	57	**5**	13	25	55	5	60	55	5	60
68 (Harvard - Kendall)	AM--Inbound	35	12	14	3	6	35	14	6	20	14	6	20
	AM--Outbound	35	**12**	**12**	**3**	**3**	35	12	3	15	12	3	15
	PM--Inbound	30	**12**	**12**	**3**	**3**	30	12	3	15	12	3	15
	PM--Outbound	30	12	17	**3**	**3**	30	12	3	15	12	3	15
69 (Harvard - Lechmere)	AM--Inbound	15*	**20**	**20**	2	6	10	20	3	23	20	3	23
	AM--Outbound	9*	**18**	**18**	0	8	10	18	3	21	18	3	21
	PM--Inbound	20	**24**	**24**	**6**	**6**	20	24	6	30	24	6	30
	PM--Outbound	20	**20**	**20**	**10**	**10**	20	20	10	30	20	10	30

* designates that Headways were calculated by dividing the current peak hour trips into 60 (Equation 5-1).

Notes: 1. The AM peak period is from 7 to 9 a.m. The PM peak period is from 4 to 6:30 p.m.

2. The AM planning period chosen is 7:30 to 8:30 a.m. The PM planning period chosen is 4:30 to 5:30 p.m.

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Appendix J. NetPlan Synchronization Factors for Scenario 3

Route Segment		Rt. 1	Rt. 2	Scen. 3 Hwy. (min.)		Time Period	Synch. Time (min.)			Daily Riders	Hwy. Factor	Demand Factor	Sync. Factor	Location of Synchron.
Begin	End			Rt. 1	Rt. 2		Min.	Max	Ideal					
Powderhouse Sq.	Broadway @ Medford	80	89	20	20	AM/PM	7	13	10	242	3	1	4	Winter Hill
Powderhouse Sq.	Broadway @ Medford	80	89-2	20	20	AM/PM	7	13	10	242	3	1	4	Winter Hill
Boston Ave. @ High St.	Powderhouse Sq.	80	94	20	20	AM/PM	7	13	10	613	3	3	6	College Ave.
Boston Ave. @ Winthrop	Powderhouse Sq.	80	96	20	20	AM/PM	7	13	10	387	3	2	5	College Ave.
Inman Sq.	Central Sq.	83	91	15	20	AM	1	4	2	124	1	1	2	Inman Sq.
Inman Sq.	Central Sq.	83	91	20	30	PM	3	7	5	124	2	1	3	Inman Sq.
Kendall Sq.	Union Square	85	CT2	20	20	AM	7	13	10	219	3	1	4	Kendall/MIT
Kendall Sq.	Union Square	85	CT2	30	20	PM	3	7	5	219	2	1	3	Kendall/MIT
Union Sq.	Sullivan Sq.	86	91	12	30	AM	2	4	3	1405	1	6	7	Union Sq.
Union Sq.	Sullivan Sq.	86	91	15	20	PM	1	4	2	1405	1	6	7	Union Sq.
Union Sq.	Sullivan Sq.	86	CT2	12	20	AM	1	4	2	1294	1	6	7	Union Sq.
Union Sq.	Sullivan Sq.	86	CT2	15	20	PM	1	4	2	1294	1	6	7	Union Sq.
Davis Sq.	Clarendon Hill	87	88	15	15	AM	5	10	7	923	3	4	7	Davis Square
Davis Sq.	Clarendon Hill	87	88	12	15	PM	1	2	2	923	1	4	5	Davis Square
Davis Sq.	McGrath Highway	88	90	15	30	AM/PM	4	11	7	1300	2	6	8	Highland-School
Davis Sq.	Clarendon Hill	88	88-3	15	15	AM	6	9	7	576	3	3	6	Davis Square
Powderhouse Sq.	Sullivan Sq.	89	89-2	20	20	AM/PM	8	12	10	939	3	4	7	Winter Hill
Cross St. @ Main St.	Sullivan Sq.	89	90	20	30	AM/PM	3	7	5	115	2	1	3	Sullivan Sq.
Broadway @ Main	Sullivan Sq.	89	101	20	12	AM/PM	1	4	2	673	1	3	4	Winter Hill
Cross St. @ Main St.	Sullivan Sq.	89-2	90	20	30	AM/PM	3	7	5	115	2	1	3	Sullivan Sq.
Broadway @ Main	Sullivan Sq.	89-2	101	20	12	AM/PM	1	4	2	673	1	3	4	Winter Hill
Cross St. @ Main St.	Sullivan Sq.	90	101	30	12	AM/PM	2	4	3	83	1	0	1	Sullivan Sq.
Union Sq.	Sullivan Sq.	91	CT2	30	20	AM	3	7	5	1229	2	5	7	Union Sq.
Union Sq.	Sullivan Sq.	91	CT2	20	20	PM	7	13	10	1229	3	5	8	Union Sq.
Playstead Rd.	Medford Sq.	94	95	20	20	AM	7	13	10	145	3	1	4	Boston-High
Playstead Rd.	Medford Sq.	94	95	20	15	PM	1	4	2	145	1	1	2	Boston-High
Boston Ave. @ Winthrop	Davis Sq.	94	96	20	20	AM/PM	7	13	10	142	3	1	4	College Ave.

References

Avail Technologies. (2011). "CommandPoint." http://www.availtec.com/CommandPoint.html.

Bagchi M. and P.R. White. (2005). "The Potential of Public Transport Smartcard Data." *Transport Policy*, 12 (5): 464-474.

Boyle D. et al. (2009). *Controlling System Costs: Basic and Advanced Scheduling Manuals and Contemporary Issues in Transit Scheduling.* TCRP Report 135. Transportation Research Board. Washington D.C.

Cambridge Systematics, Inc. (1985). "Northwest Corridor Service Study: Technical Supplement I." Memos.

Cedar, A. and N.H.M. Wilson. (1986). "Bus Network Design." *Transportation Research Part B*, Vol. 20, pp. 331–344.

Chan, J. (2007). Rail OD Estimation and Journey Time Reliability Metrics Using Automated Fare Data. Thesis, Master of Science in Transportation, MIT.

Clever Devices. (2010a). "IVN3: Intelligent Vehicle Network." Marketing Brochure.

Clever Devices. (2010b). "APC: Automatic Passenger Count System." Marketing Brochure.

Commonwealth of Massachusetts. (2010). "MBTA Bus Ridership Sets Record." http://transportation.blog.state.ma.us/blog/2010/10/mbta-bus-ridership-sets-records.html.

CTPS. (2010). *MBTA Systemwide Passenger Survey: Bus System 2008-09.* Report. Central Transportation Planning Staff.

CUBIC. (2011). "Enterprise for Transit." http://cts.cubic.com/Solutions/EnterpriseSystemsforTransit/tabid/363/language/en-US/Default.aspx.

Ehrlich, J. (2010). *Applications of Automatic Vehicle Location Systems Towards Improving Service Reliability and Operations Planning in London.* Thesis, Master of Science in Transportation, MIT.

Fattouche, G. (2007). *Improving High-Frequency Bus Service Reliability through Better Scheduling.* Thesis, Master of Science in Transportation, MIT.

Fijalkowski, J. (2009). "Analyzing Proposed Bus Service Along 83rd Street." PowerPoint Presentation. Chicago Transit Authority.

Fijalkowski, J. (2010). *Using Automatically Collected Data to Improve the Bus Service Planning Process.* Thesis, Master of Science in Transportation, MIT.

Furth, P. G., and N.H.M. Wilson. (1981). "Setting Frequencies on Bus Routes: Theory and Practice." Transportation Research Record 818: 1-7.

Furth, P. et al. (2000). *Data Analysis for Bus Planning and Monitoring.* TCRP Synthesis 34. Transportation Research Board. Washington D.C.

Furth, P., Hemily, B., Muller, T., and Strathman, J. (2006). *Using Archived AVL-APC Data to Improve Transit Performance and Management.* TCRP Report 113. Transportation Research Board. Washington D.C.

GIRO. (2008). "*NetPlan* nominated finalist for the Innovation Awards of the Transports Publics 2008 Exhibition in Paris." http://www.giro.ca/en/press-room/press-releases/prix-innovations-20080604.htm. GIRO, Inc.

Green Line Extension. (2010). "Preferred Alternative Map." http://www.greenlineextension.org.

Guihare, V and J. Hao. (2008). *Transit Network Design and Scheduling: A Global Review.* Transportation Research Part A: Policy and Practice. Transportation Research Board. Washington D.C.

Guillot, E. (1984). "Bus Transit Interface with Light Rail Transit in Western Canada." Transportation Res.-A Vol. 18A, No. 3, pp. 231-241, 1984.

Martinais, Alain. (2009). "Improving Connections, Reducing Costs, and Minimising Passenger Travel Time with NetPlan." UITP World Congress and Mobility & City Transport Exhibition. June 2009. PowerPoint Presentation. GIRO, Inc.

Massachusetts EOT. (2009). Green *Line Extension Project EEA #13886.* Draft EIR. Massachusetts Executive Office of Transportation and Public Works.

MassDOT. (2010). "Existing and Proposed MBTA Bus and Transit System." Unpublished map for the Green Line Extension Project. Massachusetts Department of Transportation.

MBTA (1980). *MBTA System Map—1980.* Massachusetts Bay Transportation Authority.

MBTA (1988). *MBTA System Map—1988.* Massachusetts Bay Transportation Authority.

MBTA. (2009). *Service Delivery Policy.* http://www.mbta.com/uploadedfiles/About_the_T/T_Projects/T_Projects_List/2009_Service_Delivery_Policy.pdf. Massachusetts Bay Transportation Authority.

MBTA. (2010). "Patrick-Murray Administration Announces MBTA Charlie Card Expansion to MetroWest Regional Transit Authority." http://www.mbta.com/about_the_mbta/news_events/?id=20607&month=&year=. Massachusetts Bay Transportation Authority.

MIT Center for Transportation & Logistics. (2003). "Memo 8—Running Time Analysis of Phase 1 Silver Line." Memo. October 7, 2003.

Parker, D. (2008). *AVL Systems for Bus Transit: Update*. TCRP Synthesis 73. Transportation Research Board. Washington D.C.

Peng, Z., K.J. Dueker, J. Strathman and J. Hopper. (1997). "A Simultaneous Route-level Transit Patronage Model: Demand, Supply, and Inter-route Relationship," *Transportation* 24: 2, May 1997, (pp. 159-181).

Seaborn, C. (2008). *Application of Smart Card Fare Payment Data to Bus Network Planning in London, UK.* Thesis, Master of Science in Transportation, MIT.

STEP. (2006). "Somerville Survey Bus Results." http://www.somervillestep.org/2006/12/somerville_bus.html. Somerville Transportation Equity Partnership.

TCRP Report 88. (2003). *A Guidebook for Developing a Transit Performance-Measurement System*. Transportation Research Board. Washington D.C.

Trepanier, M., C. Morency, and B. Agard. (2009). "Calculation of Transit Performance Measures Using Smartcard Data." *Journal of Public Transportation*, Vol. 12, No. 1, 2009, 79-96.

Uniman, D. (2009). *Service Reliability Measurement using AFC Smart Card Data - A Framework for the London Underground.* Thesis, Master of Science in Transportation, MIT.

VHB. (2005). *Beyond Lechmere: Northwest Corridor Study.* Major Investment Study/Alternatives Analysis. Vanasse-Hangin Brustlin, Inc. Boston, MA.

Wang, W. (2010). *Bus Passenger Origin-Destination Estimation and Travel Behavior Using Automated Data Collection Systems in London, UK.* Thesis, Master of Science in Transportation, MIT.