Spring 4-26-2017

Optimizing the B.O.B.

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Optimizing the B.O.B.

Final Design Review

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Prepared for:
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Submitted: 26 April 2017

Executive Summary

Kennesaw State is one of the fastest growing institutions in the state of Georgia, both the academic nature of the school and the atmosphere created by the students on campus are drawing more and more students every year. When our team developed the idea to analyses and attempt to improve the bus transportation system at Kennesaw State university (KSU) we became very excited to help this institution grow and become more efficient. The Big Owl Bus (BOB) system at KSU is used over 200,000 times a year students, faculty, staff and visitors for different events and to get around campus in a safe and timely manor. This system is made up of multiple different key components and players including: KSU Department of Transportation staff, bus driver, passengers, the bus routes, and different types of buses each with different features. The goal of this project is to suggest improvements and recommendations to the department of transportation using operations research techniques to find the optimal set of routes, improve customer overall satisfaction, and improve the timeliness of the bus on specific routes.

Approaching this problem we needed to gather data, as well as additional customer input to get a good understanding about users opinions of the BOB system. We received data from the department of transportation about bus usage trends, financial cost, specific information about bus routes, and insight into some of the process that they are in charge of. We also developed a survey to attempt to get students feedback about their experience with the BOB or their opinions about why they do not choose to ride the BOB. Our results showed us that bus frequency, timeliness of routes, and route consistencies were the main downfalls of the BOB system. However, the BOB system also had many positives including safety, cleanliness, and it being a big convince for student to get around campus.

After recovering this data we began to analyses the different parameters that we could change to make improvements on the system. We determined that four of the seven bus routes that run on a weekly basis had a large amount of student usage. Doing additional research about different optimization models that we could use, as well as consulting with our professor we decide to use a vehicle routing algorithm to determine the most optimal set of routes for these four routes. Additionally, we looked into writing another non-linear optimization model to determine the optimal number busses to run on each of these routes throughout different times of the day. This second optimization model took into the projected student demand on the new routes, bus frequency on the routes, and total route travel time including loading time and break time. The vehicle routing model solution gave us four new routes that had a better overall travel time by about 15 minutes, as well as a shorter total distance traveled. Our second model's solution gave the optimal number of busses to run throughout the day at a lower cost that the current allocated number of busses on the current routes.

To verify and make sure that our solution was real world applicable we developed and ran a simulation in Areana (simulation software). This gave us practical proof that our solution implemented into the BOB transportation system would work and would be better than the current processes. The different constraints that we included in each of our optimization models help up perfect. We also performed a sensitivity analysis on our second model to see how manipulating each constraint and variable would affect our overall solution.

After performing all this different analysis on the BOB transportation system we concluded that implementing these route changes will allow the BOB system to operate more efficiently. In addition, adding the designated number of busses throughout the day will help improve student wait times at bus stops and total route travel time We also have additional recommendations to try and improve customer satisfaction such as adding bus shelter to specific stops to increase usage and have uniform driver training to help with route and service consistency. Overall our proposed solution offers a better experience to all who ride the Big Owl Bus system at Kennesaw State University.

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Chapter 1: Overview

1. Introduction

The Department of Transportation manages the Big Owl Bus (B.O.B.) for Kennesaw State University (KSU). B.O.B. has provided transportation over 200,000 times to students on the Kennesaw and Marietta Campuses. There are a total of 16 buses of three sizes. Of the 16 buses, 14 are used regularly in routes, and two of them are reserves. These buses service over 30 stops across nine different routes. At least 15 of these bus stops are bus shelters. Most routes run Monday through Thursday between 7AM and 11PM, and Fridays from 7AM to 7PM. Two routes also run on Saturdays. Shift changes occur between 1PM and 3PM, sometimes with alternate buses. Unlike city bus systems, the utilization of the B.O.B. is fairly normally distributed throughout the day (i.e., usage steadily increases until mid-day, where it peaks, as opposed to having peaks during morning and evening rush hours and lunch). There are web and mobile apps for students to track the buses in real time.

Current concerns include (1) extended wait times on the Kennesaw-Marietta route, (2) inaccuracies in the tracking app, and (3) incorrect route usage tracking. Recent improvements to the bus system include (1) installing a motion detector at bus entrances to count the number of passengers entering and exiting the bus, (2) minor changes to route stops¸ and (3) giving drivers target time stamps for arriving at a stop. Two ten-minute dead times are scheduled into the Kennesaw-Marietta route – one for each campus. This allows drivers to catch up on a route if they fall behind schedule, and to take short breaks.

2. System Overview

2.1. Stakeholders

The primary stakeholders in this project are:

- KSU Department of Transportation staff, including bus drivers
- KSU students (passengers)

Secondary stakeholders include:

- KSU faculty, staff, departments, and other students, particularly when it comes to B.O.B. users' ability to get to classes, meetings, and events on time

Tertiary stakeholders include:

- University System of Georgia Board of Regents

2.2. System Block Diagram

The system block diagram in Figure 1 below outlines the major components of the system, denoted by circles, and their interactions, denoted by lines.

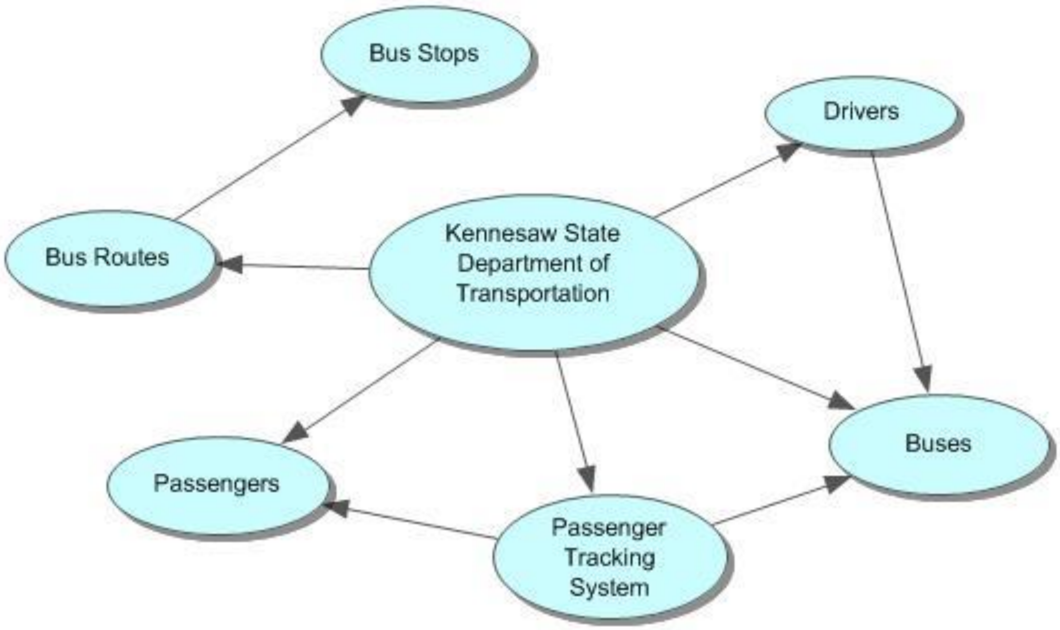

Figure 1: System Block Diagram

3. Project Background

In this project, we will work with the Department of Transportation to develop policies that allow the KSU Department of Transportation to increase student satisfaction on the B.O.B. We will do this by optimizing the routes overall, and making additional recommendations to improve the Kennesaw-Marietta route. Possible changes we will explore include: adding/removing bus stops, changing route order/direction, changing the types of busses used based on capacity and utilization, and recommending stops to add bus shelters to. Problem constraints include costs (labor, fuel, and maintenance), total mileage driven, and bus utilization.

3.1. Objective

The goal of this project is to utilize optimization, simulation, financial analysis, and student and driver input to recommend improvements to the efficiency and accessibility of the B.O.B. Kennesaw-Marietta route. A sensitivity analysis will be performed in order to make recommendations that are robust.

3.2. Justification

This project is important because the recommendations we provide have the potential to:

- Get students to classes earlier
- Improve the reliability, and in turn the usage, of the B.O.B.
- Reduce costs and make better use of student fees
- Increase accessibility of the B.O.B. through improvements to the app
- Increase student satisfaction

3.3. Problem Statement

Based on concerns expressed by the Department of Transportation, there are extended wait times on the Kennesaw-Marietta route. These delays can impact students' ability to get to class in a timely manner, which impacts both their education, and the education of their peers, if the student arrives late to class.

Chapter 2: Literature Review

Operations research is a key part of any systems engineering project. Within Operations research (OR) there are several sub categories that help engineers of multiple disciplines solve problems. Operations research brings together different forms of analytical techniques and processes then applies different business and management scenarios attempting to solve specific problems. In researching different techniques to approach our problem we first began to look at running different optimization models, using sensitivity analysis, different simulations we could program, and different service factors. "Introduction to operations research", a textbook written by F. S. Hillier and G. J. Lieberman was a great reference book for our project as it covers both optimization and simulation concepts. Specific topics include integer programming, binary integer programming, and sensitivity analysis. It includes model formulations, vocabulary, examples, and case studies. Examples are solved in a variety of ways, including LINGO, which is the software we will utilize. While this text is a good reference, it does have its limitations. The traveling salesman problem (TSP) can be solved in a number of ways, including integer linear programming (which is the method we will utilize). This book, however, instead leverages three metaheuristic methods to formulate the problem. Therefore, we may need a supplementary reference book for the TSP formulation.

An article published by the L. Eboli and G. Mazzulla in the journal of public transportation proposes a structural equation model (SEM) to analyze the impact of service quality attributes on global customer satisfaction. The model is applied to a public bus system used regularly by university students to get to campus. The model evaluates the relationships between (1) endogenous and exogenous latent variables, and (2) latent and observed variables. The authors conducted a survey to measure students' socioeconomic background and perceived bus service quality, as determined by 16 attributes. Through exploratory factor analysis (EFA), the authors identified 4 exogenous latent variables – (1) service planning and reliability, (2) comfort and other factors, (3) safety and cleanliness, and (4) network design. These variables were measured by the 16 service quality attributes (observed variables). They also used EFA to determine the endogenous latent variable – satisfaction, which was measured by the global service indicators of perceived and expected quality (observed variables). The SEM determined which service attributes were in need of improvement. [7]
Like this study, we are collecting student surveys which will measure students' socioeconomic background and perceived bus service quality. While we use statistical analysis to evaluate areas perceived to need improvement, SEM may be a powerful tool for evaluating student satisfaction in future studies. [7]

A study done in the Journal of Traffic and Transportation Engineering looks at different optimization model aspects to attempt to minimize total bus stop time (TBST) as a way to increase route reliability.[8] TBST includes the amount of time that a bus takes exiting traffic to get to a stop, loading and unloading passengers, and pulling back onto the road. TBST can be affected by a number of factors, including time of day, traffic patterns, bus stop location, and passenger payment methods. We can approximate TBST from the time stamps recorded of passenger entries onto the bus. We can do a time study to get a more accurate measure of TBST at each stop throughout the day. It is also worth exploring ways in which the KSU Department of Transportation might decrease TBST. This will not be a main component of our research project, but rather serve as means of further recommendations.

As we continued to look for similar problems we realized that our problem was similar to the TSP. A modification of the traveling salesman problem, the vehicle routing problem, similar in concept to the TSP but it looks at multiple routes instead of minimizing one overall. The author Azi in the European journal of operations research presents a branch and price approach to solve a vehicle routing problem with both time windows and multiple uses of vehicles. In this problem, vehicles make multiple delivery routes throughout the day to deliver perishable (time sensitive) goods to customers.[11] Time windows refer to the time allotted to deliver a particular good, and multiple use refers to the fact that a vehicle takes multiple trips throughout the day. [11] A potential application of this method is to determine the most effective routes for an on-campus on-demand shuttle service to deliver students to less popular destinations or for service to specific destinations at night. Time windows could be dependent on where the student was picked up and the desired drop off location.

S. Kornfeld, W. Ma, and A. Resnikoff students form Carnegie Mellon University presented a project in operations research, "Optimizing Bus Schedules to Minimize Waiting Time," using optimization to determine the optimal number of busses to schedule throughout the day in order to minimize total wait times for passengers. This study used many assumptions, some of which may be beneficial for us to apply to our own project. Those assumptions include: the public data they obtained is accurate, bus capacity is infinite, and bus arrivals are deterministic and occur at even intervals. They created two models – (1) a simpler deterministic model in which interarrival times for passengers were assumed to be constant, and (2) a Poisson model in which passenger arrivals follow a Poisson distribution. They solved both models twice: once using 1 hour time buckets, and once using 2 hour time buckets. They came up with the same bus allocations for both models, although the expected total wait times differed. While they did not take traffic delays into account (as we wish to do), they did use a variable v for the average bus speed. This value, however, was constant for the entire day. “Transit Network Design And Scheduling: a Global Review,” focuses on papers that detail route design, route frequency, and timetabling. They summarize the independent inputs needed for different planning activities, and the output(s) that result(s) from that activity. Mathematical methods for finding solutions to these activities are described. They can be categorized as follows: specific and ad hoc heuristics, neighborhood search, evolutionary search, and hybrid search []

Sensitivity analysis can be a very useful tool when using optimization to help improve different processes. This tool looks at different variables and constraints then determines what happens to the optimal solution if you manipulate by increasing it or decreasing it. Pannell, the author of "Sensitivity analysis: strategies, methods, concepts, examples," presents a “selective review” of simpler methods of sensitivity analysis (SA). He divides reasons for SA into four categories, but chooses to focus on one – making decisions or recommendations. From a decision-making standpoint, SA is particularly valuable in cases of uncertainty in parameter values. The decision maker can also evaluate the robustness of the solution, or how sensitive the solution is to changes in parameter values. A solution that is robust is insensitive to changes in parameter values, and is seen as less risky. Variables (and sets of variables) to analyze should be chosen selectively so that the amount of data analyzed does not overshadow the results obtained. Three strategies (A, B, and C) are presented, with strategy B being a simplification of strategy A, and C being a simplification of B. In short, the method is as follows: analyze each parameter individually, remove unresponsive parameters from further evaluation, determine how correlated the remaining values are and perform further experiments on those values. Experiments should focus on parameters which are highly correlated. Methods are also provided for presenting results and conclusions.

Chapter 3: Approach

1. Design Concepts

1.1. Project Objectives

Our objectives are:

1) Recommend stops to add/remove to routes.
2) Make recommendations that address student concerns, as determined by a student survey.
3) Determine the optimal number of buses for the routes.
4) Suggest addition of bus shelters to select stops.
5) Recommend changes in stop order and/or route direction, where applicable.
6) Perform a financial analysis of the B.O.B. route before and after improvements.
7) Improve the standard deviation of wait times. (Target wait times are 15 – 20 minutes).
8) Improve customer satisfaction.

1.2. Minimum Success Criteria

This project will be successful if the following criteria are met:

1) Find optimal set of routes given current stops.
2) New routes lead to a decrease in student wait times.
3) Bus stop wait times do not exceed 20 minutes on the Marietta/Kennesaw route.

1.3. Design Requirements & Specifications

Our design requirements are:

1) Conduct a student survey.
2) Meet IRB (Institutional Review Board) project guidelines.
3) Do not exceed 16 total buses across all routes, including spares.
4) Do not add bus shelters to stops where buildings and/or awnings are easily accessible.
5) Do not exceed current total route travel times.

1.4. Approach

To optimize the Kennesaw-Marietta bus route, we will:

1) Obtain bus usage data, B.O.B. financial data, and student feedback from the Department of Transportation.
2) Conduct student surveys to determine current perceptions of the bus route.
3) Create linear optimization model to maximize usage while minimizing time and cost.
4) Verify that solution meets design requirements through simulation model.
5) Perform statistical analysis to compare proposed solution to current operations.
6) Make revisions to model as necessary; reverify and revalidate.
7) Perform a sensitivity analysis on the proposed optimal solution.

2. Verification

We will verify our solution by creating a simulation model of the current bus route and our solution. We will compare the results to the results obtained through our optimization model.

Additionally, we will perform a statistical analysis to compare our obtained solution to current operations.

3. Budget

No funds will be required for to complete this project; however, we will take the Department's budget into consideration when performing analyses and making recommendations.

4. Resources

We will utilize the following software to complete this project:

- Arena (a discrete-event simulation software)
- Excel
- Excel Solver (a free Excel add-in to solve optimization models)
- Excel Solver Plus (a paid version of Excel Solver for solving larger optimization models)

5. Team Assignments

Both team members will participate in each task. Table 1 below indicates which team member will take lead on a given task, and what distinguishes the lead's tasks from the other team member's.

Table 1: Team Assignments

Lead	**Task**	**Lead's Distinguishing Tasks**
Define Problem (Chapters 1 and 3)		
Valerie	Define design requirements and specifications	Ensure list of design requirements and specifications collectively cover scope of project.
Data Collection and Analysis (Chapter 4)		
Valerie	Obtain IRB Approval and oversee student survey collection	Follow up with KSU IRB when necessary to obtain approval. Print flyers and submit survey recruitment email to KSU Student Inform. Oversees IRB close out report at semester end.
DJ	Conduct driver interviews	Interview drivers on different routes.
Valerie	Obtain and clean bus data	Contact Department of Transportation to obtain data;, and analyze for use in optimization and simulation models.
Valerie	Time study	Conduct time-study of bus routes
Optimization Models (Chapters 2, 5, and 6)		
DJ	Literature review	Oversee model-related literature review
DJ	Create optimization models	Develop mathematical formulations and program into software of choice; oversees interpretation of model results.
Sensitivity Analysis (Chapter 2 and 7)		
Valerie	Sensitivity analysis	Honors Capstone Project. To be completed entirely by lead. Complete sensitivity analysis.

Valerie	Literature review	Complete sensitivity analysis-related literature review.
Model Verification (Chapter 8)		
Valerie	Simulation	Simulate new bus routes and bus assignments
Implementation Plan (Chapters 9 and 10)		
DJ	Implementation plan	Outline required tasks and associated timeline and costs.
DJ	Financial analysis	Evaluate cost of developing the solution, the cost of the new routes, and cost of implementation
Deliverables		
DJ	Video, report	Develop video and finalize report
Valerie	PowerPoint, poster	Develop PowerPoint presentation and poster.

6. Schedule

Our projected schedule is reflected in the Gantt chart in Figure 2 below. Tasks in red denote to do items for the group senior design project, and those in blue signify tasks to be completed for the honors capstone.

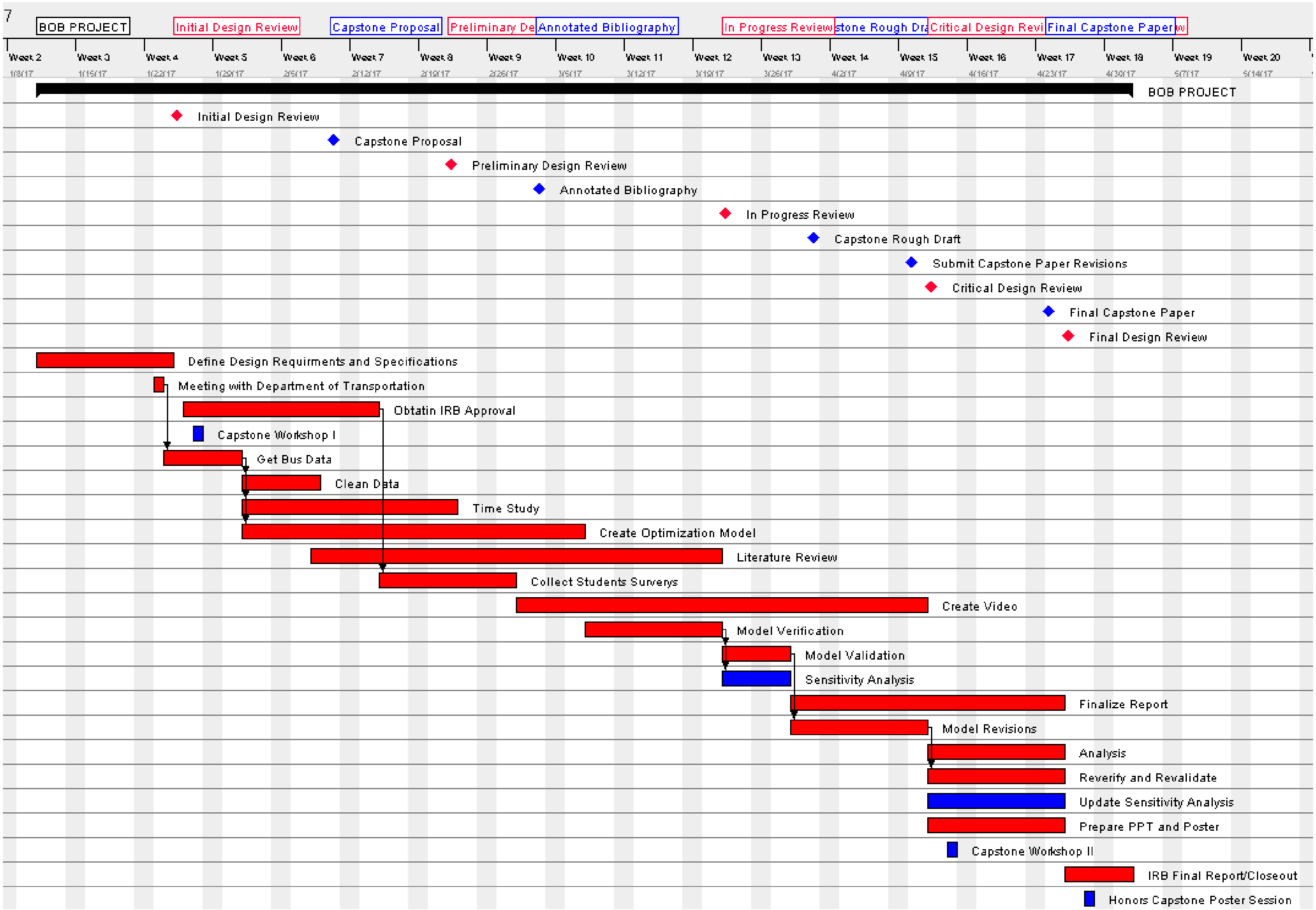

Figure 2: Gantt Chart

Chapter 4: Data Collection and Evaluation

1. Current Bus Routes

The B.O.B. currently has 9 routes, as presented in Table 2 below.

Table 2: Current B.O.B. Routes

Route and Description	Hours In Service
Kennesaw-Marietta: Transports students between the two campuses	M-Th 6:45AM – 11:00PM F 6:45AM – 7:00PM Sa 12:00PM – 8:00PM
Busbee Drive/Stadium: "service between Kennesaw Campus, KSU Center, 3305 Busbee, Busbee Park & Ride, Stadium Village and U-Pointe student apartments, as well as Fifth Third Stadium"	M-Th 7:00AM – 11:00PM F 7:00AM – 7:00PM
Chastain Pointe: "connects the center of Kennesaw Campus, parking at the West Lot and Church Lot, the Austin Residence Complex, and the Chastain Pointe offices"	M-Th 7:00AM – 10:00PM F 7:00AM – 7:00PM
Frey Road: "provides service between the Bagwell College of Education on Kennesaw Campus to the U Club Apartments on Frey Road"	M-Th 7:00AM – 7:00PM F 7:00AM – 11:00PM
Skip Spann: "service between the Bagwell College of Education on Kennesaw Campus to the East Parking Lot and The Blake student apartments"	M-Th 7:00AM – 11:00PM F 7:00AM – 11:00PM
West Campus: "connects the center of Kennesaw Campus, parking at the West Lot and Church Lot, the Austin Residence Complex, and the West-22 student apartments"	M-Th 7:00AM – 11:00PM F 7:00AM – 7:00PM
Town Pointe: "direct connection between the Rec Center on Kennesaw Campus and the Town Point office building"	M-Th 7:00AM – 10:00PM F 7:00AM – 7:00PM
Kennesaw Shopping: "operates as circulator between Kennesaw Campus, Town Center Mall and Walmart"	F-Sa 12:00PM – 8:00PM
Marietta Shopping: "operates as circulator between Marietta Campus and Walmart"	F-Sa 12:00PM – 8:00PM

Adapted from transit.kennesaw.edu

The maps of all but the shopping routes are shown below in Figure 3 (both campuses) and Figure 4 (Kennesaw Campus only).

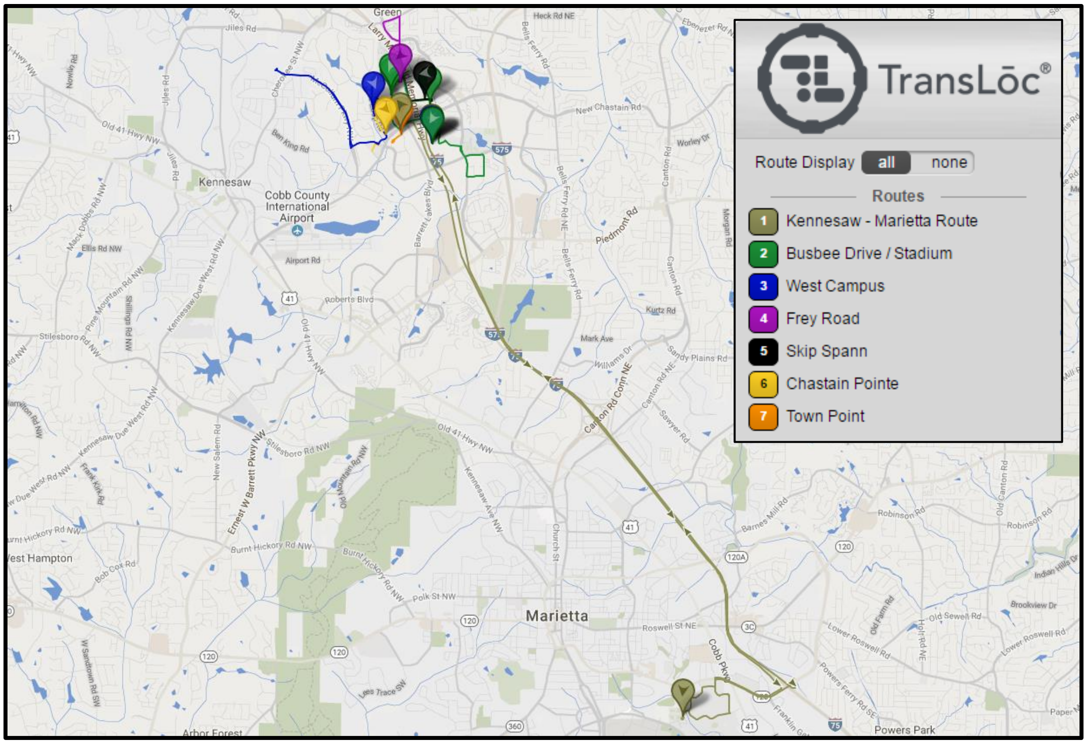

Figure 3: Current routes (excluding shopping routes), both campuses
Adapted from kennesaw.transloc.com

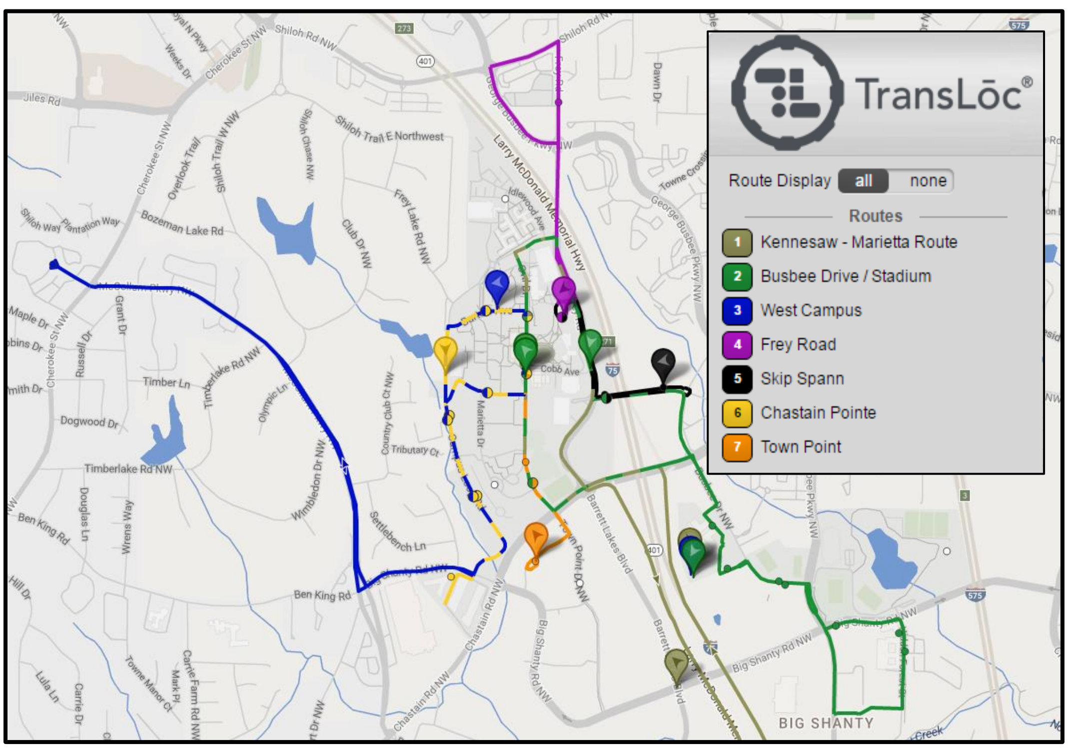

Figure 4: Current routes (excluding shopping routes), Kennesaw Campus
Adapted from kennesaw.transloc.com

2. Target Pick Up Times for Kennesaw-Marietta Route

For the Spring 2017 semester, the Department of Transportation implemented a new system where drivers have target time points for arriving and departing from key stops on the Kennesaw-Marietta Route. Each driver gets a time table similar to the one in Table 3 below. The list of time points in Table 3 are for bus 1 (denoted by "Block 1"), Monday through Thursday. Drivers get a separate schedule for Fridays. The master list of time points for Monday through Thursday as well as Friday are included in

Appendix E and Appendix F, respectively. The stops included in the time tables are:

- "Rec Center" – Dr. Betty L. Siegel Student Recreation and Activities Center (SRAC) [Kennesaw Campus]
- "Commons" – The Commons [Kennesaw Campus]
- "Courtyard" – Courtyard Apartments [Marietta Campus]
- "Joe Mack" – Joe Mack Wilson Student Center [Marietta Campus]

Table 3: Driver Time Points, Bus 1 of Kennesaw-Marietta Route, Monday through Thursday

Kennesaw / Marietta Time Points						
	Rec Center-Arrive	Rec Center - Leave	Commons	Courtyard	Joe Mack-Arrive	Joe Mack-Leave
Block 1	6:44 AM	6:45 AM	6:46 AM	7:26 AM	7:34 AM	7:35 AM
Block 1	7:59 AM	8:03 AM	8:04 AM	8:44 AM	8:52 AM	8:56 AM
Block 1	9:20 AM	9:28 AM	9:29 AM	10:01 AM	10:09 AM	10:19 AM
Block 1	10:38 AM	10:44 AM	10:45 AM	11:15 AM	11:23 AM	11:28 AM
Block 1	11:48 AM	11:59 AM	12:00 PM	12:25 PM	12:33 PM	12:38 PM
Block 1	1:00 PM	1:09 PM	1:10 PM	1:35 PM	1:43 PM	1:47 PM
Block 1	2:11 PM	2:18 PM	2:19 PM	2:44 PM	2:52 PM	2:57 PM
Block 1	3:27 PM	3:34 PM	3:35 PM	4:02 PM	4:10 PM	4:15 PM
Block 1	4:50 PM	4:55 PM	4:56 PM	5:28 PM	5:36 PM	5:41 PM
Block 1	6:16 PM	6:18 PM	6:19 PM	6:51 PM	6:59 PM	7:07 PM
Block 1	7:39 PM	**End of Shift - 8 PM**				

The objective of these time points is to ensure stops are serviced at even intervals throughout the day. There are short delays of 1 to 11 minutes built into the stops at the SRAC and the Marietta Campus Student Center. If drivers are too early or too late at a stop, they are expected to lengthen or shorten their time at that stop to get back on schedule.

3. Bus Usage Trends

Bus usage trends are crucial for the optimization and simulation models. For the purposes of this project, we consider bus usage trends to be the total number of passengers boarding or exiting a bus at a specific stop of a specific route. The number of passengers will vary according to the time of day and day of the week.

3.1. Bus Entrance Data

Bus entrance data was provided by the Department of Transportation. At the time of this report, there is no system in place to track the number of students exiting at a particular stop. The data reflects ridership counts for the Spring 2017 semester, from Monday, January 9, 2017 at 8:46 AM through Saturday, February 4, 2017 at 5:37 PM. Each data point has the following information associated with it:

- ID – internal ID assigned to the data point (*not* the student's ID number)
- Date – date the data was recorded
- Time – time data was recorded
- Bus – bus number of bus student boarded or exited
- Route – name of route the bus was assigned to
- Stop – name of the bus stop where the data was recorded
- Count – total number of passengers boarding or exiting at a stop
- On/Off – reflects whether a passenger boarded (on) or exited (off); currently, Department of Transportation does not have the capability to track when students exit the bus
- Lat – latitude at which the stop is located
- Lng – longitude at which the stop is located

A sample of the spreadsheet is copied below in Table 4 for clarity. Due to the size of the file (14,824 data points), the file is not included in the appendix.

Table 4: Sample Raw Data of Bus Boarding

Id	Date	Time	Bus	Route	Stop	Count	On/Off	Lat	Lng
111528855	1/9/2017	8:46:03	314	Skip Spann Route	Rec Center	1	on	34.03	-84.57
111528864	1/9/2017	8:46:53	408	Kennesaw-Marietta Route	Rec Center	1	on	34.03	-84.57
111528866	1/9/2017	8:47:49	408	Kennesaw-Marietta Route	Rec Center	2	on	34.03	-84.57
111528944	1/9/2017	8:48:31	408	Kennesaw-Marietta Route	Rec Center	1	on	34.03	-84.57
111529048	1/9/2017	8:54:43	408	Kennesaw-Marietta Route	Rec Center	2	on	34.03	-84.57
111529050	1/9/2017	8:55:10	408	Kennesaw-Marietta Route	Rec Center	1	on	34.03	-84.57
111529099	1/9/2017	8:57:38	408	Kennesaw-Marietta Route	Rec Center	1	on	34.03	-84.57
111529112	1/9/2017	8:58:23	316	Busbee/Stadium Route	Rec Center	1	on	34.03	-84.57
111529149	1/9/2017	8:58:41	312	Busbee/Stadium Route	Rec Center	1	on	34.03	-84.57
111529150	1/9/2017	8:59:27	312	Busbee/Stadium Route	Rec Center	1	on	34.03	-84.57
111529174	1/9/2017	9:00:39	314	Skip Spann Route	Rec Center	1	on	34.03	-84.57
111529276	1/9/2017	9:04:52	408	Kennesaw-Marietta Route	Rec Center	1	on	34.04	-84.58
111529367	1/9/2017	9:08:07	403	Busbee/Stadium Route	Rec Center	1	on	34.03	-84.57
111529382	1/9/2017	9:08:22	408	Kennesaw-Marietta Route	Rec Center	1	on	34.04	-84.58
111529543	1/9/2017	9:17:29	406	Kennesaw-Marietta Route	Rec Center	1	on	33.94	-84.52
111529685	1/9/2017	9:20:17	406	Kennesaw-Marietta Route	Rec Center	1	on	33.94	-84.52
111529863	1/9/2017	9:25:35	316	Busbee/Stadium Route	Rec Center	1	on	34.04	-84.58
111529948	1/9/2017	9:28:40	314	Skip Spann Route	The Blake	1	on	34.04	-84.58
111530228	1/9/2017	9:38:32	407	Busbee/Stadium	Rec Center	1	on	34.04	-84.58

We evaluated the average demand per hour by day of the week for each of the routes. This data is presented in the graphs that follow. Note that some days of the week are omitted for certain route because 1) the bus does not run on that particular day, or 2) there was no data collected for that day of the week. The latter is especially true for the Town Point Route, for which there was no data provided. It is also true of the Chastain Pointe Route, which runs every weekday; however, there were several days when tracking was presumably not turned on for the buses on that route. Though we had four weeks of data, we only had data for five days total on the Chastain Pointe Route – Wednesday 1/11/2017, Thursday 1/12/2017, Friday 1/13/2017, Tuesday 1/17/2017, and Wednesday 2/1/2017. Additionally, it is worth mentioning that some of the routes had data for days the bus is not scheduled to run. For example, our data shows that rides were tracked on the

Kennesaw Shopping Route on Tuesday 1/24/2017, and on the Marietta Shopping Route on Wednesday 1/25/2017, though both routes run on weekends only. Additionally, the Skip Spann Route has data logged for Sunday 1/15/2017 and Sunday 1/29/2017, even though none of the routes run on Sundays. It is likely that either the data points were collected in error, or the route ran for special hours on that day for a special event.

Note that the demand throughout the day is fairly normally distributed, keeping in mind that there is incomplete data for some of the routes.

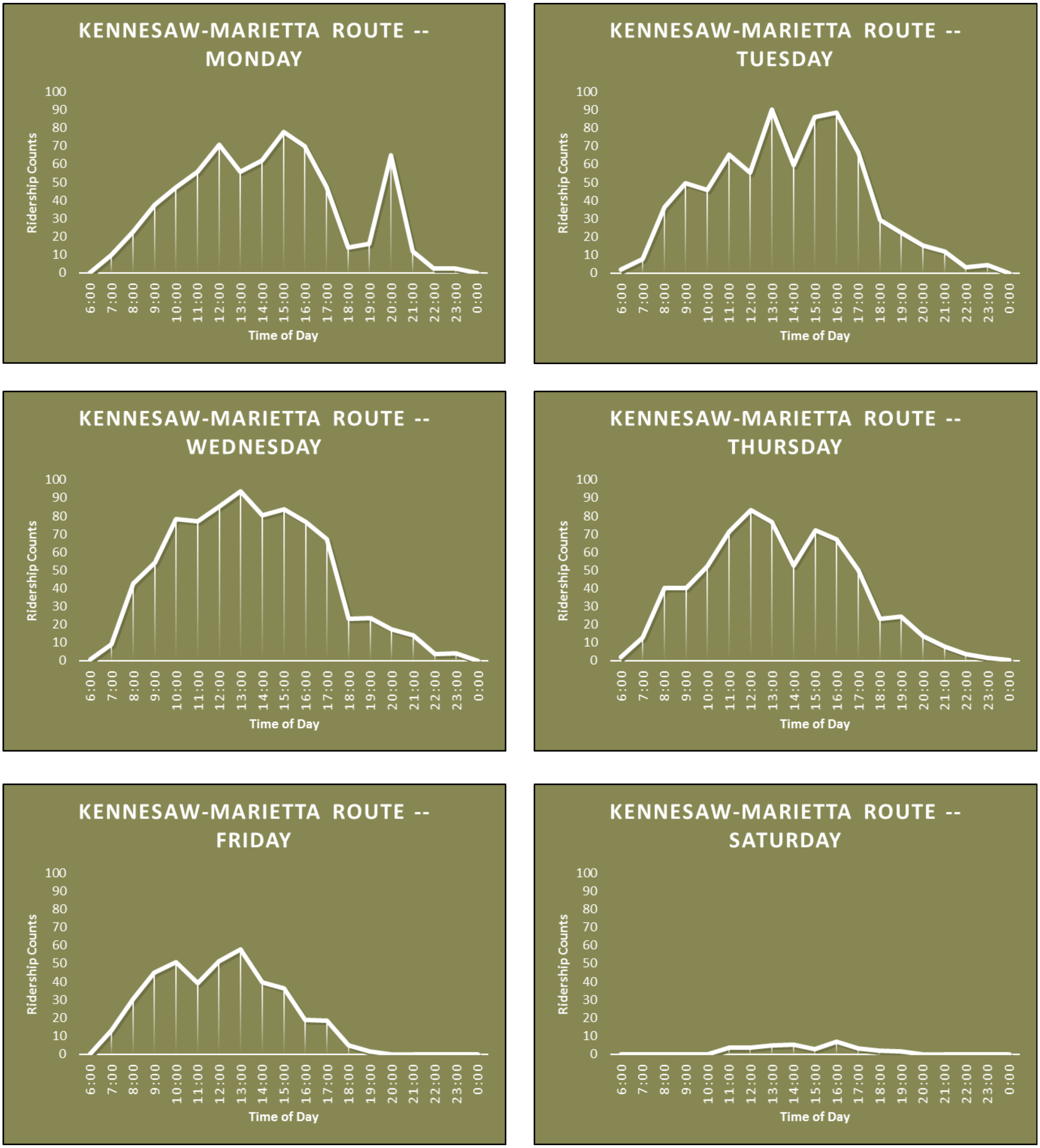

Figure 5: Kennesaw-Marietta Route Demand by Hour and Day of Week

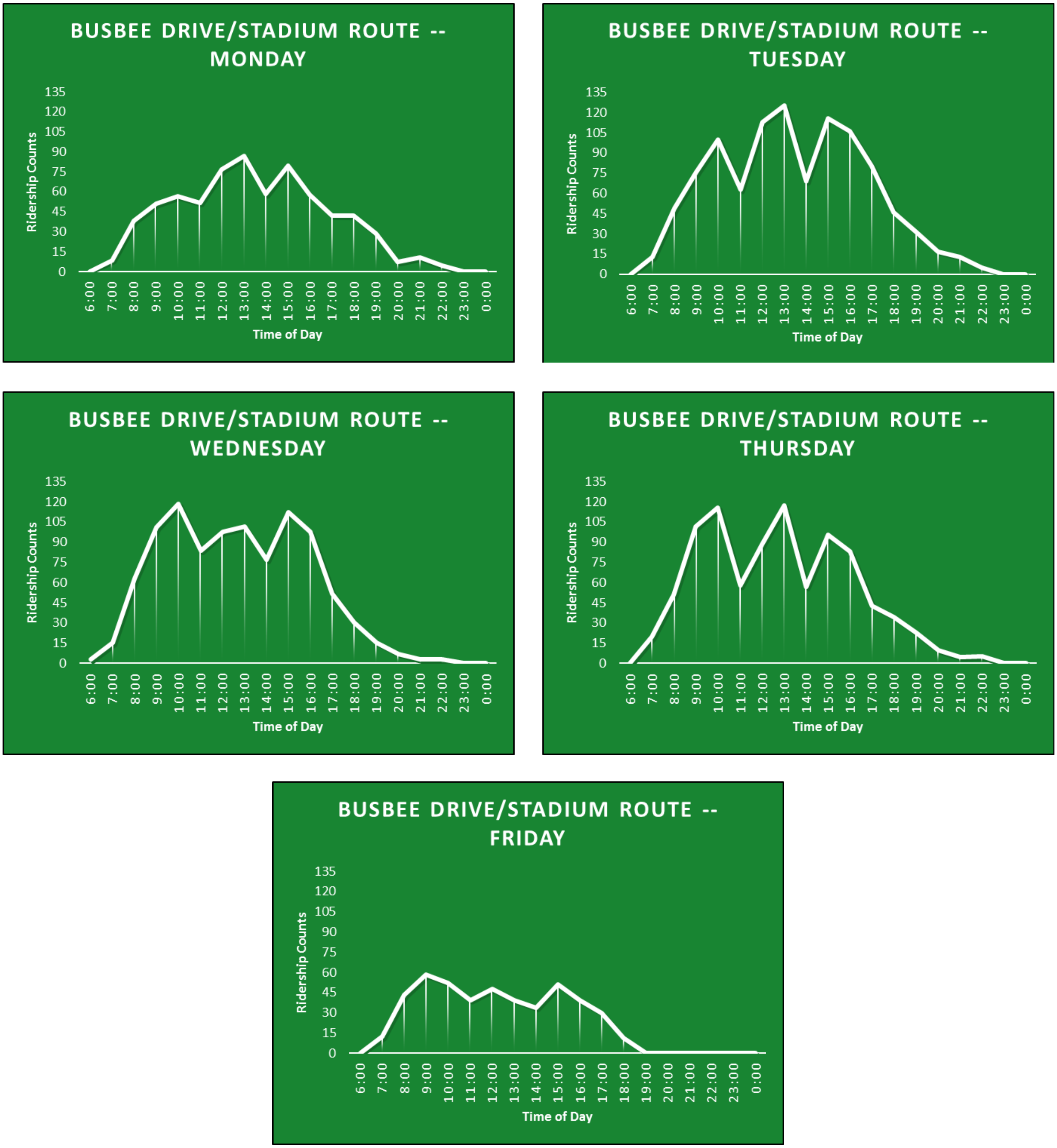

Figure 6: Busbee Drive/Stadium Route Demand by Hour and Day of Week

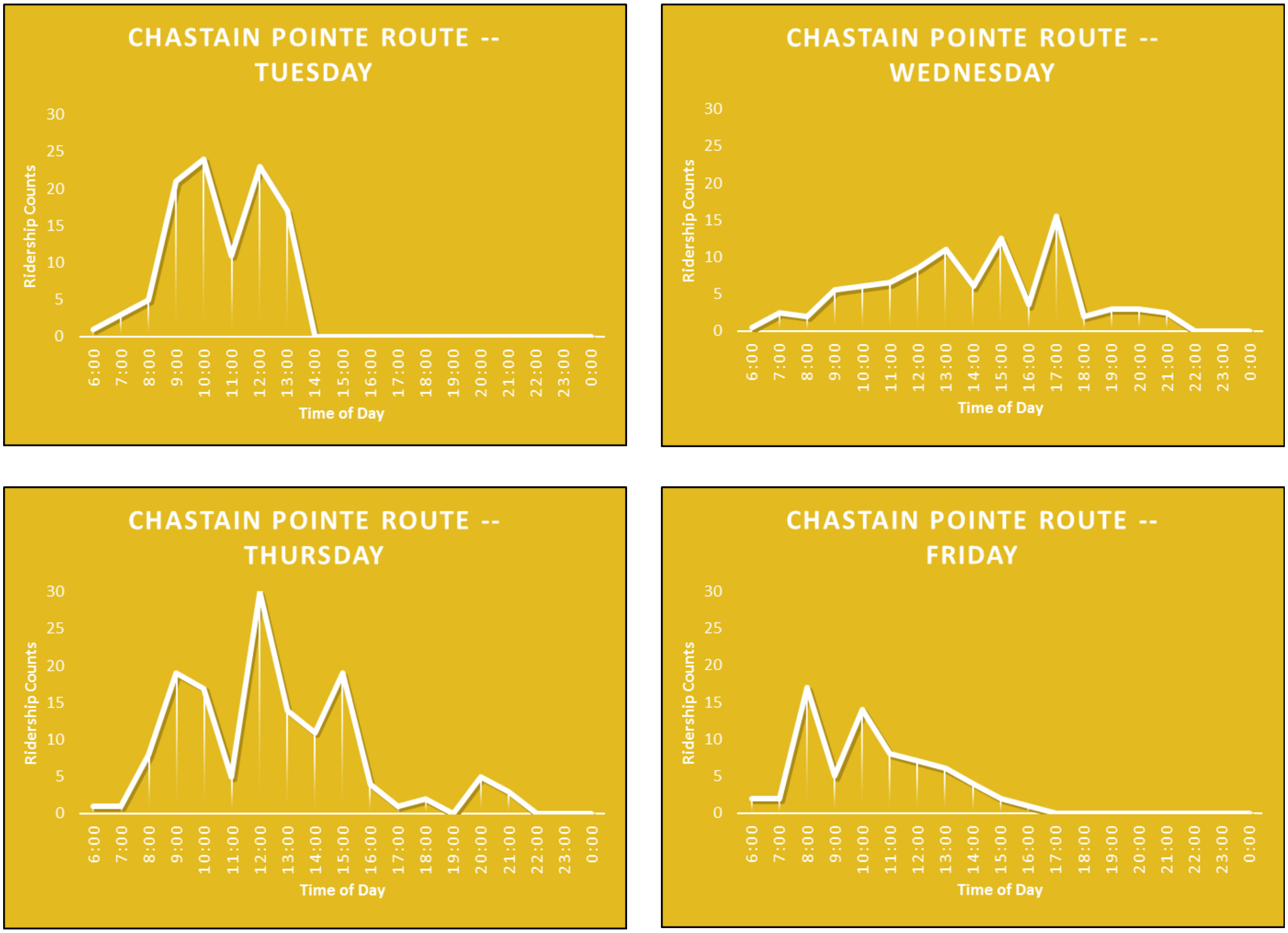

Figure 7: Chastain Pointe Route Demand by Hour and Day of Week

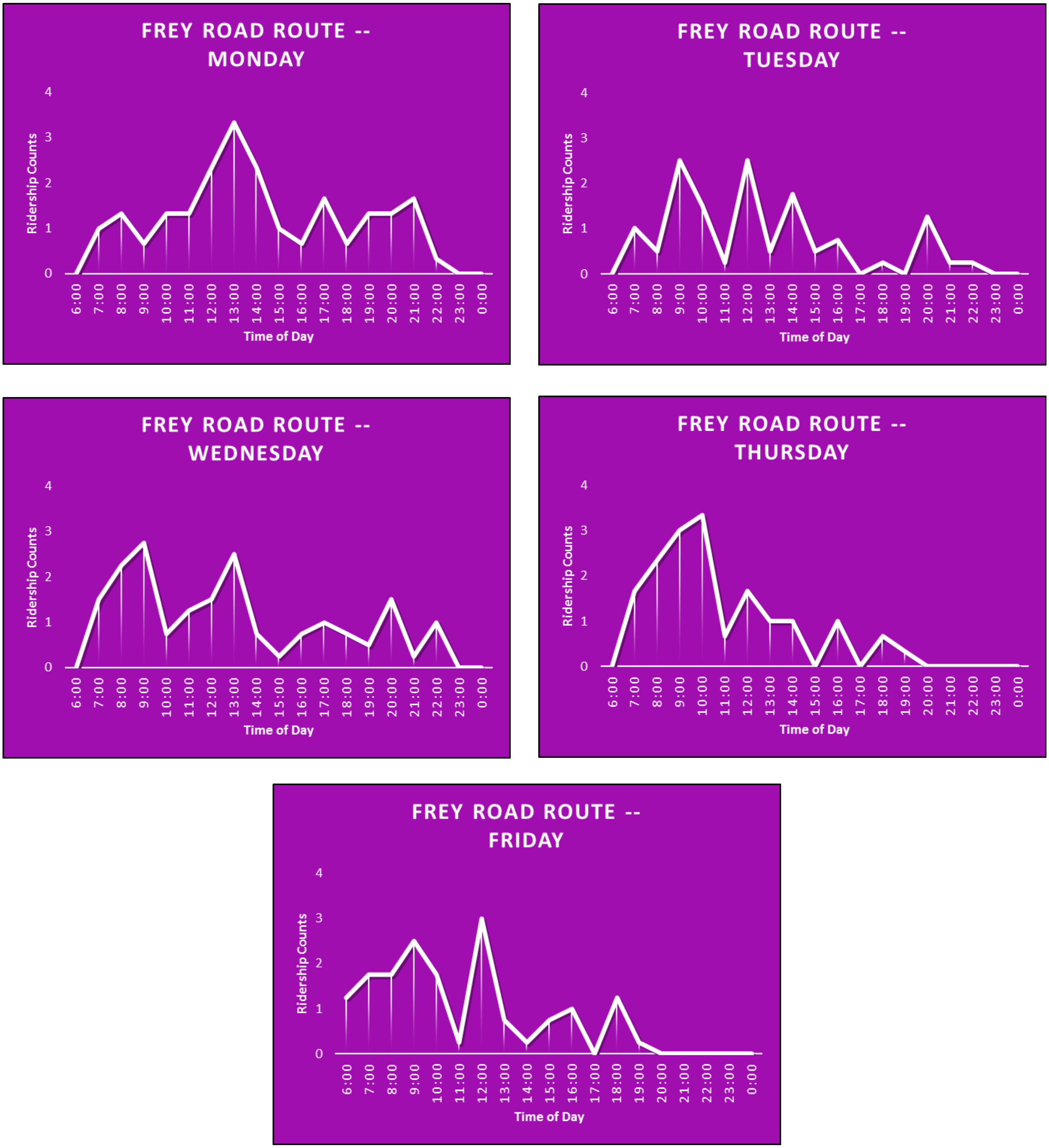

Figure 8: Frey Road Route Demand by Hour and Day of Week

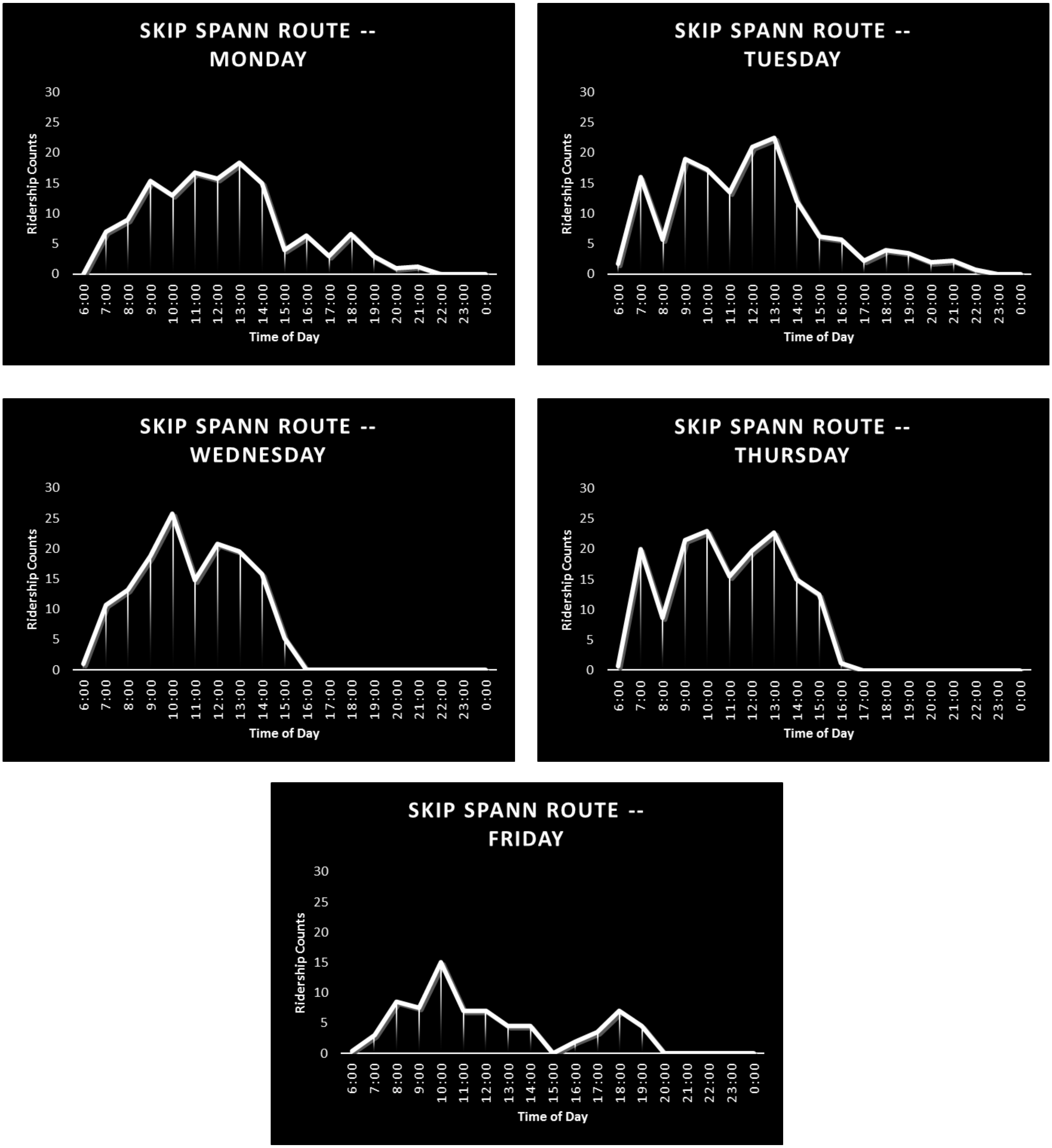

Figure 9: Skip Spann Road Route Demand by Hour and Day of Week

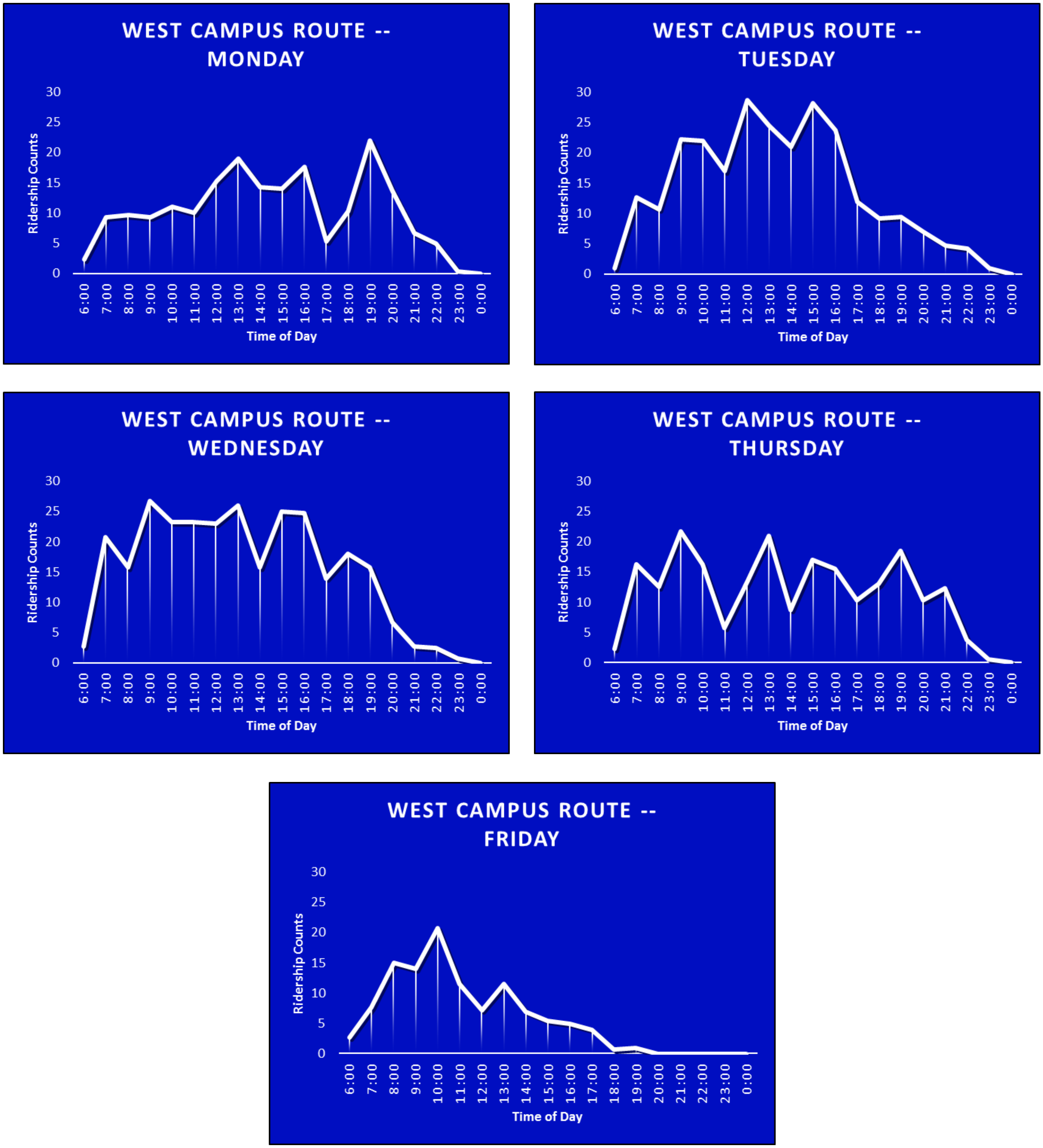

Figure 10: West Campus Route Demand by Hour and Day of Week

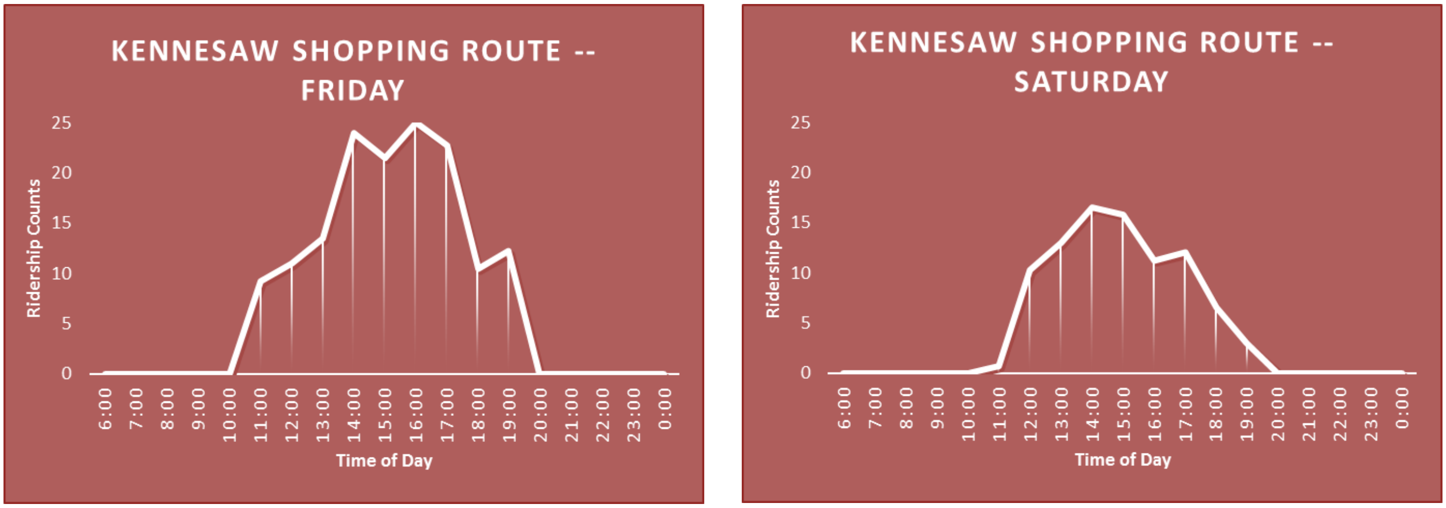

Figure 11: Kennesaw Shopping Route Demand by Hour and Day of Week

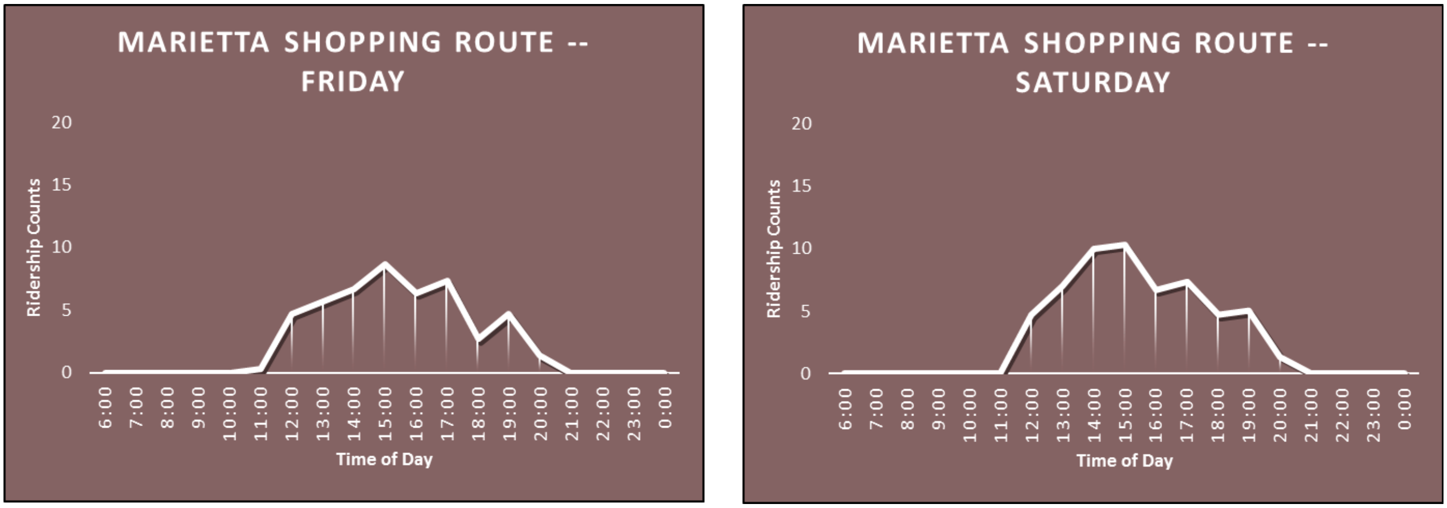

Figure 12: Marietta Shopping Route Demand by Hour and Day of Week

3.2. Bus Exit Data

The bus usage data we received was limited in that it did not reveal how many students exit at a given stop. To fill in the gaps of this missing data, we rode the Kennesaw-Marietta route on 2 separate occasions to observe the number of students exiting at a given stop. The information collected can be found in Appendix G. For the privacy of the drivers, the dates and times the data was collected have been omitted. In place of time of day, time elapsed is shown.

4. Total Bus Stop Time

The time study can also inform us on the total bus stop time for a given stop. Total bus stop time (TBST) is the total time it takes for a bus to exit traffic, passengers to board or exit the bus, boarding passenger to pay, and for the bus to pull back into traffic. We calculated the TBST as a function of the passengers boarding and exiting, and the additional amount of time the driver decides to wait at a particular stop. TBST at a stop i, in seconds, is approximated to be:

$$TBST_i = 6 + 3.589(ON_i) + 3.100(OFF_i) + break_i \quad (1)$$

In the equation above, ON_i and OFF_i represent the total number of students boarding and exiting at stop i, respectively. The variable $break_i$ represents the amount of additional time that a driver decides to delay at a stop, which can include scheduled or unscheduled breaks, bathroom or stretching breaks, waiting because the driver sees a student running toward the bus, or delaying as a way to get back on schedule if the bus arrives too early. This equation approximates the time for the bus doors to both open and close to be 6 seconds, and the time for each student to board and exit to be 3.589 seconds and 3.100 seconds, respectively. This equation assumes that passenger boarding, passenger departures, and driver breaks happen at separate times. It also assumes that the driver always stops briefly at a stop (for a minimum of 6 seconds), even if on one boards or exits the bus.

The coefficients were approximated based on the time study entries in which (1) no students boarded or exited, (2) students only boarded, and (3) students only exited. There are other factors that may impact $TBST_i$ that are not directly accounted for in the equation. Those factors include additional time spent while students load or unload their bikes from the bus, or time spent securing a passenger with a wheel chair in place. For the purposes of this equation, those factors should be accounted for in $break_i$.

5. Bus Usage Costs

We received a list of costs associated with the buses from the Department of Transportation. They are as follows:

- Budgeted transit operating costs (excluding fuel): $2,855,559
- Maintenance costs (included in operating cost): $7,000 - $8,000 per year per bus
- Budgeted transit fuel costs: $250,276
- Hourly contracted expense (driving staff, operations management staff, maintenance, bus lease, maintenance shop lease, insurance, uniforms, etc): $69.73/hr

Other relevant information closely associated with cost includes:

- Expected total hours of contract transit service: 40,951 hours
- Average hourly starting wage: $12.50/hr
- Fuel efficiency: 5 MPG
- Number of drivers currently employed: 27
- 16 vehicles total:
    - Two 10-passenger vans
    - Six 34-passenger buses
    - Eight 57-passenger buses (35 seated, 22 standing)

6. Stakeholder Opinions

We collected student and driver opinions of the B.O.B through a survey and interviews, respectively. We plan to use these opinions to shape our recommendations to improve the routes.

6.1. IRB Approval

We obtained KSU Institutional Review Board (IRB) approval for our project under Study #17-312: Optimizing the B.O.B. (Big Owl Bus).

6.2. Student Opinions

Participants were recruited for the survey primarily through flyers posted both the Marietta and Kennesaw Campuses. Additionally, we contacted members of the Student Government Association (SGA) to advertise our survey. We attempted on several occasions to email our survey through KSU Student Inform, which is a daily campus-wide announcement and notifications system for students. Unfortunately, student surveys are evaluated on a case-by-case basis, and ours was not forwarded to the student body. No feedback was provided as to the reason why.

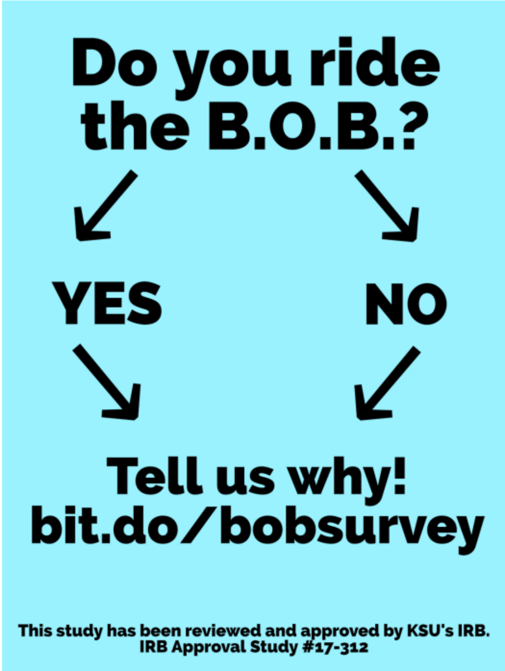

Figure 13: Two Versions of the Survey Recruitment Flyers

We conducted an anonymous survey online through Google Forms. We collected demographic information about students, including sex, age, classification, housing (resident or commuter), and methods of transportation owned (bike or car). If students indicated on the survey that they had ridden the B.O.B. before, they were then given questions regarding the frequency of use, the routes they use the most, and their reasons for riding the B.O.B. Additionally, we asked these students to rank nine categories, including cleanliness, wait times, safety, and location of stops, from great to needs improvement. Students who indicated they had not ridden the B.O.B. were asked to rank the same nine categories from 'strong influence in deciding not to ride the B.O.B.' to 'not a factor'. The complete list of survey questions can be found in Appendix H.

6.2.1. Kennesaw State University Student Body Demographics
There are 35,018 students enrolled for the 2016-2017 Academic Year. Of those students, 51% are male, and 49% are female. Student classifications are broken down as follows:

Table 5: KSU Classifications by Percent

Classification	*Percent*
Freshman	22.2%
Sophomore	21.5%
Junior	20.4%
Senior	26.2%
Graduate Student	8.1%
Dual Enrolled	1.0%
Other	0.5%
	100.0%

The average age of undergraduates is 23 years old, and the average age of graduate students is 35 years old.

All statistics were found in the Kennesaw State Univerity 2016-2017 Fact Book [16].

6.2.2. Survey Participant Demographics
In total, we received 106 responses. From the demographic information available in the KSU Fact Book, our participants were fairly representative of students at KSU. The following characteristics applied to most of the participants: female (55.7%), 18 to 24 years old (86.8%), students (93.4%), commuters (53.8%), and own a car (70.8%). Additionally, the majority of participants (84.9%) stated that they have ridden the B.O.B. at least once. For more details on the participants' demographics, reference the tables below:

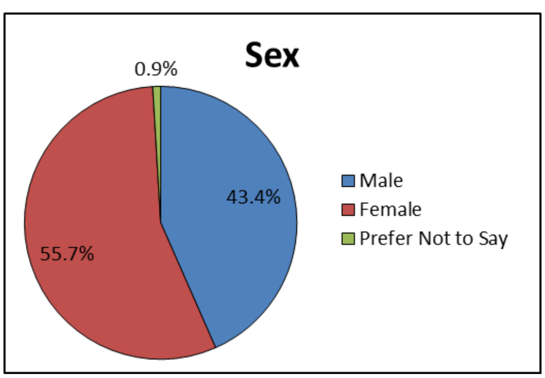

Figure 14: Survey Participant Demographics – Sex

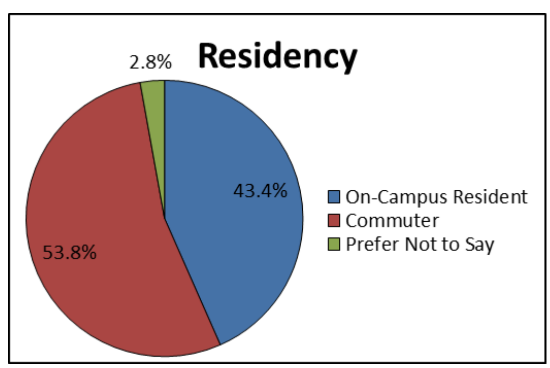

Figure 15: Survey Participant Demographics – Residency

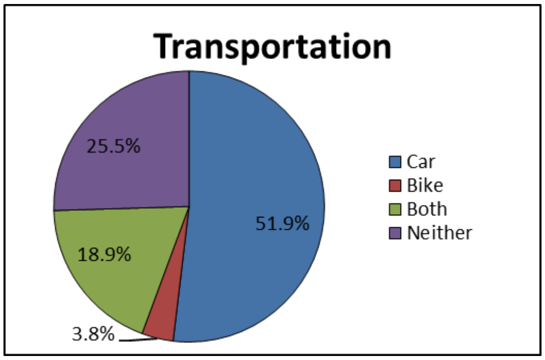

Figure 16: Survey Participant Demographics – Transportation

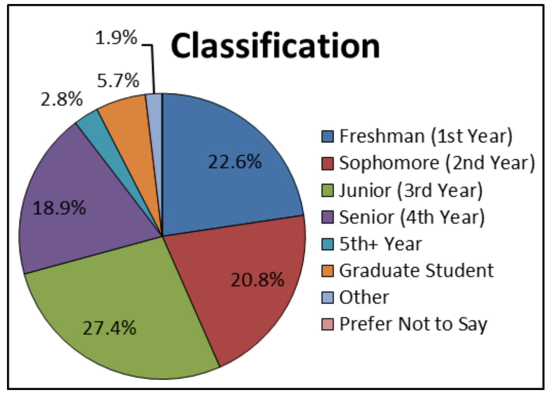

Figure 17: Survey Participant Demographics – Classification

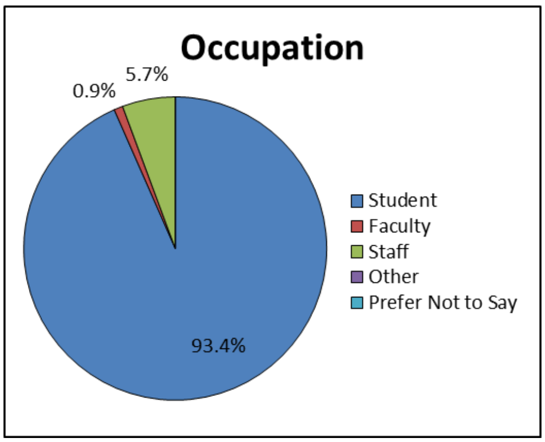

Figure 18: Survey Participant Demographics – Occupation

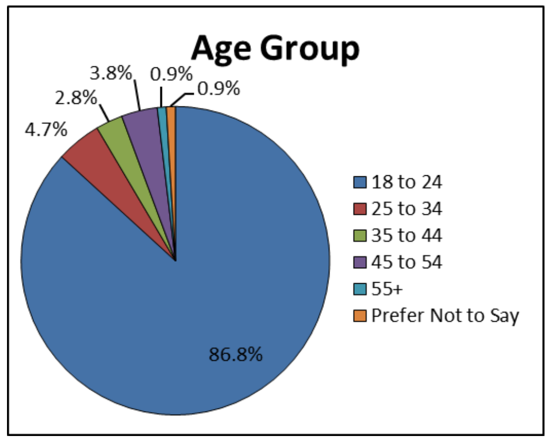

Figure 19: Survey Participant Demographics – Age Group

We created two subsamples from our sample of 106 participants, those that (1) did and (2) did not ride the B.O.B. The demographics of our subsamples closely modeled that of our larger sample.

6.2.3. Survey Participants Who Have Utilized the B.O.B.

Of the 90 survey participants who have ridden the B.O.B., 64.4% expressed that they ride it at least once per week, as indicated in Figure 20 below:

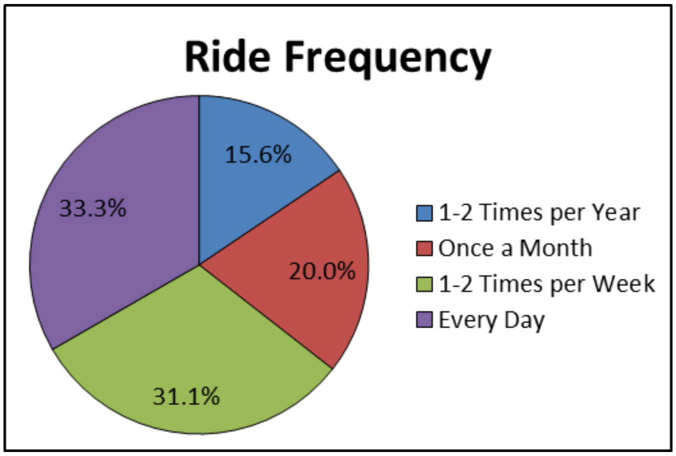

Figure 20: B.O.B. Ride Frequency

Most survey participants (65.6%) indicated that they had ridden the Kennesaw-Marietta route at least once. Another popular route was the Busbee Drive/Stadium route, which 30.0% of students said they rode. These two routes were also deemed to be the most popular routes during our analysis of the bus ridership trends.

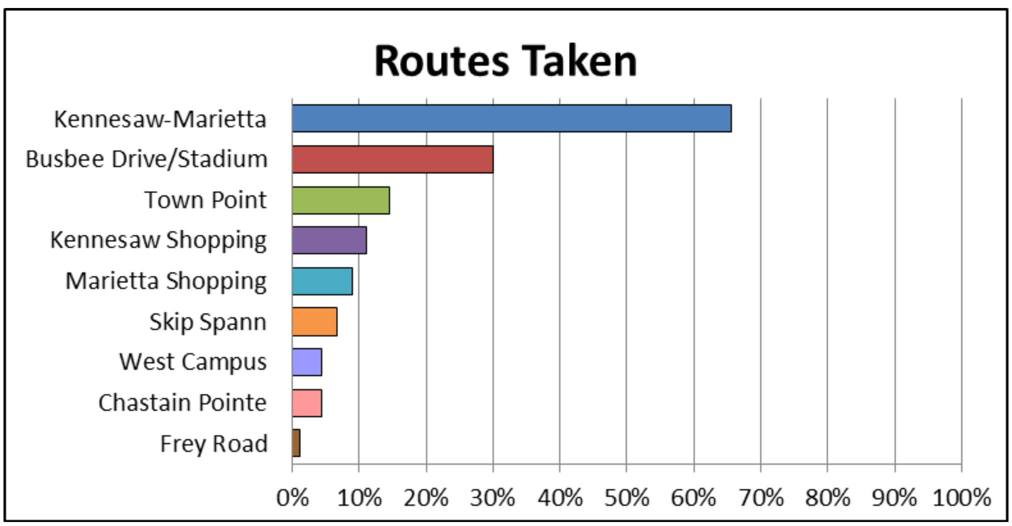

Figure 21: Routes Taken

A total of 16 participants indicating never having ridden the B.O.B. While this sample size is very small, we believe their input is still valuable for guiding our recommendations. We asked both subsamples to indicate their reasons for riding or not riding the B.O.B. Of those that have ridden the B.O.B., reasons that 40% or more of the participants expressed were: to take advantage of student fees (54.4%), to save money (48.9%), convenience (45.6%), and prefer not to drive even though the participant owned a car (40.0%). For those who also selected "other", reasons included limited parking, going to a special event (like a football game), or avoiding the rain. Of those who have not ridden the B.O.B., reasons that 40% or more of the participants expressed as being factors were: owning a car (87.5%), speed (56.3%), and convenience (43.8%). There were two participants who selected “other”. One indicated reliability as being a concern. The other was a student who commutes to the Marietta campus; since she has no need to go to the Kennesaw campus, or to use the Marietta Shopping Route, she expressed that she does not use the B.O.B.

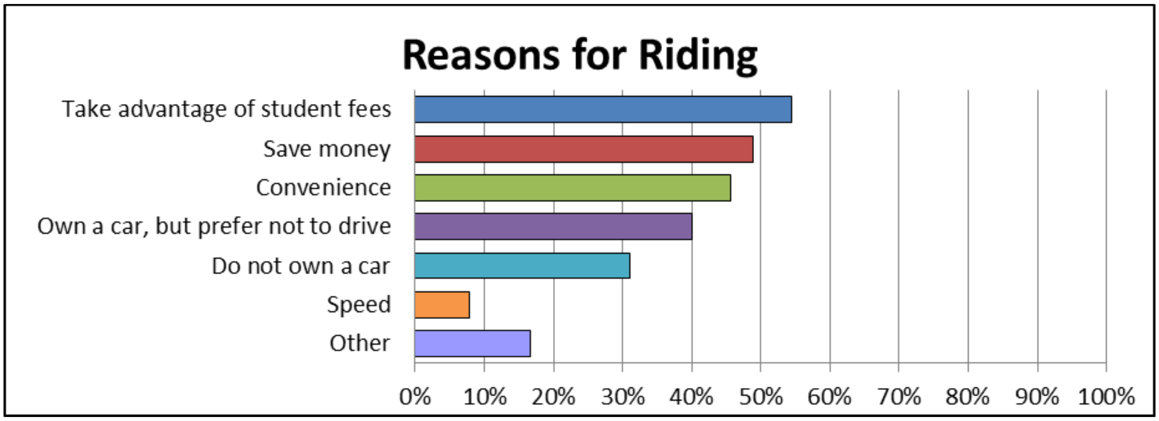

Figure 22: Reasons for Riding the B.O.B.

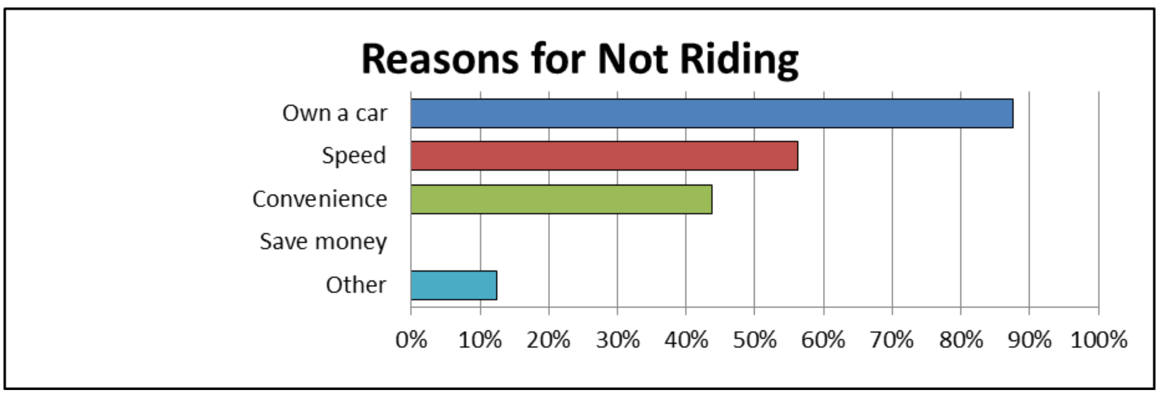

Figure 23: Reasons for Not Riding the B.O.B.

We asked all survey participants to rank their perceptions of the B.O.B.’s performance in nine areas. The subsample who rode the B.O.B. ranked their experiences as “great”, “good”, “poor”, or “needs improvement”. In the graphs that follow, these responses are color-coded from green to yellow to red. The subsample who did not ride the B.O.B. rated the performance areas as being a “strong influence”, a “weak influence”, or “not a factor” in the participant’s decision not to ride the B.O.B. These responses are color-coded in the graphs from red to yellow to green. The reason for this is that we interpret the rating “strong influence” as being a performance area that the survey participant perceives as needing improvement, and “not a factor” as being an area that is perceived by the participant as satisfactory.

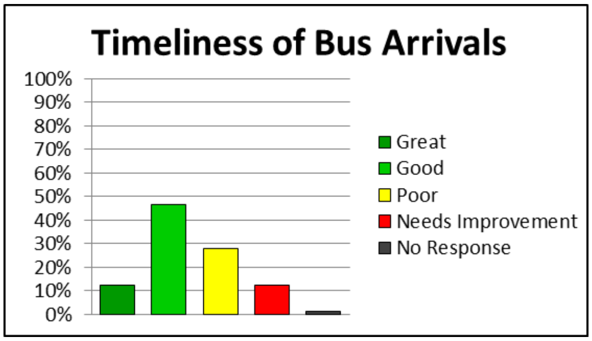

Figure 24: Timeliness of Bus Arrivals Rankings Among Participants Who Ride the B.O.B.

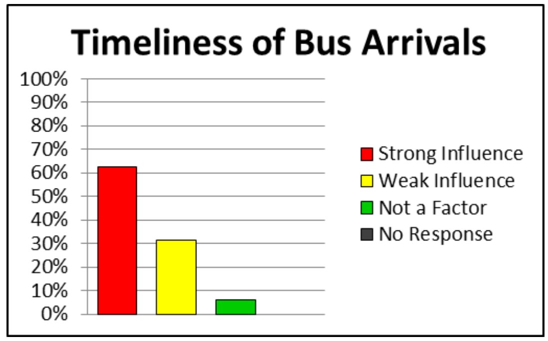

Figure 25: Timeliness of Bus Arrivals Rankings Among Participants Who Do Not Ride the B.O.B.

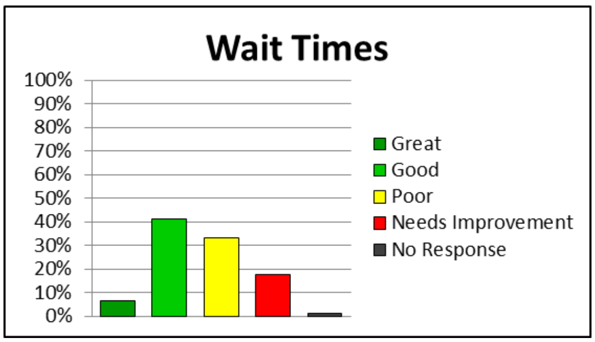

Figure 26: Wait Times Rankings Among Participants Who Ride the B.O.B.

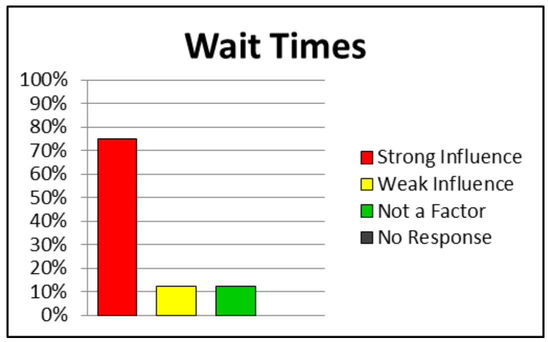

Figure 27: Wait Times Rankings Among Participants Who Do Not Ride the B.O.B.

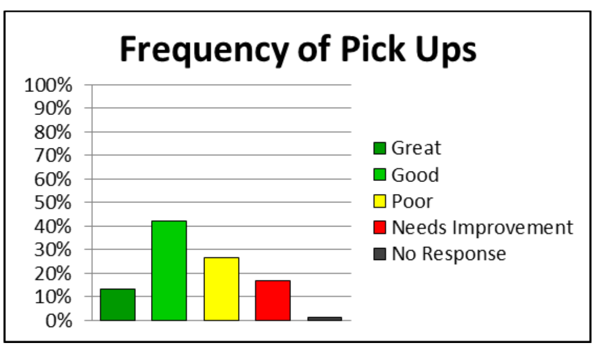

Figure 28: Frequency of Pick Ups Rankings Among Participants Who Ride the B.O.B.

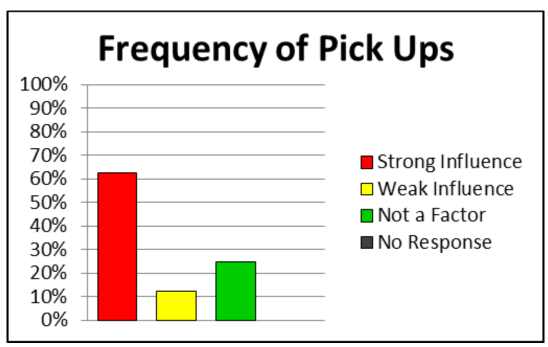

Figure 29: Frequency of Pick Ups Rankings Among Participants Who Do Not Ride the B.O.B.

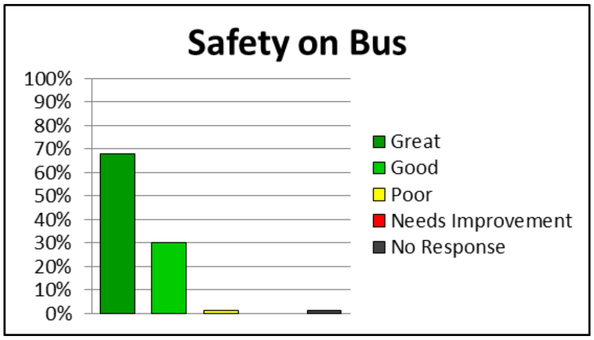

Figure 30: Safety on Bus Rankings Among Participants Who Ride the B.O.B.

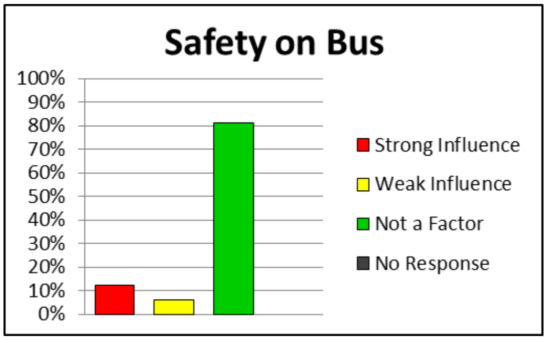

Figure 31: Safety on Bus Rankings Among Participants Who Do Not Ride the B.O.B.

Figure 32: Safety at Bus Stops Rankings Among Participants Who Ride the B.O.B.

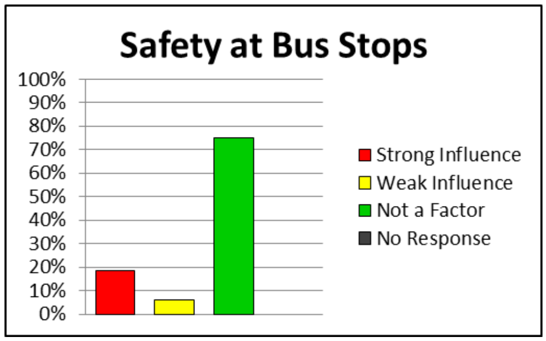

Figure 33: Safety at Bus Stops Rankings Among Participants Who Do Not Ride the B.O.B.

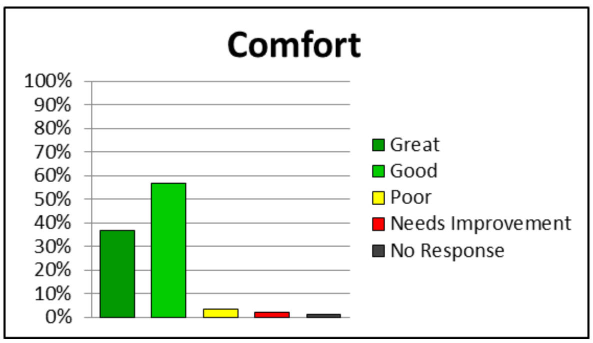

Figure 34: Comfort Rankings Among Participants Who Ride the B.O.B.

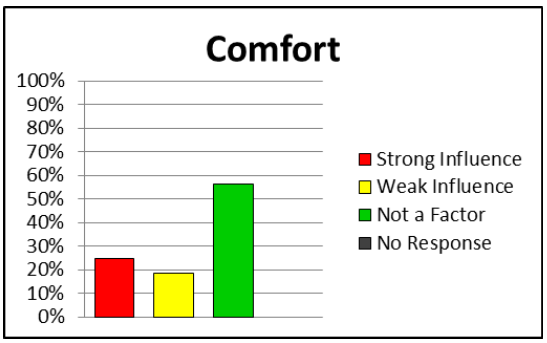

Figure 35: Comfort Rankings Among Participants Who Do Not Ride the B.O.B.

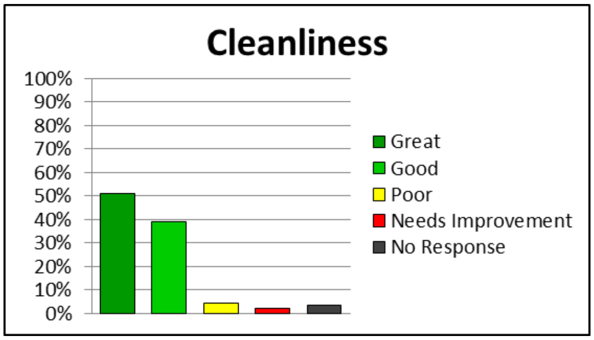

Figure 36: Cleanliness Rankings Among Participants Who Ride the B.O.B.

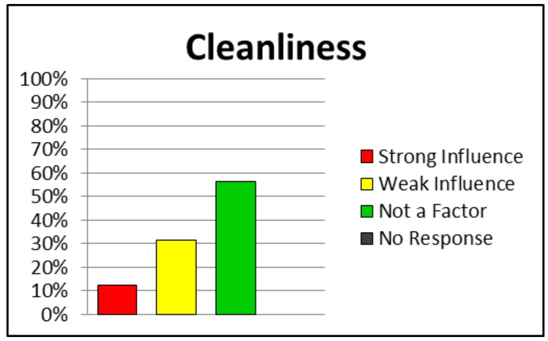

Figure 37: Cleanliness Rankings Among Participants Who Do Not Ride the B.O.B.

Figure 38: Location of Stops Rankings Among Participants Who Ride the B.O.B.

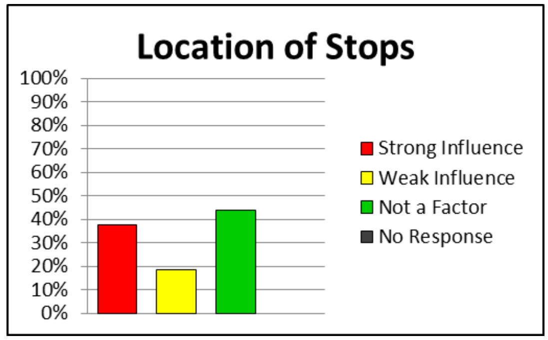

Figure 39: Location of Stops Rankings Among Participants Who Do Not Ride the B.O.B.

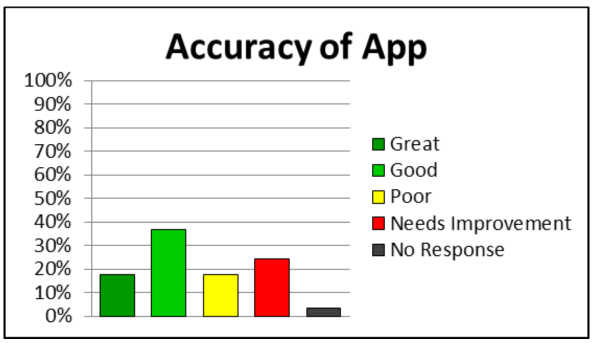

Figure 40: Accuracy of App Rankings Among Participants Who Ride the B.O.B.

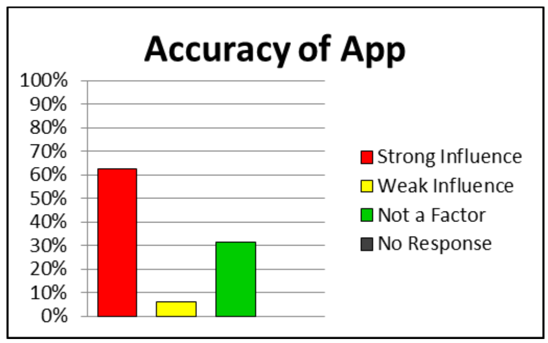

Figure 41: Accuracy of App Rankings Among Participants Who Do Not Ride the B.O.B.

Lastly, participants were asked whether or not they felt the B.O.B. is beneficial to the university. Overall, 91.5% of responses indicated that the B.O.B. is beneficial to the university. Participants were more likely to rate the B.O.B. as being beneficial if they had ridden the B.O.B. before (93.3% vs 81.3%).

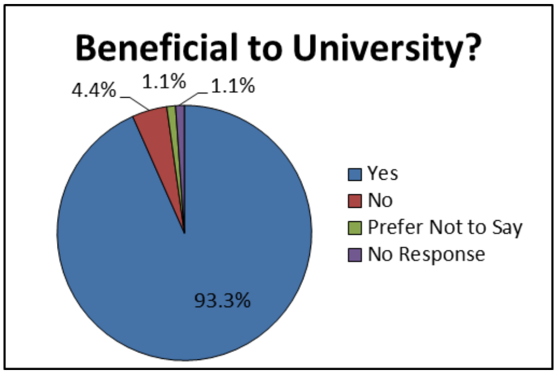

Figure 42: Benefit to University Rankings Among Participants Who Ride the B.O.B.

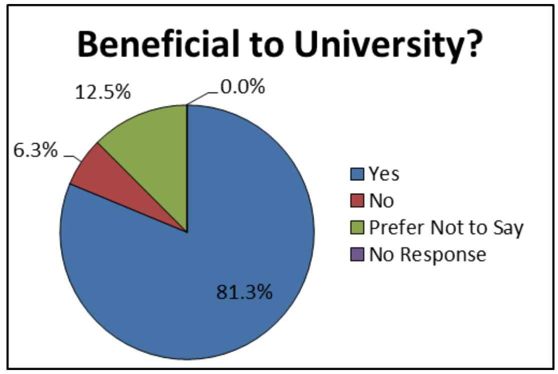

Figure 43: Benefit to University Rankings Among Participants Who Do Not Ride the B.O.B.

6.3. Driver Opinions

During our time study while we were gathering information about the bus system at Kennesaw State we talking with drivers about route concerns and other issues that they saw that might affect overall customer satisfaction. Multiple drivers talked about how each driver has different way about doing thing. A lot of times buses sit at stop a little to long while others remain consistent this causes busses to arrive really frequent to one another with a large gap afterwards. This sometimes causes buses to leapfrog one another. This is an issue for students because frequency is something that turns students away from using the bob. Other issues that were discussed include that drivers have different training and this causing inconsistencies with the routes and route time. Some take different routes occasionally and this messes up with the real time track app giving students a bad opinion about certain bus routes and the overall bus system.

7. Travel Time Between Stops

Travel times between stops were determined using the “leave at” time feature in Google Maps.

Chapter 5: Determine Optimal Routes

1. Background

We determined the optimal set of bus routes that would minimize total travel time across all of the routes. This ensures students get to their destination in a timely manner. In determining the optimal set of routes, we only considered four of the nine current routes: Kennesaw-Marietta, Busbee Drive/Stadium, Chastain Pointe, and West Campus. These routes were chosen because they run for the entire day during the weekdays and service a large portion of the campus. We excluded the Kennesaw and Marietta Shopping routes because they only run on the weekends. The Frey Road, Town Pointe, and Skip Spann routes were excluded because they service a very specific and limited part of campus.

The stops, travel time, and mileage of the four routes we evaluated were as follows:

Table 6: Original Routes

Route Name	Stops	Travel Time	Mileage
Kennesaw-Marietta	Rec Center ● Commons ● Courtyard Apartments ● Commons Apartment ● Hornet Village ● Rec. Fields ● Greek Row ● Student Center	43 min	21.7 miles
Busbee Drive/Stadium	KSU Center ● 3305 Busbee ● Park-N-Ride ● Fifth Third Stadium ● U Pointe ● Stadium Village ● Owl's Nest ● Stillwell Stadium ● Rec Center ● The Commons ● East Lot	19 min	4.9 miles
Chastain Pointe	Chastain Pointe ● West Lot ● Church Lot ● Science and Mathematics Bldg. ● Rec Center ● ARC – Lower ● House 55 ● The Commons ● Social Science Bldg.	14 min	2.8 Miles
West Campus	Social Science Bldg. ● The Commons ● West Lot ● Church Lot ● West 22 ● Rec Center ● ARC – Lower ● House 55 ● Science and Mathematics Bldg.	16 min	5.0 miles
	Total:	***92 min***	***34.4 miles***

2. Vehicle Routing Problem

We used a binary integer linear programming formulation of the vehicle routing problem (VRP) to determine the optimal set of routes. For this problem, there is a bus depot from which all routes originate and end, a known set of stops (all of which must be visited once), a desired number of routes (determined by the client or by the maximum number of vehicles available), and known costs for traveling between any two given set of stops. For our model, we considered cost to be the travel time between any two stops. The objective of our model is to determine the optimal set of routes that minimize overall travel time across all of the routes.

For our model, we considered the bus depot to be the SRAC. The stops on the Kennesaw-Marietta, Busbee Drive/Stadium, Chastain Pointe, and West Campus routes became the set of stops for the VRP. We decided to keep a total of nine routes (our model alters four of them). Travel times were determined through Google Maps, and we chose to use travel times for a typical weekday.

3. Model Formulation

Our binary integer linear programming model formulation is as follows:

Decision Variables

$$x_{i,j} = \begin{cases} 1 \text{ if traveling path bewteen stops } i \text{ and } j \\ 0 \text{ otherwise} \end{cases}$$

Parameters

n = total number of bus stops
i = bus stop index (i = 0, 1, ... n, where 0 indicates the main hub, and 1…n represent stops)
j = bus stop index (j = 0, 1, ... n, where 0 indicates the main hub, and 1…n represent stops)
t_{ij} = time to travel between stops i and j
k = total number of routes

Objective Function

Minimize Total Travel Time = $$\sum_i \sum_j t_{i,j} x_{i,j} \quad (2)$$

Constraints

Depot Vertex Indegree Constraint: $$\sum_i x_{i,0} = k \quad (3)$$

Depot Vertex Outdegree Constraint: $$\sum_j x_{0,j} = k \quad (4)$$

Bus Stop Indegree Constraint: $$\sum_i x_{i,j} = 1 \qquad \forall j \quad (5)$$

Bus Stop Outdegree Constraint: $$\sum_j x_{i,j} = 1 \qquad \forall i \quad (6)$$

Capacity Cut/Subtour Constraint [17]: $$\sum_{i \notin S} \sum_{j \in S} x_{i,j} \geq r(S) \qquad \forall S \subseteq V \setminus \{0\}, S \neq 0 \quad (7)$$

Where: V = vertex set (all stops + depot) {0…n}, V\{0} = stops, {0} = home depot
S = vertex subset of V\{0}
r(S) = min no of vehicles to serve all stops in set S in V\{0}

Binary Variable Constraint: $$x_{i,j} \in \{0,1\} \qquad \forall x_{i,j} \quad (8)$$

Because certain pairs of stops are located on opposite sides of the road, it is infeasible to travel between them. For example, consider the diagram in Figure 44. While the travel time between stops A and B would be less than the travel time between A and C or A and D, it is infeasible for the bus to travel directly from stop A to stop B as the bus would have to U-turn to pick up students, or students would have to cross the street to catch the bus. It is, however, feasible for the bus to travel between stops A and C. For each of the stops for which it is infeasible to travel between, we set the travel time between those stops to 1000 minutes. This forces the corresponding decision variable to be zero.

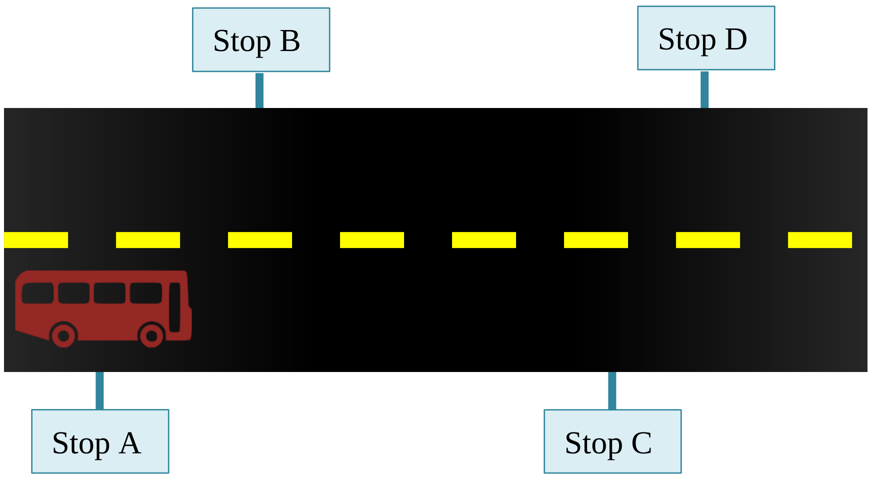

Figure 44: Feasible and Infeasible Stop Order Options

The objective function (2) minimizes total travel time across all routes. The depot vertex indegree constraint (3) states that there must be a total of k arrivals into the main hub from each of the k routes. Similarly, the depot vertex outdegree constraint (4) indicates that there must be a total of k departures from the hub, one for each of the k routes. Likewise, the bus stop indegree (5) and outdegree (6) constraints indicate that there must be only one arrival into a stop, and one departure from each stop. The capacity cut/subtour constraints (7) reinforces constraints (3) and (4) by subtracting one from the route's length if the route is invalid until the invalid route's stops are assigned to a valid route. After each cut, the model is re-run to verify authenticity.

4. Model Solution
4.1. Solution 1
The model was solved using Excel Solver Plus. Our solution is as follows:

Table 7: New Routes Solution 1

Route Name	Stops	Travel Time	Mileage
Kennesaw-Marietta	KSU Rec ● Commons ● East lot ● KSU Center ● 3305 Busbee ● Busbee Park and Ride ● Stadium ● U-point ● Owls Nest ● Marietta Campus Loop ● West 22 ● West Lot	54 mins	24.4 miles
Main Campus North	KSU Rec ● Commons ● ARC ● Chastain Point ● House 55	11 mins	2.8 miles
Main Campus South	KSU Rec ● Math and Science ● Stillwell	8 mins	0.7 miles
Chastain Point	KSU Rec ● Commons ● Social Science ● Church Lot	6 mins	0.8 miles
	Total:	***79 min***	***28.7 miles***

All buses return to the stop from which they originated. We also looked at combining specific stops that were with in 10 yards of on another to save time. There was not enough demand for each of the individual stop.

4.2. Solution 2
The model was solved using Excel Solver Plus. Our solution is as follows:

Table 8: New Routes Solution 2

Route Name	Stops	Travel Time	Mileage
Marietta/Busbee	Rec Center ● The Commons ● KSU Center ● Busbee Park-N-Ride ● 3305 Busbee ● Owl's Nest ● U Pointe ● Stadium ● Marietta Campus ● Stillwell Stadium	41 min	20.5 miles
Chastain Pointe	Rec Center ● The Commons ● House 55 ● Chastain Pointe ● ARC	11 min	2.8 miles
Main Campus	Rec Center ● Science and Mathematics Bldg ● Church Lot ● West Lot	7 min	0.9 miles
West 22	Rec Center ● The Commons ● Social Sciences Bldg ● West 22 ● East Lot	18 min	6.4 miles
	Total:	***77 min***	***30.6 miles***

Solution 2 has two additional restrictions that differ from the initial solution. The first restriction consolidated the Marietta route loop into one stop. We determined that the majority of people that get off at the Marietta Campus get off at the first stop. Part of this reasoning is it is faster for students to talk across the Marietta campus to get to their class than to stay on the bus and ride around the Marietta Loop until they get to the stop that is closest to the building. Also, to try and improve the new routes' usability, we added a second restriction that made each route have at least 4 stops. The new routes are pictured below:

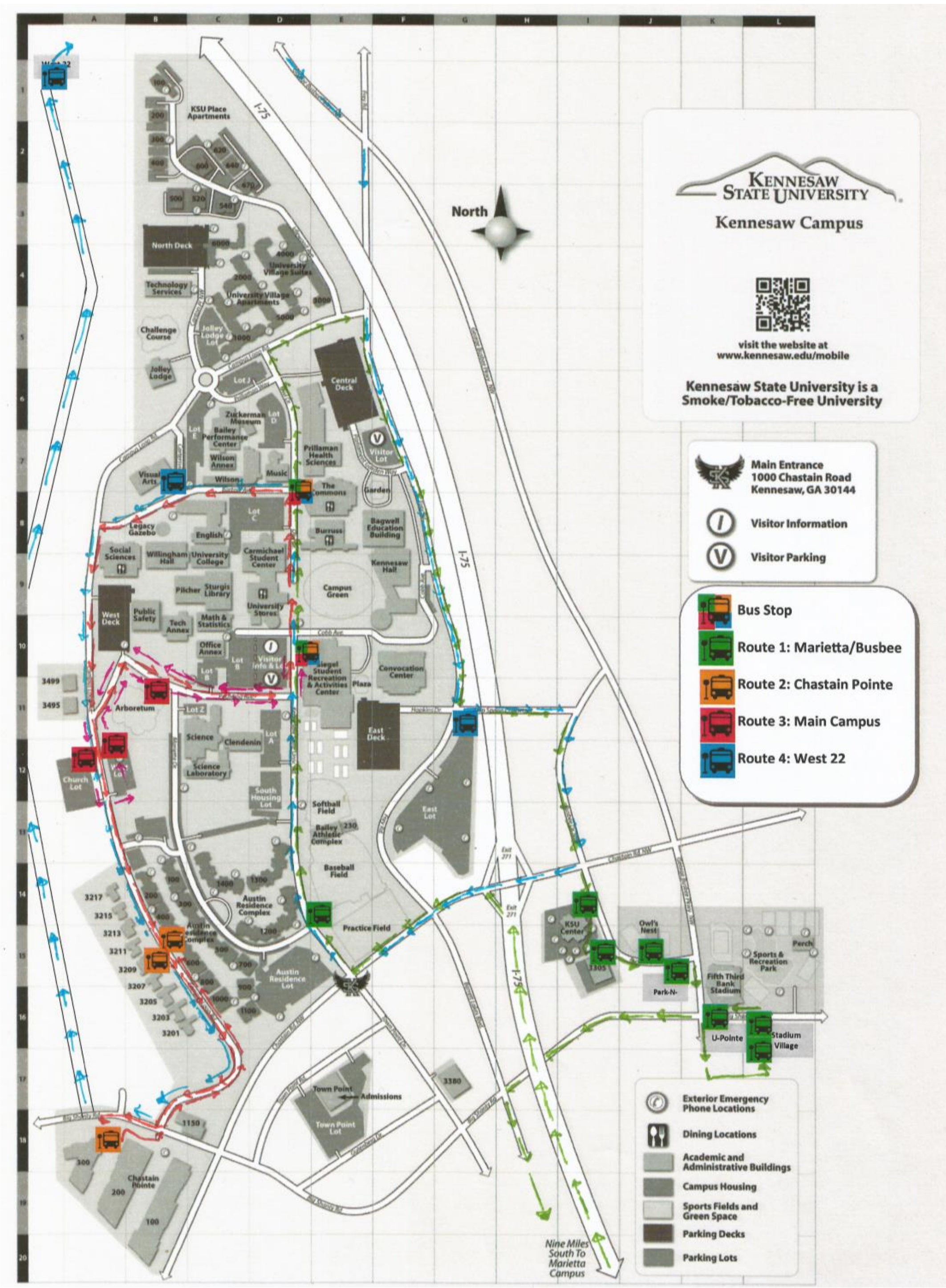

Figure 45: New Routes

Adapted from: http://www.kennesaw.edu/maps/

Chapter 6: Determine Fleet for Each Route

1. Background

After determining the optimal set of routes, we then assign vehicles to each of those new routes in order to minimize costs while still servicing students. The Department of Transportation has a set number of vehicles: two 10-passenger vans, six 34-passenger buses, and eight 57-passenger buses. Each vehicle type will be referred to as "vans", "small buses", and "large buses". For the model that follows, we seek to assign b buses of a single vehicle type to each of our 4 routes for a given time of day. This means that at any given time, a route can have only a single vehicle type on that route; however, it can have a different vehicle type on the route at a later time. Likewise, the number of vehicles on the route may change throughout the course of the day.

2. Model Formulation

Our linear programming model is:

Decision Variables

$$BT = \begin{cases} 1 \text{ if bus type } BT \text{ is used on the rotue} \\ 0 \text{ otherwise} \end{cases}$$

b_{BT} = number of each bus of type BT used on a route

Parameters

s = number of stops on route
i = bus stop index (${i}$ = 1, 2, … s)
BT = bus type ($BT \in \{v, sm, lg\}$, where v = van, sm = small bus, and lg = large bus)
n_{BT} = number of buses available of type BT (n_v = 2, n_{sm} = 6, n_{lg}= 8)
b_{BT} = number of buses of bus type BT to run (b_{BT} = 0, 1, … n_{BT})
LC_{BT} = leasing cost of bus type BT
$GasP$ = gas price ($/gallon)
FE_{BT} = fuel efficiency of bus type BT
$m_{i,i+1}$ = distance (miles) between stops i and $i+1$
MC_{BT} = maintenance cost of bus type BT
$LbrC$ = labor cost ($/hr) to run buses ($12.50/hr)
$LbrH$ = contracted labor hours
$t_{i,i+1}$ = time (minutes) between stops i and $i+1$
$TBST_i$ = total bus stop time at stop i
br_i = break time at stop i
ON_i = number of passengers boarding at stop i
OFF_i = number of passengers exiting at stop i
k_{BT} = capacity of us type BT (k_v = 10, k_{sm} = 34, k_{lg} = 57)
$CurrW$ = current wait time between buses

Objective Function

Minimize Total Cost = Leasing Cost + Fuel Cost + Maintenance Cost + Labor Cost, (9)

where:

$$\text{Leasing Cost} = \sum_{BT} LC_{BT} \cdot BT \cdot b_{BT}$$

$$\text{Fuel Cost} = \sum_{BT} GasP \cdot (1/FE_{BT}) \cdot BT \cdot b_{BT} \cdot \sum_{i} m_{i,i+1}$$

$$\text{Maintenance Cost} = \sum_{BT} MC_{BT} \cdot BT \cdot b_{BT}$$

$$\text{Labor Cost} = \sum_{BT} LbrC \cdot BT \cdot b_{BT} \cdot \left(\sum_{i} t_{i,i+1} + t_{n,1} + \sum_{i} TBST_i + \sum_{i} br_i \right)$$

Constraints

No. of Buses Available: $BT \cdot b_{BT} \le n_{BT} \qquad \forall BT$ (10)

Do Not Exceed Current Wait Times: $\dfrac{\sum_{i=1}^{n-1} t_{i,i+1} + t_{n,1} + \sum_{i} TBST_i + \sum_{i} br_i}{\sum_{BT} BT \cdot b_{BT}} \le CurrW$ (11)

Boarding at Stop i: $ON_i = \dfrac{TotalPassengerArrivalsAtStopIDuringTimeT}{\sum_{BT} BT \cdot b_{BT} \cdot k_{BT}} \qquad \forall i$ (12)

Departures at Stop i: $OFF_i = \dfrac{TotalPassengerDeparturesAtStopIDuringTimeT}{\sum_{BT} BT \cdot b_{BT} \cdot k_{BT}} \qquad \forall i$ (13)

Conditional Capacity Constraints (Preferred Bus Type at Stop i):

Choose only one bus type: $\sum_{BT} BT_i = 1$ (14)

Choose van: $\left(\sum_{i=1}^{i} ON_i - \sum_{i=1}^{i} OFF_i \right) \cdot v_i \le k_v \cdot v_i \qquad \forall i$ (15)

Choose small bus: $\left(\sum_{i=1}^{i} ON_i - \sum_{i=1}^{i} OFF_i \right) \cdot sm_i > k_v \cdot sm_i \qquad \forall i$ (16)

$$\left(\sum_{i=1}^{i} ON_i - \sum_{i=1}^{i} OFF_i\right) \cdot sm_i \le k_{sm} \cdot sm_i \qquad \forall i \tag{17}$$

Choose large bus: $$\left(\sum_{i=1}^{i} ON_i - \sum_{i=1}^{i} OFF_i\right) \cdot \lg_i > k_{sm} \cdot \lg_i \qquad \forall i \tag{18}$$

$$\left(\sum_{i=1}^{i} ON_i - \sum_{i=1}^{i} OFF_i\right) \cdot \lg_i \le k_{\lg} \cdot \lg_i \qquad \forall i \tag{19}$$

Conditional Capacity Constraints (Preferred Bus Type for Route):

Choose one bus type: $$\sum_{BT} BT = 1 \tag{20}$$

Choose large bus: $$\sum_{i} \lg_i \le M \cdot \lg \tag{21}$$

Choose van: $$\sum_{i} v_i - s + 1 \le M \cdot v \tag{22}$$

Choose small bus: $$\sum_{i} sm_i \le M \cdot (sm + \lg) \tag{23}$$

$$\sum_{i} v_i + \sum_{i} sm_i - s + 1 \le M \cdot (v + sm) \tag{24}$$

Contracted Labor Hours: $$\sum_{BT} BT \cdot b_{BT} \left(\sum_{i=1}^{n-1} t_{i,i+1} + t_{n,1} + \sum_{i} TBST_i + \sum_{i} br_i\right) \le LbrH \tag{25}$$

Binary Variable Constraint: $$BT \in \{0,1\} \qquad \forall BT \tag{26}$$

Integer Constraint: $$b_{BT} \in \{0,1,2,...n_{BT}\} \qquad \forall b_{BT} \tag{27}$$

The objective function (9) for this model minimizes the total cost given the leasing cost per bus, the fuel cost, the labor cost, and the bus maintenance cost. The first constraint (10) makes sure that the total numbers of buses are not exceeded for each bus type. The current wait time constraint (11) takes into account the total bus travel time including break time, loading time, and travel time and divides it by the amount of buses running on the route to make sure that we do not exceed current wait times. Our bus capacity constraints (14)-(19) look at the given demand for each stop and determines how many people are on a bus at while it traverses the route and checks to make sure it is less than the capacity off all buses running on the route. The bus type constraint (20)-(24) makes sure that one bus type is chosen per route. The contracted hours constraint (25) checks to make sure the total amount of hours per bus per bus type does not exceed the current budgeted driver hours for the semester. Our decision variable constraints (26), (27) only allows for our decision variables to be specific type, bus type being binary and number of buses to be an integer.

3. Model Solution

The proposed solution for the optimal number of busses to run at different times of day for each of the new routes is shown in the table below. This solution was determined by inputting the above algorithm into excel solver. With the objective of minimizing cost here are a couple key constraints that were taken into account:

- Meeting the projected demand for each new stop on each new route.
- Buss frequency being equal to or less than the current frequency.
- Not exceeding the current budgeted labor hours for bus drivers for the year.
- Using the same or less than the total number of busses that is currently allocated on similar routes.

Our resulting fleet assignment was:

Route Name	Morning Bus Assignment	Afternoon Bus Assignment	Evening Bus Assignment	Bus Frequency
Marietta/Busbee	4 large buses	4 large buses	3 large buses	20 mins
Chastain Pointe	2 small buses	3 small buses	2 small buses	10 mins
Main Campus	1 small buses	1 small buses	1 small buses	12 mins
West 22	3 small buses	2 small buses	2 small buses	15 mins

The demand for each of the new routes was determined using the data given to us by the department of transportation. This data gave us the demand for each stop on each route per hour. Looking at the overall demand per hour and then comparing each stop to it by its popularity we then estimated a percentage of people that would get off at each stop per hour. From this we calculated what the capacity would be for the new routes by subtracting the demand per stop, ON_i from the estimated percentage of people exiting the bus, OFF_i.

This solution generated with excel solver also generates a handful of reports that analyses each of the different key constraints as well as the solution then determines how cost effective it can be to tighten or loosen each constraint. More details about these reports are in the next section.

Chapter 7: Sensitivity Analysis

This section was completed entirely by Valerie Washington in fulfillment of the Honors Senior Capstone.

1. Purpose

Optimization models assume that parameter values are known with absolute certainty. In practice, however, this is rarely the case. Parameters in our fleet assignment included gas cost, labor hours available, bus stop demand, and number of buses available. None of these values can be known with absolute certainty – a bus may break down, a route may surge in popularity as the year continues, and gas prices could change from day to day. A sensitivity analysis allows me to evaluate how our optimal solution is affected under these different scenarios. Thus, I am able to evaluate the robustness of our obtained solution. As a result, our team can propose a more flexible set of recommendations. The sensitivity analysis was performed on the fleet assignment optimization model only.

2. Generating Sensitivity Reports

Sensitivity reports, which are used to perform a sensitivity analysis, can only be generated for continuous linear programming models. Because our fleet assignment optimization model was both discrete (integer) and non-linear, the model had to be adapted to generate the sensitivity reports. First, we solved the model "as-is" to determine the optimal number of buses for each of the routes at different times in the day. Next, if a decision variable was in the denominator of a constraint, I altered the constraint so that it would appear in the numerator. For example, if the constraint was $a = \frac{b}{x}$, and x was our decision variable, I changed the constraint to be in the form $ax = b$. Lastly, I had to remove all instances of $BT \cdot b_{BT}$. Recall that $BT \in \{v, sm, lg\}$ is a binary variable that indicates whether a van, small bus, or large bus is used on a route. The variable b_{BT} is the number of vans, small buses, or large buses running on a route. To remove all instances of $BT \cdot b_{BT}$, I manually set $v, sm,$ and lg to one or zero such that their sum equaled one. This removes the option of the model choosing the best bus type for the route. Because BT is no longer a decision variable, but rather a parameter, the model becomes an integer linear programming model. I did not relax the integer constraint for b_{BT} at this time. Relaxing this constraint would allow the number of buses to be a fractional value. However, rounding the solution to the nearest whole number is not guaranteed to give me an optimal, or even a feasible, solution. Therefore, for each route, time, and bus type, I generated an Answer Report (solution) in Excel. This gives me the optimal number of buses required in the form of a whole number. If the solution was considered to be infeasible, that scenario was excluded from further analysis.

Next, I relaxed the integer variable constraint, resulting in a continuous linear programming model. Similar to the integer linear programming (ILP) model, the linear programming (LP) model results in obtaining the number of buses to run during a one hour time period. For the purposes of my sensitivity analysis, I chose to interpret fractional solutions as a means to determine the expected frequency of bus pickups at any given stop. This is calculated as:

$$expected\ bus\ frequency = \frac{total\ route\ travel\ time}{number\ of\ buses} \tag{28}$$

With the model in the form of an ILP model, I was able to generate answer and sensitivity reports for the remaining scenarios. The answer reports and sensitivity reports can be found in Appendix J through Appendix L.

3. Sensitivity Analysis

I have chosen to limit my sensitivity analysis to evaluating the impact of the following parameter value changes on the objective function value (the resulting cost per hour):

- Changes in gas prices, specifically a drop to $2, or a rise to $2.60
- Increase or decrease in desired route frequency
- Changes in contracted operating costs, specifically a rise or fall of $3 per hour
- Delays in route travel time, as can occur during traffic.

Of our new routes, the Marietta/Busbee Route is projected to be the most heavily used. Additionally, this route is more likely to be impacted by traffic than the other route the bus is traveling off campus for most of the route. Therefore, I have focused my sensitivity analysis on the Marietta/Busbee Route.

3.1. Assumptions

To approximate increase in cost or savings per year, I used a few assumptions. The solutions obtained most accurately apply to ridership occurring Monday through Thursday during the Fall and Spring semesters (ridership decreases in the summer). Additionally, I assume that because this route would run for approximately 16 hours out of the day, the solution for each of the three time periods (morning, afternoon, evening) run for 5 hours each. Therefore, to approximate a minimum increase or decrease in cost per year, I multiply the hourly cost for a time of day by (5 hours/day)*(4 days/wk)*(30 wks/yr) = 600 hrs/yr

3.2. Marietta/Busbee Route

3.2.1. Optimal Solutions

The optimal solutions by bus type are summarized in the tables below. The original optimal solutions from Chapter 6 is highlighted in grey. Note that there are feasible solutions for both the small and large buses, but not for vans. Therefore, it is okay for the department to use either bus type during the morning and evening hours (assuming the bus isn't being used on another route). Because the afternoon solution requires a larger bus, however, the Department may elect to use large buses for the entire day for simplicity.

Table 9: Optimal Solutions by Bus Type for Marietta/Busbee during Morning

	ILP Model			LP Model		
Bus Type	**Optimal Solution**	**Pick Up Frequency**	**Resulting Cost**	**Optimal Solution**	**Pick Up Frequency**	**Resulting Cost**
Van	Infeasible	---	---	---	---	---
Small Bus	4 buses	16.25 mins	$313.74/hr	3.26 buses	19.93 mins	$256.07/hr
Large Bus	4 buses	16.25 mins	$322.44/hr	3.25 buses	20.00 mins	$261.99/hr

Table 10: Optimal Solutions by Bus Type for Marietta/Busbee during Afternoon

	ILP Model			LP Model		
Bus Type	**Optimal Solution**	**Pick Up Frequency**	**Resulting Cost**	**Optimal Solution**	**Pick Up Frequency**	**Resulting Cost**
Van	Infeasible	---	---	Infeasible	---	---
Small Bus	Infeasible	---	---	Infeasible	---	---
Large Bus	4 buses	19.75 mins	$314.73/hr	3.95 buses	20.00 mins	$310.8/hr

Table 11: Optimal Solutions by Bus Type for Marietta/Busbee during Evening

	ILP Model			LP Model		
Bus Type	**Optimal Solution**	**Pick Up Frequency**	**Resulting Cost**	**Optimal Solution**	**Pick Up Frequency**	**Resulting Cost**
Van	Infeasible	---	---	---	---	---
Small Bus	3 buses	15.33 mins	$246.09/hr	2.3 buses	20.00 mins	$188.67/hr
Large Bus	3 buses	15.33 mins	$255.32/hr	2.3 buses	20.00 mins	$195.74/hr

3.2.2. Impact on Changes in Gas Prices

Changes in gas prices could drastically affect the annual fuel budget. A decrease in gas prices by $0.30/gallon could lead to a total savings of at least $8,298 per year for this route, if the large buses are used. The savings would be at least $4,990 per year if the smaller buses were used during the morning and evening. While the savings in gas is lower this way, keep in mind that an additional $7,794 would be saved per year for using the smaller buses over the larger ones when possible. Similarly, if gas prices were to increase, the cost per year would increase in a similar fashion. An increase in gas costs from $2.30 to $2.75 could result in an additional cost of $12,456 per year, if using the large buses for the entire day.

Table 12: Impact of Changes in Gas Prices on Optimal Solution for Marietta/Busbee during Morning

	Decrease in Gas Price to $2.00			Increase in Gas Price to $2.75		
Bus Type	**Decrease in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Decrease**	**Decrease in Cost**	**Increase in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Increase**	**Increase in Cost**
Van	---	---	---	---	---	---
Small Bus	$1.14/hr	$78.43/hr	$3.70/hr	$1.70/hr	$1E+30/hr	$5.55/hr
Large Bus	$1.42/hr	$80.61/hr	$4.61/hr	$2.13/hr	$1E+30/hr	$6.92/hr

Table 13: Impact of Changes in Gas Prices on Optimal Solution for Marietta/Busbee during Afternoon

	Decrease in Gas Price to $2.00			Increase in Gas Price to $2.75		
Bus Type	**Decrease in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Decrease**	**Decrease in Cost**	**Increase in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Increase**	**Increase in Cost**
Van	---	---	---	---	---	---
Small Bus	---	---	---	---	---	---
Large Bus	$1.17/hr	$78.68/hr	$4.61/hr	$1.75/hr	$1E+30/hr	$6.92/hr

Table 14: Impact of Changes in Gas Prices on Optimal Solution for Marietta/Busbee during Evening

	Decrease in Gas Price to $2.00			Increase in Gas Price to $2.75		
Bus Type	**Decrease in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Decrease**	**Decrease in Cost**	**Increase in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Increase**	**Increase in Cost**
Van	---	---	---	---	---	---
Small Bus	$1.6/hr	$82.03/hr	$3.69/hr	$2.41/hr	$1E+30/hr	$5.54/hr
Large Bus	$2.01/hr	$85.11/hr	$4.61/hr	$3.01/hr	$1E+30/hr	$6.92/hr

3.2.3. Impact on Changes in Labor Costs

Small changes in the contracted labor expense can have a large impact on the costs for the year. When only considering this one route for 5 hours of the day, 4 days a week, and only 2 semesters of the year, a change of $3 in the contracted cost could raise or lower the total cost by approximately $17,100 per year, regardless of the bus type being used.

Table 15: Impact of Changes in Operating Costs on Optimal Solution for Marietta/Busbee during Morning

	Decrease in Operating Cost by $3/hr			Increase in Operating Cost by $3/hr		
Bus Type	**Decrease in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Decrease**	**Decrease in Cost**	**Increase in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Increase**	**Increase in Cost**
Van	---	---	---	---	---	---
Small Bus	$3/hr	$78.43/hr	$9.78/hr	$3/hr	$1E+30/hr	$9.78/hr
Large Bus	$3/hr	$80.61/hr	$9.75/hr	$3/hr	$1E+30/hr	$9.75/hr

Table 16: Impact of Changes in Operating Costs on Optimal Solution for Marietta/Busbee during Afternoon

	Decrease in Operating Cost by $3/hr			Increase in Operating Cost by $3/hr		
Bus Type	**Decrease in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Decrease**	**Decrease in Cost**	**Increase in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Incrase**	**Increase in Cost**
Van	---	---	---	---	---	---
Small Bus	---	---	---	---	---	---
Large Bus	$3/hr	$78.68/hr	$11.85/hr	$3/hr	$1E+30/hr	$11.85/hr

Table 17: Impact of Changes in Operating Costs on Optimal Solution for Marietta/Busbee during Evening

	Decrease in Operating Cost by $3/hr			Increase in Operating Cost by $3/hr		
Bus Type	**Decrease in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Decrease**	**Decrease in Cost**	**Increase in b_{BT} Coefficient**	**Allowable b_{BT} Coefficient Incrase**	**Increase in Cost**
Van	---	---	---	---	---	---
Small Bus	$3/hr	$82.03/hr	$6.90/hr	$3/hr	$1E+30/hr	$6.90/hr
Large Bus	$3/hr	$85.11/hr	$6.90/hr	$3/hr	$1E+30/hr	$6.90/hr

3.2.4. Impact of Changes in Pick Up Frequency

Pick up frequency and total cost have an inverse relationship. If the desired pick up frequency decreases, it causes total cost to increase. The original route frequency constraint specified a desired frequency of at most 20 minutes. As noted in the tables below, the change in cost of decreasing the maximum route frequency by 5 minutes is different from the change in cost of increasing the maximum route frequency by 5 minutes. Note that it is not possible to decrease the pick up frequency to 15 minutes in two of the scenarios below: when using the small buses during the morning, or the large buses in the afternoon. As reflected in the tables below, it is very costly to pick up more frequently from a stop; however, the KSU Department of Transportation can expect to save a lot if it were to increase the wait time between buses. Increasing the maximum pick up frequency could lead to a savings of $92,226 per year; however, doing so has the potential to upset passengers and decrease bus utilization.

Table 18: Impact of Changes in Pick Up Frequency on Optimal Solution for Marietta/Busbee during Morning

	Decrease in Pick Up Frequency to 15 Minutes				Increase in Pick Up Frequency to 25 Minutes			
Bus Type	**Increase in Frequency RHS**	**Allowable Frequency RHS Increase**	**Frequency Shadow Price**	**Increase in Cost**	**Decrease in Frequency RHS**	**Allowable Frequency RHS Decrease**	**Frequency Shadow Price**	**Decrease in Cost**
Van	---	---	---	---	---	---	---	---
Small Bus	1.08 buses	0.01 buses	$0/hr	---	0.65 buses	1E+30 buses	$0/hr	$0/hr
Large Bus	1.08 buses	2.75 buses	$80.61/hr	$87.33/hr	0.65 buses	1.3 buses	$80.61/hr	$52.40/hr

Table 19: Impact of Changes in Pick Up Frequency on Optimal Solution for Marietta/Busbee during Afternoon

	Decrease in Pick Up Frequency to 15 Minutes				Increase in Pick Up Frequency to 25 Minutes			
Bus Type	**Increase in Frequency RHS**	**Allowable Frequency RHS Increase**	**Frequency Shadow Price**	**Increase in Cost**	**Decrease in Frequency RHS**	**Allowable Frequency RHS Decrease**	**Frequency Shadow Price**	**Decrease in Cost**
Van	---	---	---	---	---	---	---	---
Small Bus	---	---	---	---	---	---	---	---
Large Bus	1.32 buses	0.99 buses	$78.68/hr	---	0.79 buses	0.81 buses	$78.68/hr	$62.16/hr

Table 20: Impact of Changes in Pick Up Frequency on Optimal Solution for Marietta/Busbee during Evening

	Decrease in Pick Up Frequency to 15 Minutes				Increase in Pick Up Frequency to 25 Minutes			
Bus Type	**Increase in Frequency RHS**	**Allowable Frequency RHS Increase**	**Frequency Shadow Price**	**Increase in Cost**	**Decrease in Frequency RHS**	**Allowable Frequency RHS Decrease**	**Frequency Shadow Price**	**Decrease in Cost**
Van	---	---	---	---	---	---	---	---
Small Bus	0.77 buses	3.7 buses	$82.03/hr	$62.89/hr	0.46 buses	1.56 buses	$82.03/hr	$37.73/hr
Large Bus	0.77 buses	5.7 buses	$85.11/hr	$65.25/hr	0.46 buses	1.86 buses	$85.11/hr	$39.15/hr

3.2.5. Impact of Changes to Route Travel Time

Because the Marietta/Busbee route has to travel between Kennesaw and Marietta, it is almost guaranteed that the route will at times experience unexpected travel delays. Travel time delays can be caused by traffic, drivers taking breaks, or other factors. Because of travel time being defined in this way, if a driver saved 10 minutes because there was no traffic on the road, but then decided to make up the time by waiting at the next bus stop for 10 minutes, the net change in travel time would be zero. Delays in route travel time can be costly, due in large part to of the high contracted hourly labor cost. Moreover, if travel time increases, but one desires to maintain the same route frequency, the costs raise even higher as it would require more buses on the route.

Table 21: Impact of Changes in Travel Time on Optimal Solution for Marietta/Busbee during Morning

	Decrease in Travel Time by 5 Minutes				**Increase in Travel Time by 10 Minutes**			
Bus Type	**Decrease in Frequency RHS**	**Allowable Frequency RHS Decrease**	**Frequency Shadow Price**	**Decrease in Cost**	**Increase in Frequency RHS**	**Allowable Frequency RHS Increase**	**Frequency Shadow Price**	**Increase in Cost**
Van	---	---	---	---	---	---	---	---
Small Bus	0.25 buses	1E+30 buses	$0/hr	$0/hr	0.5 buses	0.01 buses	$0/hr	---
Large Bus	0.25 buses	1.3 buses	$80.61/hr	$20.15/hr	0.5 buses	2.75 buses	$80.61/hr	$40.31/hr

Table 22: Impact of Changes in Travel Time on Optimal Solution for Marietta/Busbee during Afternoon

	Decrease in Travel Time by 5 Minutes				**Increase in Travel Time by 10 Minutes**			
Bus Type	**Decrease in Frequency RHS**	**Allowable Frequency RHS Decrease**	**Frequency Shadow Price**	**Decrease in Cost**	**Increase in Frequency RHS**	**Allowable Frequency RHS Increase**	**Frequency Shadow Price**	**Increase in Cost**
Van	---	---	---	---	---	---	---	---
Small Bus	---	---	---	---	---	---	---	---
Large Bus	0.25 buses	0.81 buses	$78.68/hr	$19.67/hr	0.5 buses	0.99 buses	$78.68/hr	$39.34/hr

Table 23: Impact of Changes in Travel Time on Optimal Solution for Marietta/Busbee during Evening

	Decrease in Travel Time by 5 Minutes				**Increase in Travel Time by 15 Minutes**			
Bus Type	**Decrease in Frequency RHS**	**Allowable Frequency RHS Decrease**	**Frequency Shadow Price**	**Decrease in Cost**	**Increase in Frequency RHS**	**Allowable Frequency RHS Increase**	**Frequency Shadow Price**	**Increase in Cost**
Van	---	---	---	---	---	---	---	---
Small Bus	0.25 buses	1.56 buses	$82.03/hr	$20.51/hr	0.75 buses	3.7 buses	$82.03/hr	$61.52/hr
Large Bus	0.25 buses	1.86 buses	$85.11/hr	$21.28/hr	0.75 buses	5.7 buses	$85.11/hr	$63.83/hr

Chapter 8: Simulation

1. Model Overview

We developed a simulation model to verify the bus assignments found in Chapter 6 for the new routes. Here, we briefly describe how our model works.

Each bus stop is treated as containing three distinct areas: a passenger arrival area, a passenger departure area, and a passenger boarding area. Passengers arrive (enter the system) and wait at the bus stop in the passenger arrival area. The bus arrives at the bus stop and visits the passenger departure area. If there are any passengers who need to get off the bus, they do so at this time and exit the system. After passengers are finished exiting the bus, the bus enters the boarding area. At this point, passengers may enter the boarding area, and subsequently board the bus if there is room available on the bus. The number of passengers allowed into the waiting area is limited to the number of seats remaining on the bus. For example, if there are five people in the arrival area, but only two empty seats left on the bus, only two will enter the boarding area. The bus then leaves the boarding area for the next stop.

A snapshot of the Arena simulation model can be found in Appendix M. Unlike the optimization model, the simulation assumes arrivals, departures, and drive times to be random. This allows for better interpretation of how our solution may function in the real world.

2. Simulation Results

For each simulation, passenger wait times were satisfactory. On average, passengers did not wait at a stop longer than the desired bus arrival frequency. Additionally, the maximum number of passengers on board did not reach the bus capacity for any of the scenarios. This indicates that it is unlikely that a passenger would be denied entry to a bus because it was too full. The small values for maximum number of people on board for the Chastain Pointe, West 22, and Main Campus routes suggest that the Department of Transportation may want to explore replacing some of the small buses with vans, which would decrease total cost. This was not indicated as the solution for our optimization model because the Department is currently only leasing two vans, both of which are in use on other routes. Lastly, we used the simulation model to evaluate inter-arrival times of the buses. Overall, the average bus inter-arrival times were close to or less than the target pick up frequency of the route. Because short breaks were accounted for in the total route time of our model, these breaks could be reduced to guarantee that the desired pick up frequency is achieved.

Table 24: Marietta/Busbee Simulation Results

Time of Day	Avg. Passenger Wait Time	Avg. Bus Freq.	Avg. Std. Dev. Of Bus Freq.	Avg. No. On Board	Max. No. On Board	Simulation Length
Morning	10.06 mins	21.03 mins	no data	19.4 ppl	35 ppl	52 mins
Afternoon	8.93 mins	20.2 mins	no data	22.8 ppl	49 ppl	50 mins
Evening	11.84 mins	22.55 mins	no data	5.4 ppl	9 ppl	90 mins

Table 25: Chastain Pointe Simulation Results

Time of Day	Avg. Passenger Wait Time	Avg. Bus Freq.	Avg. Std. Dev. Of Bus Freq.	Avg. No. On Board	Max. No. On Board	Simulation Length
Morning	5.26 mins	9.07 mins	0.56 mins	2.5 ppl	6 ppl	90 mins
Afternoon	5.96 mins	12.47 mins	1.98 mins	1.7 ppl	6 ppl	90 mins
Evening	4.84 mins	7.57 mins	2.6 mins	1.2 ppl	2 ppl	90 mins

Table 26: West 22 Simulation Results

Time of Day	Avg. Passenger Wait Time	Avg. Bus Freq.	Avg. Std. Dev. Of Bus Freq.	Avg. No. On Board	Max. No. On Board	Simulation Length
Morning	7.22 mins	14.04 mins	0.87 mins	3.7 ppl	6 ppl	90 mins
Afternoon	7.93 mins	14.73 mins	0.47 mins	3.6 ppl	6 ppl	90 mins
Evening	7.99 mins	12.82 mins	1.32 mins	3.0 ppl	5 ppl	90 mins

Table 27: Main Campus Simulation Results

Time of Day	Avg. Passenger Wait Time	Avg. Bus Freq.	Avg. Std. Dev. Of Bus Freq.	Avg. No. On Board	Max. No. On Board	Simulation Length
Morning	6.57 mins	11.83 mins	0.46 mins	1.8 ppl	3 ppl	90 mins
Afternoon	5.46 mins	11.23 mins	0.55 mins	1.3 ppl	2 ppl	90 mins
Evening	6.94 mins	11.11 mins	0.4 mins	1.2 ppl	3 ppl	90 mins

Chapter 9: Recommendations and Implementation

1. Recommendations

On top of the new routes that were determined using the vehicle routing optimization model in chapter 5 there are additional recommendations that would be beneficial to KSU transportation users and the KSU department of transportation.

Each stop throughout the network of routes at KSU needs to have some form of harsh weather protection (rain, harsh UV) Several stops have bus shelters and others that are located in front of buildings that can offer accommodation pending bad weather. However, ALL stops need these bus shelters if not located within 15 feet of a building that can provide shelter. Providing these shelters offer a designated place to wait that can be comfortable and could potentially increase usability.

2. Implementation

As Kennesaw State University continues to grow and serve its students at a high quality level it needs to continually invest in and explore new ways to make the university more efficient and effective. First thing to remember with any form of change is that change needs to be clearly communicated to all effected parties in advance as well as when the specified modifications will be implemented. Management needs to take into account the best time for change to occur, weather it should happen all at once or slowly integrated into the current system over a period of time. To prevent confusion all outdated material that represents old processes needs to be updated or removed for the sake of clarity.

Implementing a multiple route change that affects a large amount (students, faculty, staff, drivers, and visitors) of people would likely be most successfully if done in between semesters. One of the first steps would be to update all communities starting with the DOT staff about the new routes and changes:

1) Update drivers and other DOT staff on new routes
    a. Test that drivers can easily maneuver new paths
    b. Train drivers on new routes
    c. Reprogram interface in buses with new routes/stop orders
    d. Announce changes to student assistants
    e. Make updates to route maps all round campus (bus shelters, inside buses, and in high volume traffic areas around campus).
    f. Make updates to website
    g. Take down all material about the old routes
    h. Announce changes to students, faculty, and staff well in advance of the start of the school year and continually remind them about the new routes and where they can find them.

The second major step that should be taken to ensure the implementation process goes smooth is any additional changes or features that are being added are being added with the same level of quality as previous.

2) All other changes should be done well

a. New Bus shelters where needed (East Lot, West lot, and Stadium)
b. Any other additional equipment or features are added in a logical order to prevent frustration
c. Any changes to buses or bus features
d. Maker sure that employees respect the new changes and even though travel times and routes have changed timeliness is still a priority.

Finally, you need to allow time to follow up with the changes that were made, as well as the staff opinions about the modifications to make sure that the changes do not need to be altered to fit the system better.

3) Reach out to staff about changes to make sure they work just as well or better than the old routes.
    a. Get student feedback.
    b. Make sure that usability on new routes stay the same or increase, if not what can you do to change it.
    c. Continue to track student usage so that you can continually invest on additional changes.

3. Gantt Chart:

Having a staff member dedicated to overseeing this process or hiring a project manager is key to achieve the success of this project. This project will approximately take four weeks to implement all changes including: the new routes and update all necessary information. Below is a rough outline of the project schedule and key task that need to be done in a chronological order.

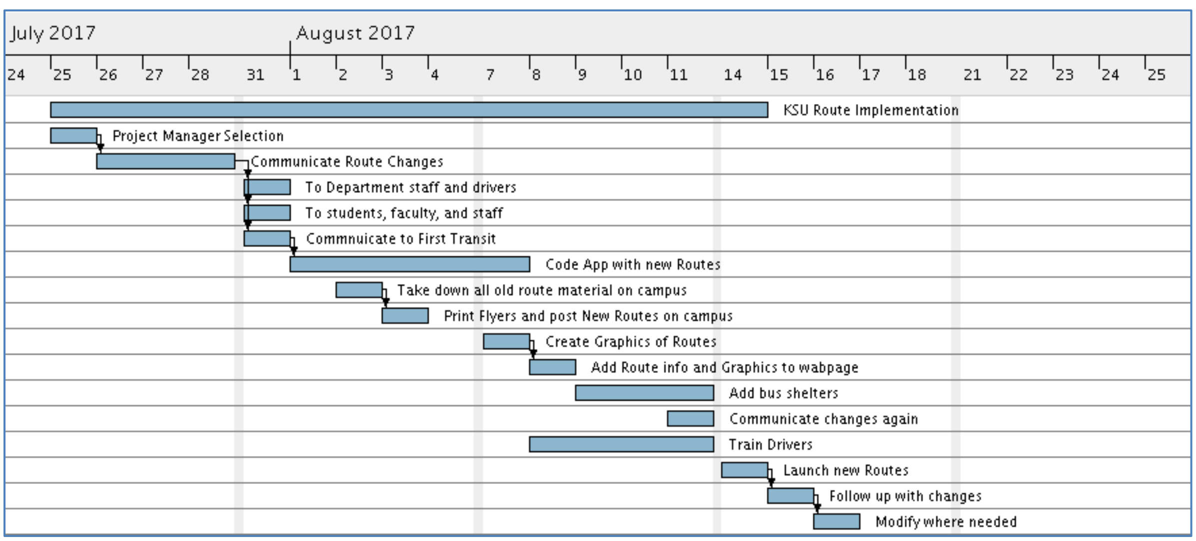

Figure 46: Gantt Chart, Implementation Plan

Chapter 10: Financial Analysis

1. Project Costs

Had the KSU Department of Transportation hired a team to complete this project, it would have cost approximately $22,086. The labor and resources costs can be found in Table 29. Wage rates were determined by the median salary of employees in similar positions and resource costs reflect how much the resource would have cost us if we did not have access to them for free as KSU students. Our actual out-of-pocket costs were $3.24 for printing some of the flyers and other project materials while on campus.

2. Implementation Costs

The implementation process needs to be handled by someone can focus on the project and delegate necessary responsibility to others to ensure the quality of the modifications and the timeline is successful. Additionally in order to effectively communicate all these changes the schools graphic designers and web coordinator will need to spend some time updating the new routes on the website, creating the new flyers, and working on other means to reach out to students and faculty to communicate the changes. Lastly you will also need some additional help removing any material describing the old routes and other additional small tasks to make the implantations effective.

Table 28: Implementation Costs

Project manager:	4 weeks – 40 hours	160 hrs. X 14.50 =	$2,320
Updating and communicating, updating app	2 weeks – 40 hours	80 hrs. X 12.50 =	$1,000
Removing old flyers, printing new routes, and adding them all over campus shelters	4 days – 8 hours	32 hrs. X 8.00 =	$ 256
Adding Bus Shelters	3 shelters -2,500 each (includes labor cost)	3 X 2500 =	$7,500
Training new drivers (27 drivers)	7 hours	7 hrsX12.50X27 =	$2,363
Fuel cost for showing drivers new routes			$500
Estimates total:			**$13,939**

Table 29: Project Costs

Manpower Requirements

	Estimated Work Hours by Task		Totals by Task	
Task	**V. Washington**	**DJ Starzec**	**Hours**	**Cost**
Define design requirements	5	5	10	$ 450.00
Meet with client	1	1	2	$ 90.00
IRB approval, surveys + interviews, IRB closeout	7.5	7	14.5	$ 655.00
Obtain and clean bus data	15.5	0.5	16	$ 795.00
Data analysis	20	7	27	$ 1,280.00
Time study	3.5		3.5	$ 175.00
Create optimization model	15	33	48	$ 2,070.00
Literature review	16	6	22	$ 1,040.00
Sensitivity analysis	15		15	$ 750.00
Simulation (verification)	35		35	$ 1,750.00
Implementation plan		6	6	$ 240.00
Financial analysis		5	5	$ 200.00
Deliverables	30	20	50	$ 2,300.00
Total time (hrs)	163.5	90.5	254	---
Rate ($/hr)	50.00	40.00		
Total cost ($)	$ 8,175.00	$ 3,620.00		$ 11,795.00

Resource Requirements

Item and Description	**Quantity**	**Unit Cost**	**Cost**
Arena (simulation software)	1	$ 2,500.00	$ 2,500.00
Excel Solver Premium	1	$ 7,785.00	$ 7,785.00
Printing Costs (flyers, etc)	100	$ 0.06	$ 6.00
Total cost ($)			$ 10,291.00

Total Costs	$ 22,086.00
Less BSU Discount	$ (22,086.00)
Invoice Amount	$ -

3. Route Costs

Currently the department of transportation at Kennesaw State University pays $69.73 an hour to operate the buses and run the bus system. This figure includes driving staff, operations management staff, maintenance, bus lease, maintenance shop lease, insurance, and uniforms. Not included in this $69.73 is the cost of fuel consumption, which is broken down in the tables below per route. Also calculated below is the hourly expense to run each route per bus. The current routes have a total cost of $317.59 per hour, which is more than the new routes cost $316.56 per hour. This difference of about a dollar can begin to grow close to $5000 if you run only 2 busses on each route for 12 hours a day for a semester. This might not seem like you are saving a lot however, the cost is less in addition to the total routes per hour is more efficient with the new routes 49% more efficient. This means you can run more routes in an hour with the new routes in addition to saving money.

3.1. Current Routes

Table 30: Cost of Current Routes

Current Routes	Miles	Fuel Cost per Route	Drive Time (mins)	Routes per Hour	Cost per Hour	Hourly Expense	TOTAL
Marietta (LG)	21.7	$12.48	43	1.40	$17.41	$69.73	$87.14/hr
Chastain Pointe	2.8	$1.29	14	4.29	$5.52	$69.73	$75.25/hr
West Campus	5	$2.30	16	3.75	$8.63	$69.73	$78.36/hr
Bussbee	4.9	$2.25	19	3.16	$7.12	$69.73	$76.85/hr
							$317.59/hr

3.2. Alternative Routes

Table 31: Cost of Alternative Routes Set 1

New routes:	Miles	Fuel cost per Route	Drive Time (mins)	Routes per Hour	Cost per Hour	Hour Expense	TOTAL
Marietta/Busbee (LG)	20.5	$11.79	41	1.46	$17.25	$69.73	$86.98/hr
Chastain Pointe	2.8	$1.29	11	5.45	$7.03	$69.73	$76.76/hr
West Campus	6.4	$2.94	18	3.33	$9.81	$69.73	$79.54/hr
Main Campus	0.9	$0.41	7	8.57	$3.55	$69.73	$73.28/hr
							$316.56/hr

The overall cost of these routes with running the suggested number of busses is relatively the same. However, with the new routes busses run more frequently and with a shorter overall distance allowing students to get to their destination faster. One day of running the new routes with the determined busses cost an approximate total of $12,000.

Chapter 11: Conclusions

In conclusion, we recommended a new set of routes for the KSU Department of Transportation to utilize in place of four of its current routes. These new routes minimize total travel time, and as a result, should get students to their destinations faster. Our new routes decrease total travel time by 15 minutes. Next, we determined the optimal bus fleet to assign to each of the new routes, keeping in mind that certain buses were already in use on some of the other routes that we chose not to evaluate. There are a variety of factors that can impact our optimal solution, including gas prices, traffic, and desired route frequency. Many of these factors are beyond the control of the Department of Transportation; however, knowing the impact of these factors on total cost in advance can help the Department better allocate their line items in the budget. Our solution did not result in a significant decrease in cost; however, passengers can expect reduced travel times, which should increase passenger perceptions of the route.

1. Design Concepts

We were able to meet all of our target design concepts, including our minimum success criteria, except for one project objective, which was out of our control.

1.1. Project Objectives

We successfully met all of our project objectives except for: "improve the standard deviation of wait times", which the Department of Transportation requested us to evaluate. The data we were provided was insufficient to use as a basis for determining wait times at a bus stop because of the way data is recorded. With its current system, the bus only records data when a passenger is boarding. So if a bus passes a stop because no one is there, or if the driver stops to let people off but no one boards, then no data will be recorded. Therefore, we could not estimate current wait times, and as a result, we could not estimate the standard deviation of wait times. We did, however, perform an analysis of expected standard deviations of bus inter-arrival times as part of our simulation.

2. Possible Extensions

Possible extensions of our project that the Department of Transportation may wish to explore include:

- *Consideration of all routes in vehicle routing problem.* We chose to optimize the total route travel time for four of the nine routes. Consideration of the remaining five routes has the potential to decrease total route travel time even more.
- *Monetization of the value of B.O.B. services to students*. Comparing the value of certain routes to students against the actual cost to run the routes can help the Department determine which routes may be worth altering or eliminating.
- *Consolidation of current routes.* We chose to maintain the total number of routes offered by the Department of Transportation; however, it is worth exploring how the consolidation of routes affect both travel time and cost.

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Appendix A: Team Assignments

For team assignments, please visit Table 1: Team Assignments on page 8.

Appendix B: Acknowledgements

We would like to thank the KSU Department of Transportation for making this project possible. Additionally, we would like to thank Drs. Khalid and Wiles for their continued support and assistance as we completed our project.

Appendix C: Contact Information

The BOBtimizers can be contacted as follows:

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Appendix D: Reflections

We face several challenges in completing this project, all of which have made us more equipped to develop and solve real-world optimization and simulation models on our own. One problem we had never really faced before was having a model that was so large that it could not be solved in the student versions of the software we had access to. While textbook problems are relatively small and simple, real-world problems are often large and complex, and to approach them, they must be simplified in a way that does not also remove is applicability to the real-world. One example of this is our optimization model in Chapter 6 (determining optimal fleet). Originally, we attempted to develop the model in a way that would allow us to determine the best fleet for all four routes for different times of the entire day, all at once. Eventually, and with much help from Dr. Khalid, we decided on developing a model that could find the optimal solution for a specific route at specific time, which, as one might imagine, was a lot simpler to accomplish.

Another challenge we encountered was having a problem that was too large to solve on our standard go-to software. Our first optimization model (Chapter 5) has 25^2 decision variables, and a number of constraints. We were unable to solve the problem in LINGO (student version), or Excel Solver (free version). We looked into available open-source software, but were still limited by either its abilities, or its steep learning curve and our limited timeline. Our solution was to use a series of 2-week trials of Excel Solver Plus so that we could obtain a solution.

Similarly, the simulation model offered many challenges in the restrictions Arena places on the total number of variables, modules, attributes, etc. Additionally, because we "ran out" of variables, it was frustrating having to each module to change the travel times, arrival rates, etc. every time we ran a new route/time. This problem in particular awakened a desire to learn how to program simulation models, such as in Java, MATLAB, or R.

Lastly, we ran into some scheduling issues because of these different software problems not accepting our model because the size of the model was too large. We did not leave any buffer room or time in the schedule for us to mess up. Once we set the schedule and started, it was hard to catch up and get back on track. Looking forward into future project, I think it would be beneficial to give a little room in-between tasks to help us stay on schedule in case we fall behind.

Appendix E: Time Points Master List – Kennesaw-Marietta Route, Monday through Thursday

Table 32: Driver Time Points Master List, Kennesaw-Marietta Route, Monday through Thursday

(continued on next page)

Kennesaw/Marietta Time Points						
	Rec Center-Arrive	Rec Center - Leave	Commons	Courtyard	Joe Mack-Arrive	Joe Mack-Leave
Block 4	x	x	x	7:01 AM	7:10 AM	7:16 AM
Block 1	6:44 AM	6:45 AM	6:46 AM	7:26 AM	7:34 AM	7:35 AM
Block 2	7:04 AM	7:05 AM	7:06 AM	7:46 AM	7:54 AM	7:55 AM
Block 3	7:24 AM	7:27 AM	7:28 AM	8:08 AM	8:16 AM	8:20 AM
Block 4	7:44 AM	7:47 AM	7:48 AM	8:28 AM	8:36 AM	8:40 AM
Block 1	7:59 AM	8:03 AM	8:04 AM	8:44 AM	8:52 AM	8:56 AM
Block 2	8:19 AM	8:23 AM	8:24 AM	9:04 AM	9:12 AM	9:16 AM
Block 3	8:44 AM	8:48 AM	8:49 AM	9:24 AM	9:32 AM	9:36 AM
Block 4	9:04 AM	9:09 AM	9:10 AM	9:45 AM	9:53 AM	9:58 AM
Block 1	9:20 AM	9:28 AM	9:29 AM	10:01 AM	10:09 AM	10:19 AM
Block 2	9:38 AM	9:46 AM	9:47 AM	10:19 AM	10:27 AM	10:34 AM
Block 3	9:59 AM	10:07 AM	10:08 AM	10:38 AM	10:46 AM	10:51 AM
Block 4	10:20 AM	10:26 AM	10:27 AM	10:57 AM	11:05 AM	11:10 AM
Block 1	10:38 AM	10:44 AM	10:45 AM	11:15 AM	11:23 AM	11:28 AM
Block 2	10:54 AM	11:04 AM	11:05 AM	11:35 AM	11:43 AM	11:48 AM
Block 3	11:11 AM	11:22 AM	11:23 AM	11:48 AM	11:56 AM	12:01 PM
Block 4	11:30 AM	11:41 AM	11:42 AM	12:07 PM	12:15 PM	12:16 PM
Block 1	11:48 AM	11:59 AM	12:00 PM	12:25 PM	12:33 PM	12:38 PM
Block 2	12:08 PM	12:18 PM	12:19 PM	12:44 PM	12:52 PM	12:57 PM
Block 3	12:23 PM	12:33 PM	12:34 PM	12:59 PM	1:07 PM	1:12 PM
Block 4	12:38 PM	12:48 PM	12:49 PM	1:14 PM	1:22 PM	1:27 PM
Block 1	1:00 PM	1:09 PM	1:10 PM	1:35 PM	1:43 PM	1:47 PM
Block 2	1:19 PM	1:28 PM	1:29 PM	1:54 PM	2:02 PM	2:06 PM
Block 3	1:34 PM	1:42 PM	1:43 PM	2:08 PM	2:16 PM	2:21 PM

Table 32: Driver Time Points Master List, Kennesaw-Marietta Route, Monday through Thursday
(continued from previous page)

Kennesaw/Marietta Time Points						
	Rec Center-Arrive	**Rec Center - Leave**	**Commons**	**Courtyard**	**Joe Mack-Arrive**	**Joe Mack-Leave**
Block 4	1:51 PM	1:59 PM	2:00 PM	2:25 PM	2:33 PM	2:38 PM
Block 1	2:11 PM	2:18 PM	2:19 PM	2:44 PM	2:52 PM	2:57 PM
Block 2	2:30 PM	2:37 PM	2:38 PM	3:03 PM	3:11 PM	3:16 PM
Block 3	2:45 PM	2:51 PM	2:52 PM	3:17 PM	3:25 PM	3:30 PM
Block 4	3:03 PM	3:10 PM	3:11 PM	3:36 PM	3:44 PM	3:49 PM
Block 1	3:27 PM	3:34 PM	3:35 PM	4:02 PM	4:10 PM	4:15 PM
Block 2	3:46 PM	3:51 PM	3:52 PM	4:20 PM	4:28 PM	4:33 PM
Block 3	4:02 PM	4:07 PM	4:08 PM	4:38 PM	4:46 PM	4:51 PM
Block 4	4:21 PM	4:26 PM	4:27 PM	4:57 PM	5:05 PM	5:10 PM
Block 1	4:50 PM	4:55 PM	4:56 PM	5:28 PM	5:36 PM	5:41 PM
Block 2	5:08 PM	5:13 PM	5:14 PM	5:46 PM	5:54 PM	6:01 PM
Block 3	5:26 PM	5:32 PM	5:33 PM	6:05 PM	6:13 PM	6:17 PM
Block 4	5:45 PM	5:53 PM	5:54 PM	6:26 PM	6:34 PM	6:40 PM
Block 1	6:16 PM	6:18 PM	6:19 PM	6:51 PM	6:59 PM	7:07 PM
Block 2	6:36 PM	6:43 PM	6:44 PM	7:16 PM	7:24 PM	7:29 PM
Block 3	6:50 PM	**End of Shift - 7 PM**	x	x	x	x
Block 4	7:12 PM	7:13 PM	7:14 PM	7:44 PM	7:52 PM	8:02 PM
Block 1	7:39 PM	**End of Shift - 8 PM**	x	x	x	x
Block 2	7:51 PM	7:52 PM	7:53 PM	8:18 PM	8:26 PM	8:31 PM
Block 4	8:24 PM	8:25 PM	8:26 PM	8:51 PM	8:59 PM	9:04 PM
Block 2	8:53 PM	8:54 PM	8:55 PM	9:20 PM	9:28 PM	9:33 PM
Block 4	9:26 PM	9:27 PM	9:28 PM	9:53 PM	10:01 PM	10:06 PM
Block 2	9:55 PM	9:56 PM	9:57 PM	10:22 PM	10:30 PM	**10:35 PM**
Block 4	10:28 PM	**10:35 PM**	10:36 PM	10:56 PM	11:04 PM	**End of Shift**
Block 2	10:57 PM	**End of Shift 11 PM**	x	x	x	x

Appendix F: Time Points Master List – Kennesaw-Marietta Route, Friday

Table 33: Driver Time Points Master List, Kennesaw-Marietta Route, Friday

	Rec Center- Arrive	Rec Center - Leave	Commons	Courtyard	Joe Mack- Arrive	Joe Mack- Leave	
Block 1	9:20 AM	9:26 AM	9:27 AM	10:04 AM	10:12 AM	10:16 AM	
Block 1	10:40 AM	10:48 AM	10:49 AM	11:23 AM	11:31 AM	11:34 AM	
Block 1	11:58 AM	12:05 PM	12:06 PM	12:40 PM	12:48 PM	12:52 PM	
Block 1	1:16 PM	1:23 PM	1:24 PM	1:58 PM	2:06 PM	2:10 PM	
Block 1	2:37 PM	2:44 PM	2:45 PM	3:19 PM	3:27 PM	3:29 PM	
Block 1	3:57 PM	4:02 PM	4:03 PM	4:38 PM	4:46 PM	4:47 PM	
Block 1	5:17 PM	5:18 PM	5:19 PM	5:54 PM	6:02 PM	6:03 PM	
Block 1	6:33 PM	**6:35 PM**	6:36 PM	7:06 PM	7:13 PM	**7:13 PM**	
Block 1	6:44 AM	6:45 AM	6:46 AM	7:26 AM	7:34 AM	7:35 AM	
Block 1	7:59 AM	8:06 AM	8:07 AM	8:47 AM	8:55 AM	8:56 AM	
Block 2	7:09 AM	7:10 AM	7:11 AM	7:51 AM	7:59 AM	8:01 AM	
Block 2	8:25 AM	8:32 AM	8:33 AM	9:13 AM	9:21 AM	9:22 AM	
Block 2	9:46 AM	9:52 AM	9:53 AM	10:30 AM	10:38 AM	10:42 AM	
Block 2	11:06 AM	11:13 AM	11:14 AM	11:48 AM	11:56 AM	12:00 PM	
Block 2	1:44 PM	1:51 PM	1:52 PM	2:26 PM	2:34 PM	2:36 PM	
Block 2	3:03 PM	3:10 PM	3:11 PM	3:45 PM	3:53 PM	3:55 PM	
Block 2	4:25 PM	4:30 PM	4:31 PM	5:06 PM	5:14 PM	5:15 PM	
Block 2	5:45 PM	5:48 PM	5:49 PM	6:24 PM	6:32 PM	**6:35 PM**	
Block 2	7:05 PM	7:05 PM	**7:06 PM**	**End of Service**			
Block 2	12:24 PM	12:31 PM	12:32 PM	1:06 PM	1:14 PM	1:18 PM	
Block 3				7:01 AM	7:10 AM	7:11 AM	
Block 3	7:35 AM	7:40 AM	7:41 AM	8:21 AM	8:28 AM	8:29 AM	
Block 3	8:53 AM	8:59 AM	9:00 AM	9:37 AM	9:45 AM	9:49 AM	
Block 3	10:13 AM	10:20 AM	10:21 AM	10:55 AM	11:03 AM	11:05 AM	
Block 3	11:29 AM	11:37 AM	11:38 AM	12:12 PM	12:20 PM	12:24 PM	
Block 3	12:48 PM	12:56 PM	12:57 PM	1:31 PM	1:39 PM	1:41 PM	
Block 3	2:07 PM	2:13 PM	2:14 PM	2:48 PM	2:56 PM	2:58 PM	Last Trip
Block 3	3:26 PM	3:32 PM	3:33 PM	4:07 PM	4:15 PM	4:16 PM	
Block 3	4:46 PM	4:47 PM	4:48 PM	5:23 PM	5:31 PM	5:32 PM	**End of Serv.**
Block 3	6:02 PM	6:02 PM	**6:03 PM**	End of Service			

Appendix G: Time Study Data

Table 34: Time Study 1, Kennesaw-Marietta Route

Time Elapsed	Action and Comments	On	Off
0:00:00	Pick up at Marietta Campus Student Center; 5 already on board; App was accurate for pick up time	13	0
0:03:28	Left Marietta Campus Student Center to Kennesaw Campus, taking I-75; enters campus through Chastain Road (pass through Austin Residential Complex)		
0:23:46	Stop at SRAC; all students get off bus; driver also exits bus to take a break and talk to next driver; one student boards and exits bus shortly after; one gets on with a bike (puts on bus bike rack)	16	19
0:30:30	Switch bus drivers; bus is moved a few yards in front of the bus stop, presumably to make room for other buses to access the bus stop more easily; continue to wait at stop; 2 students comment about the long wait and get off the bus	6	2
0:36:33	Leave SRAC; take service vehicles only route to The Commons		
0:38:06	Pick up at the Commons	14	0
0:38:56	Leave The Commons to Marietta Campus Courtyard Apartments via I-75; enter campus via main entrance; one student appears to be standing in a no standing zone		
0:59:00	All but 17 get off; slight delay for student grabbing bike	0	16
1:00:12	Leave stop for Courtyard apartments stop 2		
1:01:03	Stop at Courtyard	1	3
1:01:25	Leave CY; travel to Commons Apartments		
1:03:16	Stop at Commons Apartments; none enter or exit	0	0
1:03:27	Leave Commons Apartments		
1:04:38	Stop at Hornet Village	3	5
1:05:08	Leave HV		
1:06:02	Stop at soccer fields	1	3
	Depart soccer fields		
1:07:17	Stop at Greek houses	0	2
	Leave Greek houses to Student Center; on the way out of the Greek houses, we run into another Kennesaw-Marietta bus, and delay while the drivers talk to one another (~30 seconds), and the driver lets another student onto the bus	1	
1:11:26	Stop at Student Center; approximately 7 left on bus		1

Table 35: Time Study 2, Kennesaw-Marietta Route

Time Elapsed	Action and Comments	On	Off
0:00:00	Pick up at Marietta Campus Student Center; 0:00:30 to 0:02:39 - driver loads/unloads ramp and secures wheelchair	6	
0:03:22	Depart for Kennesaw campus, travelling via I-75. According to Google Maps, fastest route at 29 minutes would be to take S Marietta to Cherokee St to Church St Ext to Cobb Parkway to Greers Chapel to Barret Parkway to Barret Lakes to Big Shanty to Town Point Drive		

0:40:18	Stop at Austin Residential Complex; note: this stop is not on the route, stopped by request of students; have to pass this stop anyways to continue to SRAC		2
0:40:27	Leave Austin Residential Complex		
0:42:08	Stop at SRAC; 0:42:47 to 0:44:50 - driver assists student with wheelchair unload; 0:45:10 to 0:47:58 - driver takes bathroom break	11	6
0:48:22	leave SRAC		
0:50:05	Stop at The Commons	8	
0:50:40	Depart The Commons; note: this bus does not announce upcoming stops -- driver is announcing; take I-75 back to Marietta Campus		
1:13:28	Stop at CY stop 1		4
1:14:19	Stop at CY stop 2	1	5
1:16:31	Stop at Commons Apt		3
1:16:48	Leave Commons Apts		
1:18:04	Stop at Hornet Village	2	4
1:18:27	Leave HV		
1:19:40	Pass stop at soccer fields without stopping (no one wanted to get off)		
1:20:09	Stop at Greek houses		1
1:20:26	Leave Greek houses		
1:23:40	Stop at Marietta Student Center		1

Appendix H: Student Survey Questions

ONLINE SURVEY QUESTIONS

Demographics:

Sex: ___ M ____ F

Age Group:
- 18 to 24
- 25 to 34
- 35 to 44
- 45 to 54
- 55+

Occupation:
- Student
- Faculty
- Staff
- Other: __________

Classification:
- Freshman (1st year)
- Sophomore (2nd year)
- Junior (3rd year)
- Senior (4th year)
- 5+ years
- Graduate student
- Other

Are you an on-campus resident or a commuter?
- On campus resident
- Commuter

Do you own a car or bike? (Check all that apply)
- Car
- Bike

Have you ever ridden the B.O.B?
- Yes
- No

<table>
<tr>
<td>
YES:
On average, how often do you ride the B.O.B.?

1-2 times per year
Once a month
1-2 times per week
3+ times per week
Every day

Which routes do you use most often? Check all that apply.

Kennesaw-Marietta Route
Busbee Drive/Stadium
West Campus
Frey Road
Skip Spann
Chastain Pointe
Town Point
Kennesaw Shopping
Marietta Shopping

What best describes your reasons for riding the B.O.B.? Check all that apply.

Do not own a car
Own a car, but preferred not to drive
Save money
Convenience
Take advantage of student fees
Speed
Other (please explain)

Please elaborate here:

What was your experience with the B.O.B.? (Rank 1 to 4 (1 - Great to 4 - Needs Improvement))

Timeliness of bus arrival
Wait times
Frequency of pick ups
Safety on bus
Safety at bus stops
Comfort
Cleanliness
Location of stops
Accuracy of app

</td>
<td>
NO:
What best describes your reasons for not riding the B.O.B.? Check all that apply.

Own a car
Save money
Convenience
Speed
Other (please explain)

Please elaborate here:

What factors have contributed to your decision not to ride the B.O.B.? (Rank 1 to 3 (1 – Strong Influence to 3 – Not a Factor))

Timeliness of bus arrival
Wait times
Frequency of pick ups
Safety on bus
Safety at bus stops
Comfort
Cleanliness
Location of stops
Accuracy of app

If you would like to elaborate, please do so here:

Do you think the B.O.B. is beneficial to the University?

Yes
No

Additional comments:
</td>
</tr>
</table>

If you would like to elaborate, please do so here: Do you think the B.O.B. is beneficial to the University? - Yes - No Additional comments:	

Appendix I: Snapshot of Excel files

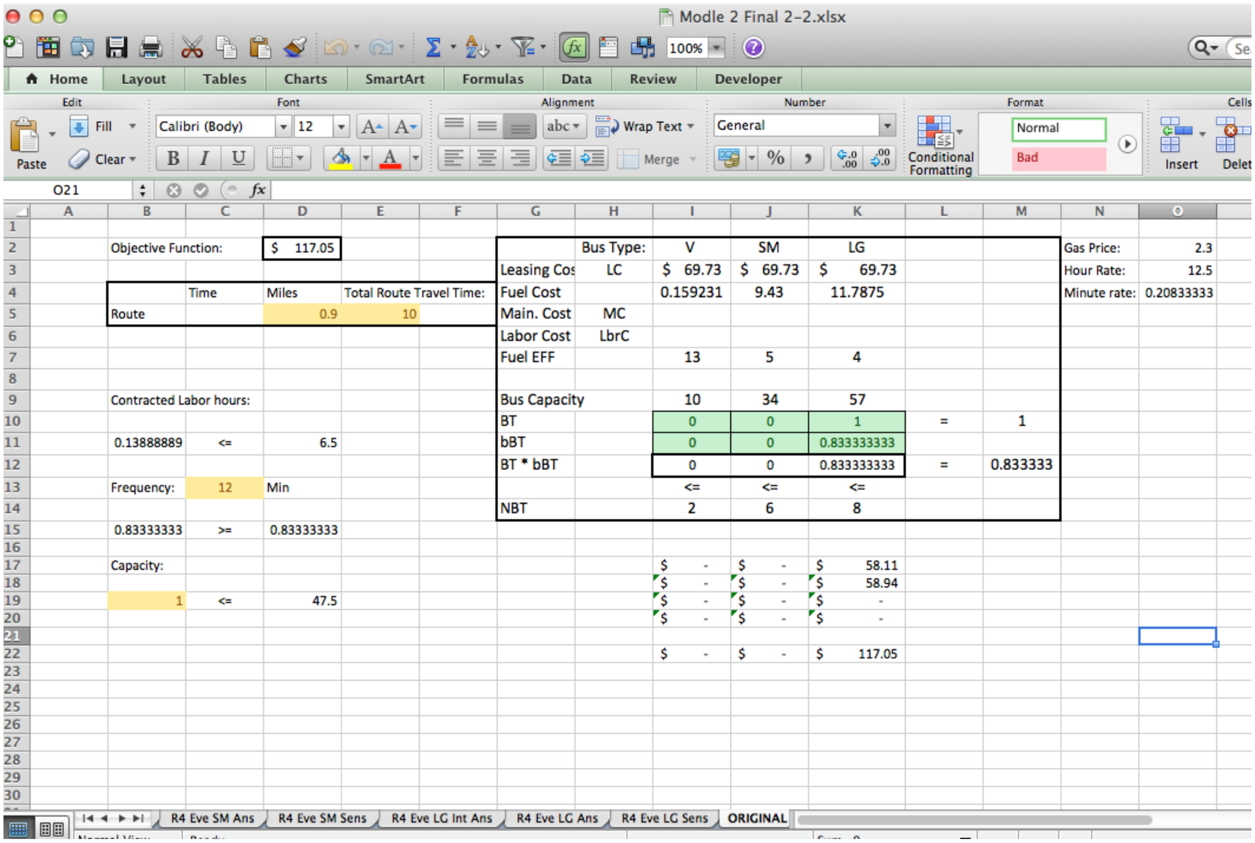

Figure 47: Excel Solver Snapshot – Determining Optimal Fleet

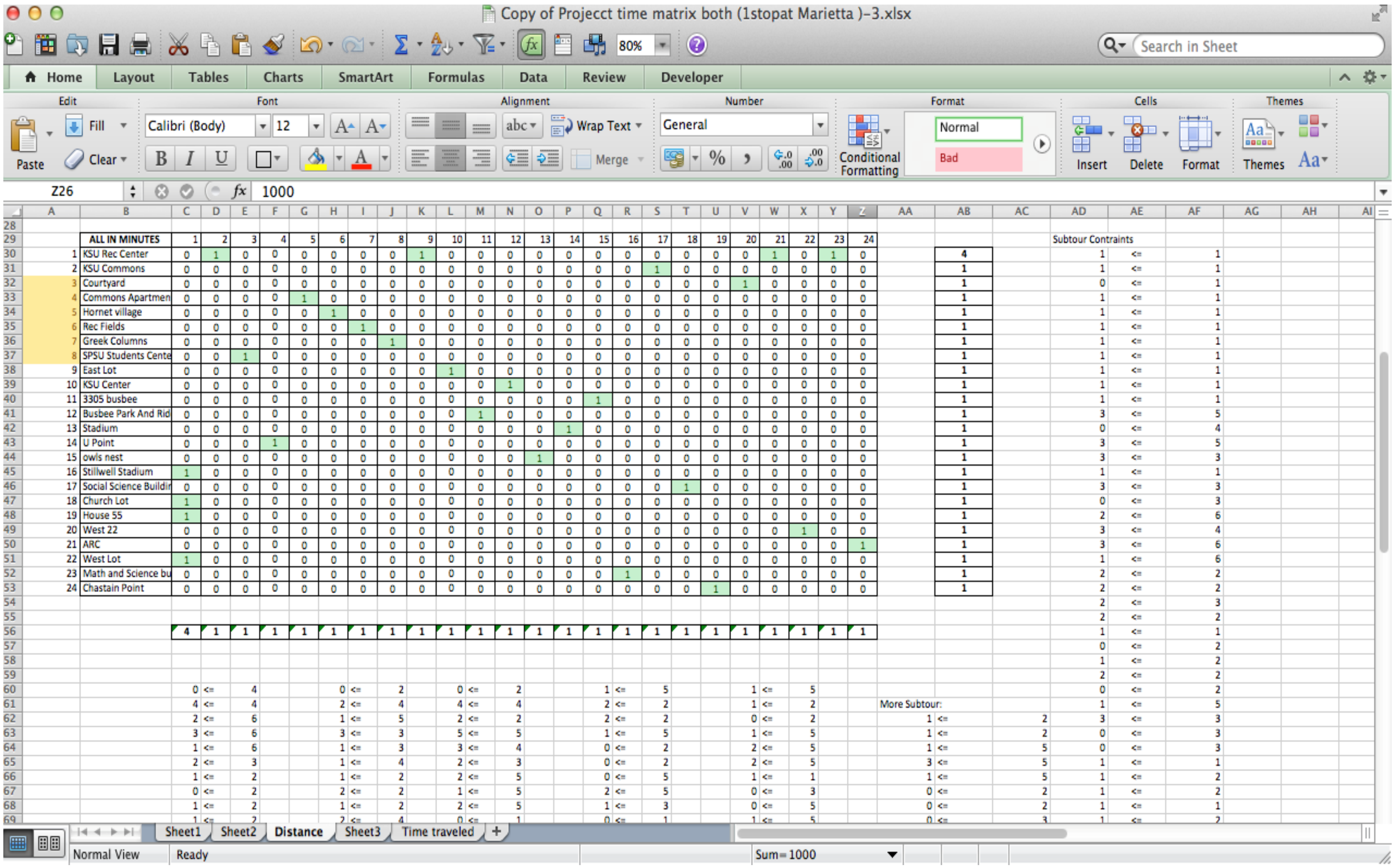

Figure 48: Excel Solver Snapshot – Determining Optimal Routes

Appendix J: Marietta/Busbee Morning Fleet Assignment Excel Solver Answer and Sensitivity Reports

3. Vans

Infeasible solution. No answer or sensitivity reports generated.

4. Small Buses

4.1. Integer Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.032 Seconds.

Iterations: 0 Subproblems: 2

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 313.74

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	2	0	Integer
$J$11	bBT SM	0	4	Integer
$K$11	bBT LG	0	0	Integer

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	4.333333333	$B$11<=$D$11	Not Binding	2.166666667
$B$15	Frequency:	4	$B$15>=$D$15	Not Binding	0.75
$B$19	Capacity:	111	$B$19<=$D$19	Not Binding	25
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	4	$J$12<=$J$14	Not Binding	2
$K$12	BT * bBT LG	0	$K$12<=$K$14	Not Binding	8
$I$11:$K$11=Integer					

4.2. Continuous Variable Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0 Seconds.

Iterations: 2 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ 313.74	$ 256.07

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Contin
$J$11	bBT SM	4	3.264705882	Contin
$K$11	bBT LG	0	0	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	3.536764706	$B$11<=$D$11	Not Binding	2.963235294
$B$15	Frequency:	3.264705882	$B$15>=$D$15	Not Binding	0.014705882
$B$19	Capacity:	111	$B$19<=$D$19	Binding	0
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	3.264705882	$J$12<=$J$14	Not Binding	2.735294118
$K$12	BT * bBT LG	0	$K$12<=$K$14	Not Binding	8

4.3. Continuous Variable Solution Sensitivity Report

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$I$11	bBT V	0	0	0	1E+30	0
$J$11	bBT SM	3.264705882	0	78.43461538	1E+30	78.43461538
$K$11	bBT LG	0	0	0	1E+30	0

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$B$11	Contracted Labor hours:	3.536764706	0	6.5	1E+30	2.963235294
$B$15	Frequency:	3.264705882	0	3.25	0.014705882	1E+30
$B$19	Capacity:	111	-2.306900452	0	0.5	93
$I$12	BT * bBT V	0	0	2	1E+30	2
$J$12	BT * bBT SM	3.264705882	0	6	1E+30	2.735294118
$K$12	BT * bBT LG	0	0	8	1E+30	8

5. Large Buses

5.1. Integer Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.031 Seconds.

Iterations: 0 Subproblems: 2

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ 322.44	$ 322.44

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Contin
$J$11	bBT SM	0	0	Contin
$K$11	bBT LG	4	4	Integer

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	4.333333333	$B$11<=$D$11	Not Binding	2.166666667
$B$15	Frequency:	4	$B$15>=$D$15	Not Binding	0.75
$B$19	Capacity:	111	$B$19<=$D$19	Not Binding	117
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	0	$J$12<=$J$14	Not Binding	6
$K$12	BT * bBT LG	4	$K$12<=$K$14	Not Binding	4
$K$11=Integer					

5.2. Continuous Variable Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.031 Seconds.

Iterations: 2 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 261.99

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Contin
$J$11	bBT SM	3.264705882	0	Contin
$K$11	bBT LG	0	3.25	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	3.520833333	$B$11<=$D$11	Not Binding	2.979166667
$B$15	Frequency:	3.25	$B$15>=$D$15	Binding	0
$B$19	Capacity:	111	$B$19<=$D$19	Not Binding	74.25
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	0	$J$12<=$J$14	Not Binding	6
$K$12	BT * bBT LG	3.25	$K$12<=$K$14	Not Binding	4.75

5.3. Continuous Variable Solution Sensitivity Report

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$I$11	bBT V	0	0	0	1E+30	0
$J$11	bBT SM	0	0	0	1E+30	0
$K$11	bBT LG	3.25	0	80.61076923	1E+30	80.61076923

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$B$11	Contracted Labor hours:	3.520833333	0	6.5	1E+30	2.979166667
$B$15	Frequency:	3.25	80.61076923	3.25	2.75	1.302631579
$B$19	Capacity:	111	0	0	1E+30	74.25
$I$12	BT * bBT V	0	0	2	1E+30	2
$J$12	BT * bBT SM	0	0	6	1E+30	6
$K$12	BT * bBT LG	3.25	0	8	1E+30	4.75

Appendix K: Marietta/Busbee Afternoon Fleet Assignment Excel Solver Answer and Sensitivity Reports

1. Vans

No feasible solution. No answer or sensitivity reports generated.

2. Small Buses

No feasible solution. No answer or sensitivity reports generated.

3. Large Buses

3.1. Integer Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.031 Seconds.

Iterations: 1 Subproblems: 2

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 314.73

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Integer
$J$11	bBT SM	0	0	Integer
$K$11	bBT LG	0	4	Integer

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	5.266666667	$B$11<=$D$11	Not Binding	1.233333333
$B$15	Frequency:	4	$B$15>=$D$15	Not Binding	0.05
$B$19	Capacity:	179	$B$19<=$D$19	Not Binding	49
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	0	$J$12<=$J$14	Not Binding	6
$K$12	BT * bBT LG	4	$K$12<=$K$14	Not Binding	4
$I$11:$K$11=Integer					

3.2. Continuous Variable Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.015 Seconds.

Iterations: 2 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ 314.73	$ 310.80

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Contin
$J$11	bBT SM	0	0	Contin
$K$11	bBT LG	4	3.95	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	5.200833333	$B$11<=$D$11	Not Binding	1.299166667
$B$15	Frequency:	3.95	$B$15>=$D$15	Binding	0
$B$19	Capacity:	179	$B$19<=$D$19	Not Binding	46.15
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	0	$J$12<=$J$14	Not Binding	6
$K$12	BT * bBT LG	3.95	$K$12<=$K$14	Not Binding	4.05

3.3. Continuous Variable Solution Sensitivity Report

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$I$11	bBT V	0	0	0	1E+30	0
$J$11	bBT SM	0	0	0	1E+30	0
$K$11	bBT LG	3.95	0	78.68253165	1E+30	78.68253165

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$B$11	Contracted Labor hours:	5.200833333	0	6.5	1E+30	1.299166667
$B$15	Frequency:	3.95	78.68253165	3.95	0.986708861	0.809649123
$B$19	Capacity:	179	0	0	1E+30	46.15
$I$12	BT * bBT V	0	0	2	1E+30	2
$J$12	BT * bBT SM	0	0	6	1E+30	6
$K$12	BT * bBT LG	3.95	0	8	1E+30	4.05

Appendix L: Marietta/Busbee Evening Fleet Assignment Excel Solver Answer and Sensitivity Reports

1. Vans

Infeasible solution. No answer or sensitivity reports generated.

2. Small Buses

2.1. Integer Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.016 Seconds.

Iterations: 0 Subproblems: 2

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 246.09

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Integer
$J$11	bBT SM	0	3	Integer
$K$11	bBT LG	0	0	Integer

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	2.3	$B$11<=$D$11	Not Binding	4.2
$B$15	Frequency:	3	$B$15>=$D$15	Not Binding	0.7
$B$19	Capacity:	25	$B$19<=$D$19	Not Binding	77
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	3	$J$12<=$J$14	Not Binding	3
$K$12	BT * bBT LG	0	$K$12<=$K$14	Not Binding	8
$I$11:$K$11=Integer					

2.2. Continuous Variable Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.015 Seconds.

Iterations: 2 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 188.67

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Contin
$J$11	bBT SM	0	2.3	Contin
$K$11	bBT LG	0	0	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	1.763333333	$B$11<=$D$11	Not Binding	4.736666667
$B$15	Frequency:	2.3	$B$15>=$D$15	Binding	0
$B$19	Capacity:	25	$B$19<=$D$19	Not Binding	53.2
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	2.3	$J$12<=$J$14	Not Binding	3.7
$K$12	BT * bBT LG	0	$K$12<=$K$14	Not Binding	8

2.3. Continuous Variable Solution Sensitivity Report

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$I$11	bBT V	0	0	0	1E+30	0
$J$11	bBT SM	2.3	0	82.03	1E+30	82.03
$K$11	bBT LG	0	0	0	1E+30	0

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$B$11	Contracted Labor hours:	1.763333333	0	6.5	1E+30	4.736666667
$B$15	Frequency:	2.3	82.03	2.3	3.7	1.564705882
$B$19	Capacity:	25	0	0	1E+30	53.2
$I$12	BT * bBT V	0	0	2	1E+30	2
$J$12	BT * bBT SM	2.3	0	6	1E+30	3.7
$K$12	BT * bBT LG	0	0	8	1E+30	8

3. Large Buses

3.1. Integer Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.031 Seconds.

Iterations: 0 Subproblems: 2

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 255.32

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Integer
$J$11	bBT SM	0	0	Integer
$K$11	bBT LG	0	3	Integer

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	2.3	$B$11<=$D$11	Not Binding	4.2
$B$15	Frequency:	3	$B$15>=$D$15	Not Binding	0.7
$B$19	Capacity:	25	$B$19<=$D$19	Not Binding	146
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	0	$J$12<=$J$14	Not Binding	6
$K$12	BT * bBT LG	3	$K$12<=$K$14	Not Binding	5
$I$11:$K$11=Integer					

3.2. Continuous Variable Solution Answer Report

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: Simplex LP

Solution Time: 0.031 Seconds.

Iterations: 2 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
$D$2	Objective Function:	$ -	$ 195.74

Variable Cells

Cell	Name	Original Value	Final Value	Integer
$I$11	bBT V	0	0	Contin
$J$11	bBT SM	0	0	Contin
$K$11	bBT LG	0	2.3	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
$B$11	Contracted Labor hours:	1.763333333	$B$11<=$D$11	Not Binding	4.736666667
$B$15	Frequency:	2.3	$B$15>=$D$15	Binding	0
$B$19	Capacity:	25	$B$19<=$D$19	Not Binding	106.1
$I$12	BT * bBT V	0	$I$12<=$I$14	Not Binding	2
$J$12	BT * bBT SM	0	$J$12<=$J$14	Not Binding	6
$K$12	BT * bBT LG	2.3	$K$12<=$K$14	Not Binding	5.7

3.3. Continuous Variable Solution Sensitivity Report

Variable Cells

Cell	Name	Final Value	Reduced Cost	Objective Coefficient	Allowable Increase	Allowable Decrease
$I$11	bBT V	0	0	0	1E+30	0
$J$11	bBT SM	0	0	0	1E+30	0
$K$11	bBT LG	2.3	0	85.105	1E+30	85.105

Constraints

Cell	Name	Final Value	Shadow Price	Constraint R.H. Side	Allowable Increase	Allowable Decrease
$B$11	Contracted Labor hours:	1.763333333	0	6.5	1E+30	4.736666667
$B$15	Frequency:	2.3	85.105	2.3	5.7	1.861403509
$B$19	Capacity:	25	0	0	1E+30	106.1
$I$12	BT * bBT V	0	0	2	1E+30	2
$J$12	BT * bBT SM	0	0	6	1E+30	6
$K$12	BT * bBT LG	2.3	0	8	1E+30	5.7

Appendix M: Arena Simulation Model

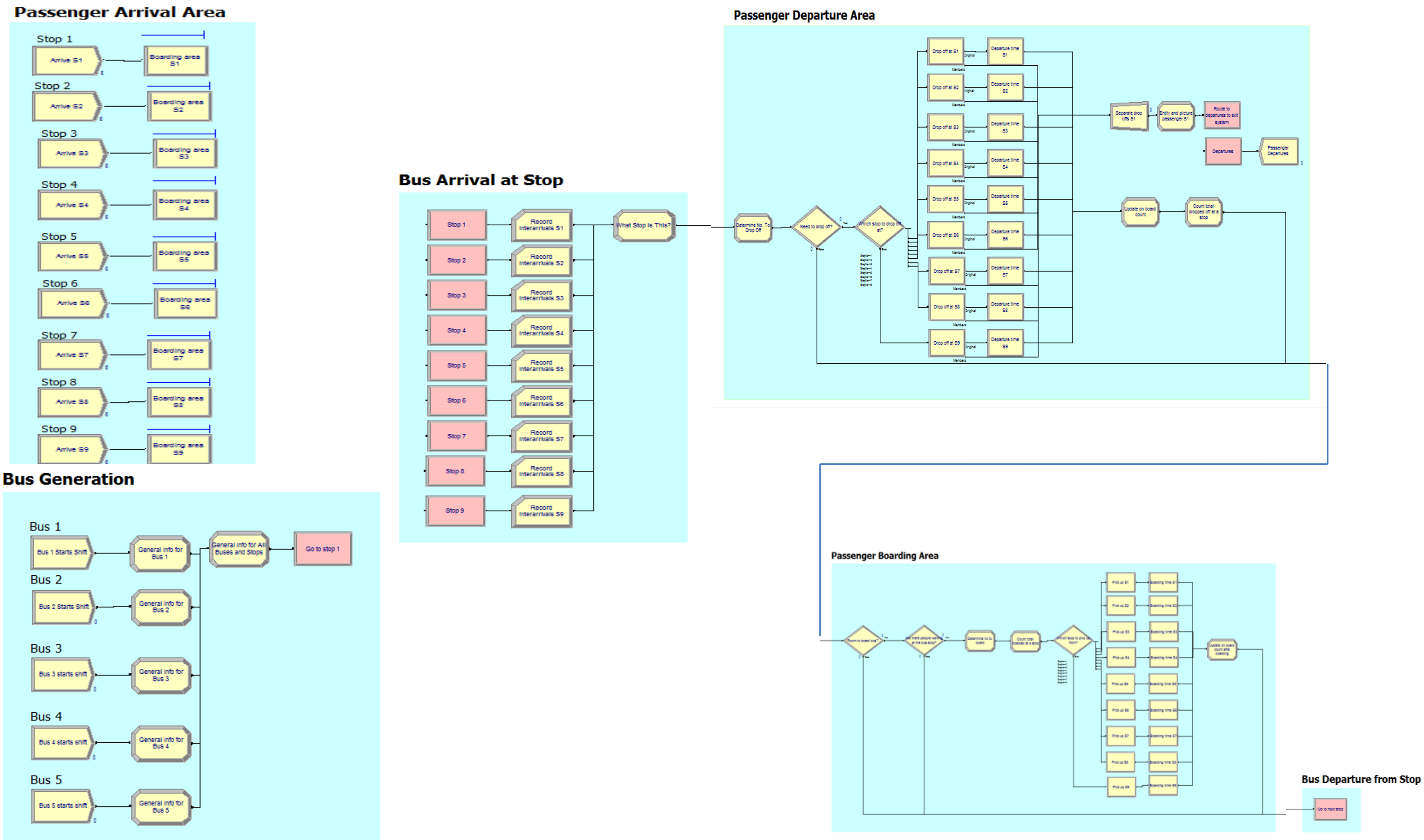

Figure 49: Arena Model Snapshot