March
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Commuter Bus Demand, Incentives for Modal Shift, and Impact on GHG

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Karyn E. Polito, *Lieutenant Governor*
Stephanie Pollack, *MassDOT Secretary & CEO*

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16. Abstract
In response to Governor Charles Baker's Executive Order No. 569, MassDOT Rail and Transit Division is interested in identifying ways to reduce greenhouse gas (GHG) emissions from the transportation sector by incentivizing mode shift through the provision of improved transit service. This project focuses on determining whether there is an opportunity to expand commuter bus service in the Greater Boston area and the necessary incentives commuters need to make a modal shift. This project has utilized existing models to estimate the status quo of mode split and GHG emissions and has developed user cost and agency cost models that are used to model operations of a new commuter bus service for each origin-destination (OD) pair at the spatial resolution of towns. Then, an efficiency metric defined as the ratio of change in cost for providing the additional service over the reduction of GHG emissions (after the introduction of the new commuter bus service) is applied, and the combinations of fare and commuter bus frequency that maximize this efficiency metric for each OD pair are determined. The final outcomes of this project are rankings of OD pairs that present the maximum efficiency.

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Commuter Bus Demand, Incentives for Modal Shift, and Impact on GHG Emissions

Final Report

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Executive Summary

This study of Commuter Bus Demand, Incentives for Modal Shift, and Impact on GHG Emissions was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program with funding from Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. The purpose of this study is to identify the potential for reducing greenhouse gas (GHG) emissions from the transportation sector in the Greater Boston area by expanding commuter bus services in the region.

This project addresses two main objectives:

1. The methodological objective is to develop a data-based model to quantify the user and agency cost as well as GHG emissions associated with commuting patterns by private vehicles and expanded commuter bus services.
2. The applied objective is to analyze available demand and traffic performance data for origin-destination (OD) pairs in the Greater Boston area and apply the proposed models to rank OD pairs by potential to attract commuters to express commuter buses from driving private cars and reduce overall GHG emissions. A related objective is to identify the most cost-efficient corridors that achieve the greatest reduction in GHG emissions per dollar invested in expanded commuter bus service.

Methodology

This study builds on data and demand models that have been developed for the Greater Boston area by the Central Transportation Planning Staff (CTPS), which is the Boston Region Metropolitan Planning Organization. A simplified travel demand model for the region was developed to account for commuter mode choice and associated traffic emissions at the spatial aggregation of 164 towns and the Boston Central Business District (CBD). This model uses data for each OD pair regarding monetary costs, out-of-vehicle travel time, and in-vehicle travel time for 12 transportation modes considered in the CTPS travel demand model, as listed in Table 1.

Table 1: 12 transportation modes in CTPS travel demand model

	Name	Description
1	SOV	Single Occupancy Vehicle (drive alone)
2	HOV 2	High Occupancy Vehicle (shared ride) – two or more persons
3	WALK	Walk
4	BIKE	Bike
5	DAT+B	Drive-Access Transit: Boat
6	DAT+CR	Drive-Access Transit: Commuter Rail
7	DAT+RT	Drive-Access Transit: Rapid Transit
8	DAT+LB	Drive-Access Transit: Local Bus
9	WAT+B	Walk-Access Transit: Boat
10	WAT+CR	Walk-Access Transit: Commuter Rail
11	WAT+RT	Walk-Access Transit: Rapid Transit
12	WAT+LB	Walk-Access Transit: Local Bus

The general structure of the model is illustrated in Figure 1, in which data inputs are used to calculate probabilities that commuters in each OD pair choose each of the 12 available modes. The mode choice model is a nested logit model using parameters from the CTPS travel demand model. Estimates from this simplified model are calibrated against reported mode flows from CTPS to account for variations of socioeconomic characteristics and other factors that were not explicitly modeled.

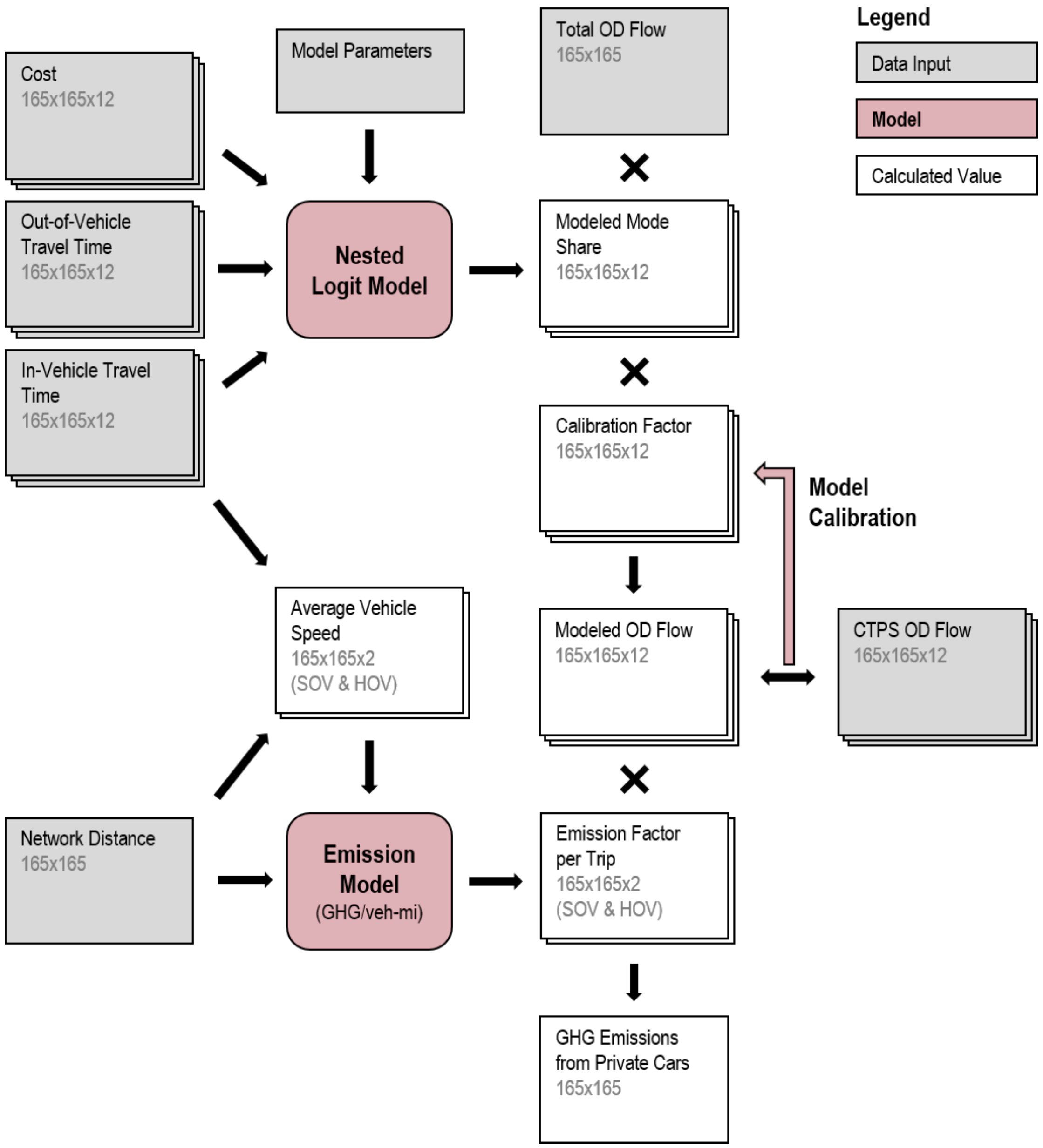


Figure 1: Overview of model methodology

GHG emissions from cars are estimated using an emission factor model based on reported traffic speeds, distance traveled, and the estimated number of vehicles traveling. The goal of new or expanded commuter bus service is to attract enough commuters out of their cars so that GHG emissions from traffic drop by more than the GHG emissions from the new commuter bus services.

New commuter bus services are considered for each OD pair by optimizing the number of buses dispatched per peak period and the fare charged to each passenger. For each combination of number of buses and fare, a model of user-experienced costs is used to estimate monetary costs, out-of-vehicle travel time, and in-vehicle travel time to be used as inputs to the mode choice model. Furthermore, these decision variables, along with the distance traveled and the speed of traffic, are used to estimate GHG emissions from the buses and costs associated with capital and operations that are incurred by the agency.

Results

Before considering the introduction of new commuter services, the emission model for cars is used to establish a baseline estimate of current emissions from cars driven by commuters in the morning and evening peak periods. Table 2 summarizes the total emissions across the entire region, and Figure 2 shows where the top emitting OD pairs are located. GHG emissions are reported in mass of CO_2 equivalent (CO_2e), which represents the combined global warming effect of all emitted chemicals in units of equivalent mass of CO_2.

Table 2: Status quo trip flows and emission estimates

	AM Peak (6am – 9am)	PM Peak (3pm – 6pm)
SOV Trips per Day	797,930	1,418,400
HOV Trips per Day	203,960	383,490
Total Private Vehicle Trips in Peak Period	1,001,890	1,801,890
SOV Emissions (tons CO_2e)	2792	3956
HOV Emissions (tons CO_2e)	263	444
Total Private Vehicle Emissions (tons CO_2e)	3055	4400

The study considers several scenarios for fare policies and also compares costs if capital expenses associated with vehicles are included or left out. The most general set of assumptions considers the potential to operate anywhere from one to eight buses per direction per peak period and to charge a fare ranging from free up to $20/ride. Among all the OD pairs in the Greater Boston area, this study identifies those for which GHG emissions can be reduced through the introduction of a new commuter bus mode. The study also ranks these OD pairs to identify which routes reduce GHG emissions at the lowest cost per unit of GHG. Table shows an example of ranked OD pairs for the case that all numbers of buses and possible fares are considered, and agency costs include the capital costs of procuring vehicles. Only corridors longer than eight miles are included in the table in order to focus on longer trips where express buses are more likely to be appropriate. The top OD pairs for efficiency are mapped in Figure 3 and for maximum GHG emission reduction in Figure 4.

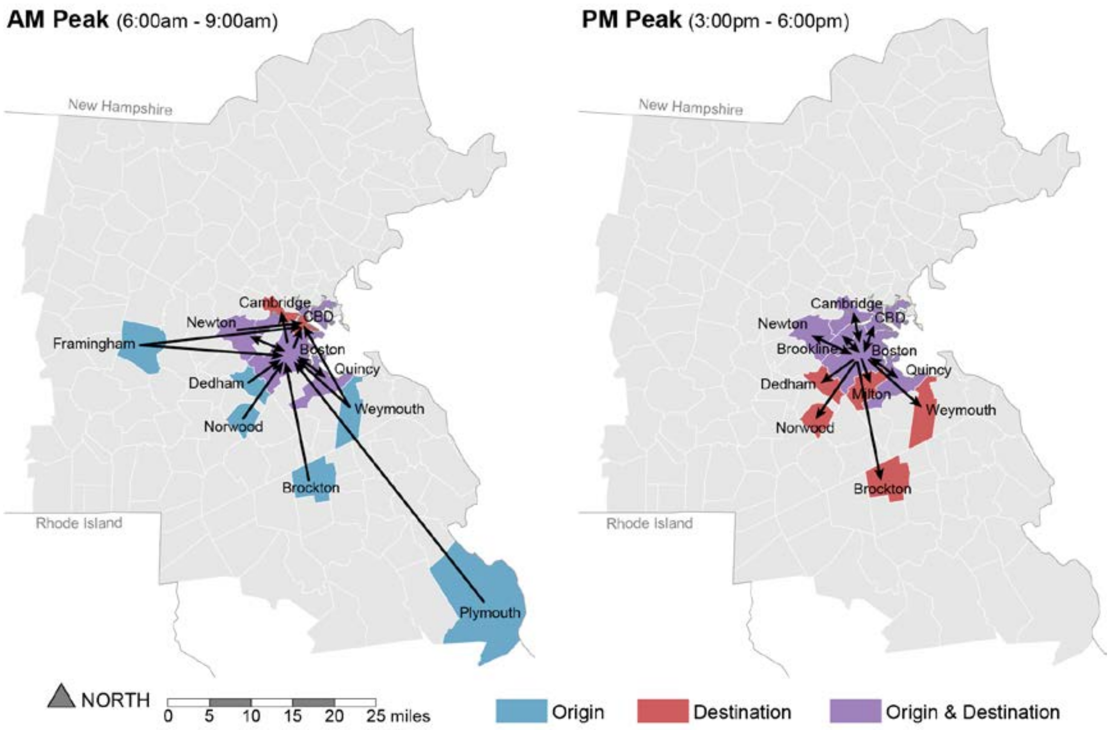


Figure 2: Top 15 GHG emitting OD pairs in the AM and PM peaks

Table 3: OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	229.88	-0.016
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	68.77	-0.049
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	309.35	-0.065
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	337.95	-0.109
GLOUCESTER	BEVERLY	10.14	2	0	57	-247	-0.01%	55.29	-0.224
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	297.47	-0.226
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	558.70	-0.263
WALTHAM	BURLINGTON	9.64	1	0	8	-469	-0.03%	189.03	-0.403
NORWOOD	BOSTON CBD	14.70	4	4	231	-183	0.00%	440.80	-2.408

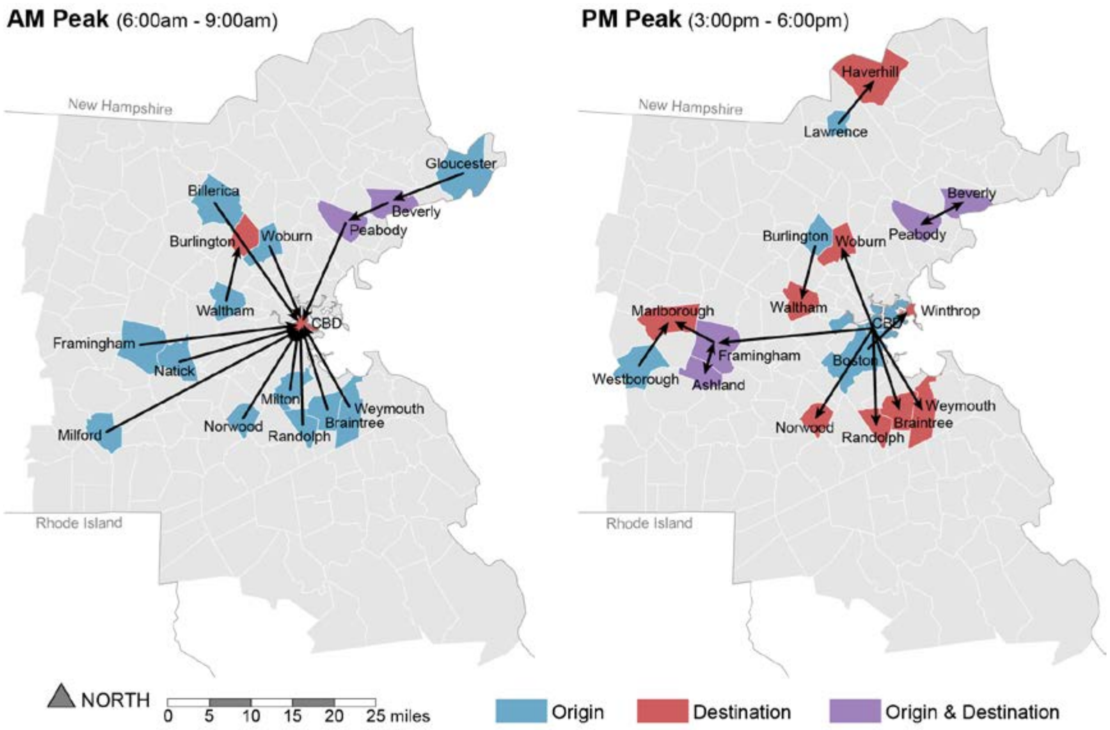


Figure 3: Top OD pairs for cost-efficient reduction of GHG

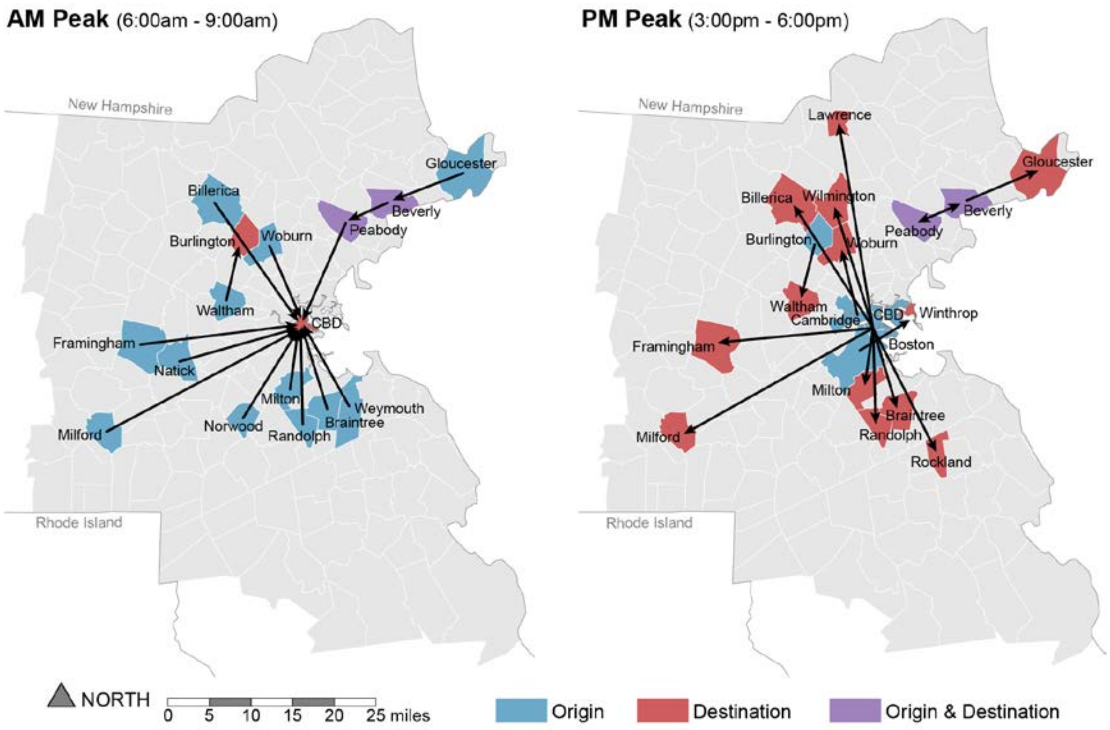


Figure 4: Top OD pairs for GHG emission reduction with commuter buses

Insights

- There are OD pairs for which GHG emissions can likely be reduced through the introduction of commuter bus services. The magnitude of potential reduction in a corridor depends on the total number of commuters, the distance between the origin and destination, and the current mode share for cars versus transit.
- Total emission reduction across all potential OD pairs adds up to 451 kg CO_2e/day in the morning peak and 3,940 kg CO_2e/day in the evening peak when fares are eliminated (thereby maximizing ridership). Using buses powered by alternative fuels would improve the GHG reduction performance, but such vehicles typically cost more to purchase and operate.
- The results are particularly sensitive to assumptions related to the access time for the proposed commuter bus mode. This value is affected by assumptions related to access distance, the value of waiting time, and the inherent preference (or dis-preference) that commuters have for commuter buses relative to other transit modes.
- Overall, the most promising OD pairs for reducing GHG emissions tend to be to or from Boston and the Boston CBD. However, there are some outlying OD pairs that arise, which indicates some opportunity to design commuter routes to support suburb-to-suburb travel.
- Some OD pairs appear to be profitable on their own. Many others that require subsidy may reduce GHG emissions but at a cost per unit GHG that is high relative to other GHG abatement methods. For example, an OD pair with efficiency of \$0.001 per gCO_2e reduced equates to \$1,000 per metric ton CO_2e. By comparison, the U.S. Environmental Protection Agency estimates the social cost of carbon to be as much as \$212 per ton CO_2e. That said, there are many other benefits of commuter buses that help justify the services; for example, commuter bus services provide more choices to travelers, allows greater numbers of people to access employment centers, and provide a means to reduce traffic congestion.

Table of Contents

List of Tables

List of Figures

List of Acronyms

Acronym	**Expansion**
ASC	Alternative-specific constant
CARB	California Air Resources Board
CBD	Central Business District
CMEM	Comprehensive Modal Emissions Model
CO_2e	Carbon dioxide equivalent
CTPS	Central Transportation Planning Staff
DAT+B	Drive-access transit: Boat
DAT+CR	Drive-access transit: Commuter rail
DAT+RT	Drive-access transit: Rapid transit
DAT+LB	Drive-access transit: Local bus
EMFAC	Emission Factors
FHWA	Federal Highway Administration
GHG	Greenhouse gas
HBO	Home-based other trips
HBSc	Home-based school trips
HBW	Home-based work trips
HOV	High occupancy vehicle
IVTT	In-vehicle travel time
MassDOT	Massachusetts Department of Transportation
MTS	Massachusetts Travel Survey
MEASURE	Mobile Emissions Assessment System for Urban and Regional Eval.
MOVES	Motor Vehicle Emissions Simulator
MVRTA	Merrimack Valley Regional Transit Authority
MWRTA	MetroWest Regional Transit Authority
NHB	Non-home-based trips
NM	Non-motorized
OD	Origin-destination
OVTT	Out-of-vehicle travel time
SOV	Single occupant vehicle
SPR	State Planning and Research
TAZ	Traffic Analysis Zone
VMT	Vehicle miles traveled
VOT	Value of time
VSP	Vehicle specific power
VT-Meso	Virginia Tech Mesoscopic Emissions Model
VT-Micro	Virginia Tech Microscopic Emissions Model
WAT+B	Walk-access transit: Boat
WAT+CR	Walk-access transit: Commuter rail
WAT+RT	Walk-access transit: Rapid transit
WAT+LB	Walk-access transit: Local bus

1.0 Introduction

This study of Commuter Bus Demand, Incentives for Modal Shift, and Impact on GHG Emissions was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

MassDOT has the responsibility for introducing new policies and programs that will help implement Governor Charles Baker's Executive Order No. 569, "Establishing an Integrated Climate Change Strategy for the Commonwealth," including policies that might result in modal shift toward more environmentally sustainable alternatives to driving personal vehicles. MassDOT's Rail and Transit Division has the ability to inform how state and federal transit dollars may be invested to have the greatest impact on GHG emission reduction for passenger transportation in the state. As a result, MassDOT's Rail and Transit Division is interested in a deeper understanding of the potential market size for expanded commuter bus service into Boston and its impact on modal split and resulting greenhouse gas (GHG) emission reductions.

This project primarily addresses the question of whether there is, in fact, an opportunity to expand commuter bus service in the Boston region, and what are the necessary incentives commuters need to make a modal shift. Additionally, this research reports potential GHG emission reductions resulting from the estimated modal shift to commuter bus.

This project addresses two main objectives:

1. Methodological Objective: Develop a data-based modeling method to quantify the user and agency cost as well as GHG emissions associated with commuting patterns by private vehicle and public transit when commuter bus service is expanded in regional corridors.
2. Applied Objective: Analyze available demand and traffic performance data for origin-destination (OD) pairs in the Greater Boston area and apply the proposed models to rank OD pairs by potential for GHG emission reduction or improved efficiency (GHG emission reduction per dollar spent) from the introduction of new commuter bus service.

The mode choice models rely heavily on readily available data from the Central Transportation Planning Staff (CTPS), which is the Boston Region Metropolitan Planning Organization. Commuting corridors are defined in terms of OD pairs at the level of towns to facilitate computational efficiency, ensure that the OD pairs under study have sufficient demand to make the implementation of a commuter bus service meaningful, and ease communication of commuter bus service if it were to be implemented. Analysis of incentives is in the context of identifying transit fare subsidies that can achieve desirable mode share for commuter buses based on a mode choice model that will be developed.

2.0 Research Methodology

The research methodology includes estimation of the status quo of commuting corridors in the Greater Boston area in terms of mode share and GHG emissions. Mode share status quo is estimated with the use of CTPS's mode choice model, and calibration factors are implemented to account for discrepancies caused by different levels of aggregation, as well as assumptions and simplifications of the model due to missing data such as socioeconomic characteristics. The status quo GHG emissions are estimated using California Air Resources Board's (CARB) 2014 Emission Factors (EMFAC) Model as a function of the average speed on the specific corridor for only private vehicles under the assumption that existing bus and rail transit will keep operating as usual. Next, analytical relationships are developed to estimate agency and user cost as a function of number of buses dispatched per hour, i.e., frequency and fare charged. Finally, combinations of fare and bus frequency are optimized to maximize efficiency, defined as GHG emission reductions per agency dollar spent, and are ranked based on the total GHG emission reductions achieved, as well as their efficiency. This allows the Project Team to determine the OD pairs with the highest potential of achieving GHG emission reductions. The general structure of the mode share and GHG emission estimation method are shown in Figure 2.1. The components of this method are described in this chapter.

2.1 Review of Available Data and Models

2.1.1 CTPS Mode Choice Model

A "multinomial logit model" in transportation is a fitted logistic regression model used to predict the probabilities for more than two discrete choices, given a set of independent variables (*1*). For example, what mode will people choose given their demographics? Multinomial logit models have become one of the most commonly used methods due to their flexibility and generalizability. A multinomial logit model may be "nested," in the sense that correlated choices can be grouped together rather than fully independent (e.g., a person chooses bus given that they choose transit).

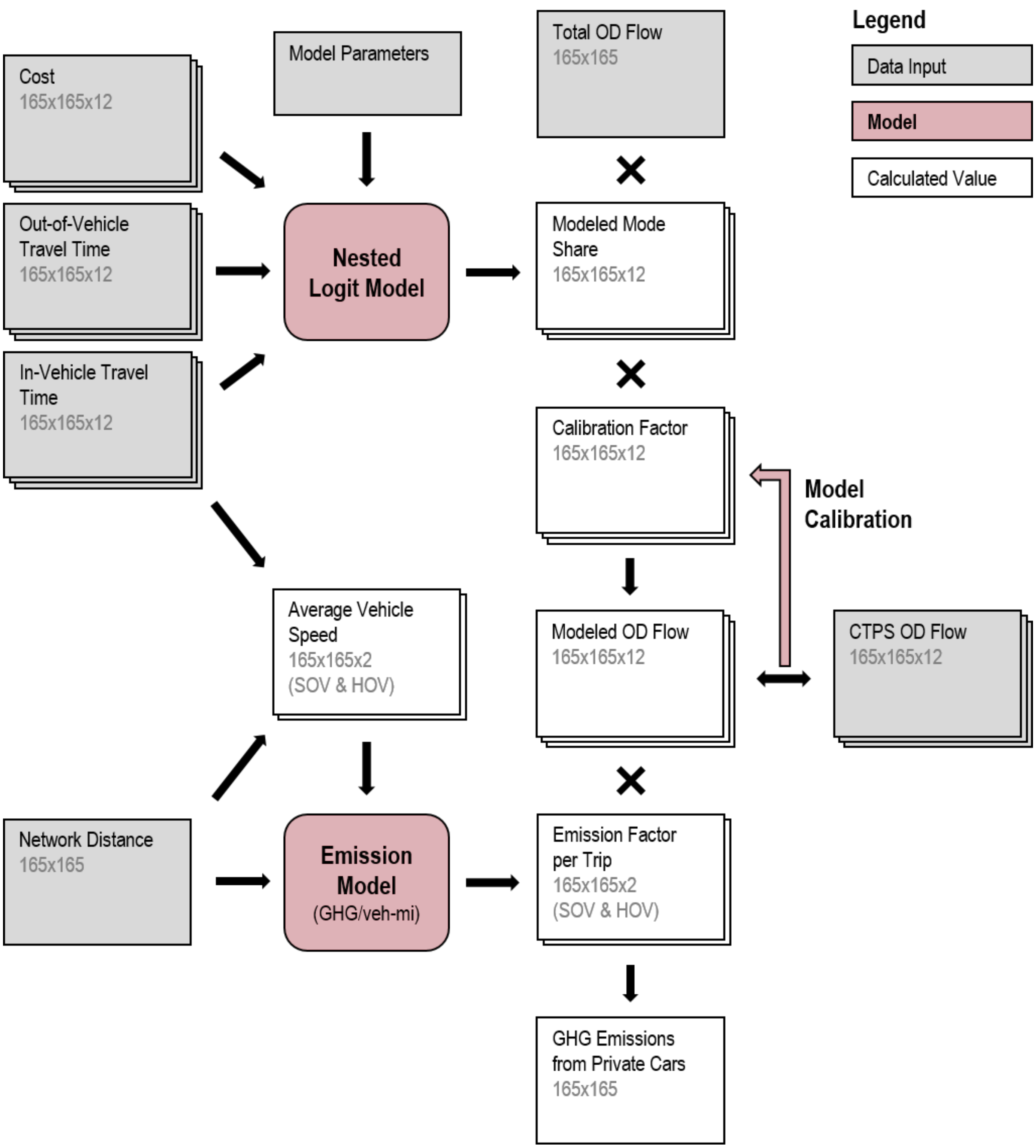


Figure 2.1: Mode share and GHG emission estimation methodology

The mode choice model used by CTPS is a nested multinomial logit model built from the 2011 Massachusetts Travel Survey (MTS). The CTPS model was estimated using a combination of TransCAD and Biogeme software. TransCAD is a much simpler and faster software to make estimates, but has limited logit estimation capabilities. Biogeme is a more robust estimation software capable of more complex models as well as two-level nested logits, but is much slower and requires a substantial amount of setup. Given their strengths and weaknesses, TransCAD was used for smaller test model structures and sensitivity of inputs, and Biogeme was then used to provide the final model estimation. There are 13 mode choices used in the model:

1.	(SOV)	Single occupancy vehicle (drive alone)
2.	(HOV 2)	High occupancy vehicle (shared ride)—two persons
3.	(HOV 3+)	High occupancy vehicle (shared ride)—three or more persons
4.	(WALK)	Walk
5.	(BIKE)	Bike
6.	(DAT+B)	Drive-access transit: Boat
7.	(DAT+CR)	Drive-access transit: Commuter rail
8.	(DAT+RT)	Drive-access transit: Rapid transit
9.	(DAT+LB)	Drive-access transit: Local bus
10.	(WAT+B)	Walk-access transit: Boat
11.	(WAT+CR)	Walk-access transit: Commuter rail
12.	(WAT+RT)	Walk-access transit: Rapid transit
13.	(WAT+LB)	Walk-access transit: Local bus

These mode choices are nested in a two-level nested choice model. This nested choice model is depicted in Figure 2.2.

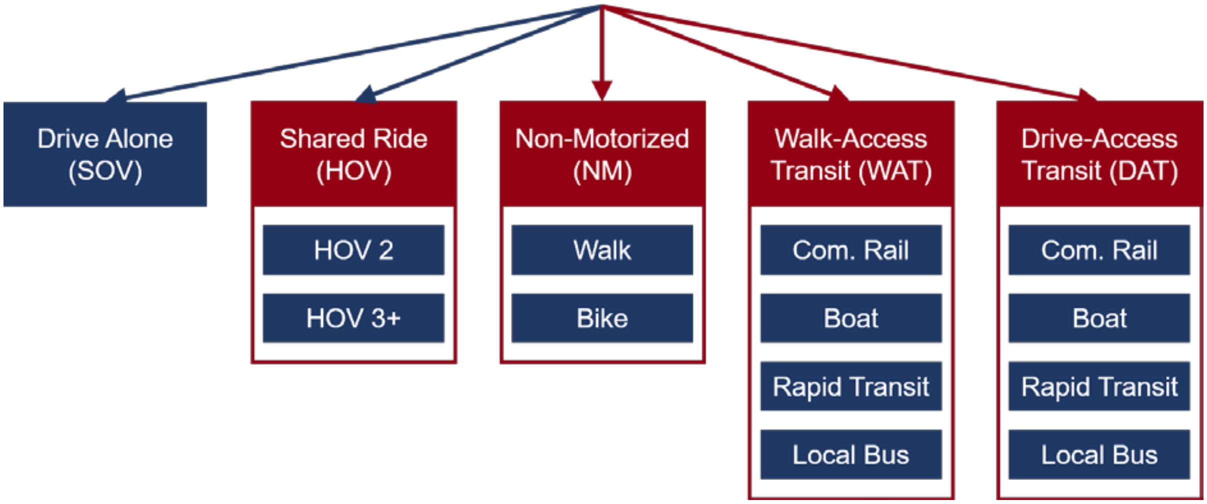


Figure 2.2: CTPS mode choice model structure

These choices were made for four different trip purposes:

- home-based work trips (HBW)
- home-based other trips (HBO)
- non-home-based trips (NHB)
- home-based school trips (HBSc)

The trip distribution of mode choices and trip purposes in the 2011 MTS data is shown in Table 2.1. The fact that driving alone accounts for the vast majority of home-based work trips suggests that there is enormous potential for mode shift. However, it should also be noted that these data are a sample of the entire Commonwealth of Massachusetts, not just the Greater Boston area. This is an important distinction, since much of western and central Massachusetts have far fewer transit options and thus are much more automobile dependent. Furthermore, the MTS data was collected in 2011 and may not entirely reflect current travel behavior. Since 2011, there have been increases in transit and bicycle ridership (*2*). Furthermore, transportation network companies (e.g., Lyft and Uber) did not exist in Boston in 2011, and these new services are not included in the model. Despite these shortcomings, the MTS data is still an extremely detailed disaggregate sample of the population, and the resulting CTPS mode choice model is useful for comparing travel by car and transit and considering the effect of new commuter bus service on travel choices in the region. For this project, only data for the home-based work trips were utilized, since the focus was on commuting corridors.

Table 2.1: 2011 Massachusetts Household Survey trip distribution

Mode Description	HBW	HBO	NHB	HBSc1	HBSc2	HBSc3
Auto-Drive Alone	12,736	4,608	1,043			107
High Occupancy Auto:						
Auto-Two Occupants	1,106	5,691	658	1,099	827	58
Auto-Three or More Occupants	336					
Transit-Walk Access:						
Commuter Rail	270	42	8	1	4	13
Rapid Transit	1,060	602	273	31	35	94
Local Bus	363	532	116	57	71	37
Boat/Ferry	4	2	2			
Transit-Drive Access:						
Commuter Rail	666	51	17	4	8	7
Rapid Transit	399	108	42	5	9	18
Local Bus	352	23	11	1	4	3
Boat/Ferry	29	1	1			
Non-Motorized:						
Walk	721	1,496	868	326	179	37
Bike	67	275	106	49	24	6

The value of time (VOT) estimated from the data for each of the trip purposes is listed in Table 2.2. There are typically different VOTs for different trip purposes, and oftentimes they are unique to a person. Table 2.2 reflects general values determined by CTPS's model. In instances where time is highly valued, trip time may outweigh the mode's cost itself, affecting the choice.

Table 2.2: Value of time estimates

Purpose	Value of Time ($/hour)
Home-based work trip (HBW)	10.75
Home-based other trip (HBO)	3.67
Non-home based trips (NHB)	6.33
Home-based school trip (HBSc)	4.64 (Age ≤ 14) 6.36 (14 < Age ≤ 18) 7.24 (Age > 18)

CTPS had estimated several models, then chose the best model based on model fit and the Federal Transit Administration guidelines, shown in Table 2.3 for acceptable coefficient ranges. The final results of CTPS's mode choice model are shown in Table 2.4 and Table 2.5. The model coefficients, often called β values, are the coefficients in the logistic regression equation for the model and reflect how much each variable affects the outcome. The alternative-specific constants (ASCs) on the right side of the table reveal the inherent preferences for each mode relative to driving alone if all other input variables were equal.

Table 2.3: Acceptable Federal Transit Administration coefficient ranges

Variable	Trip Purpose	Acceptable Coefficient Range
IVTT (in-vehicle travel time)	Home-based work trip (HBW)	[-0.03, -0.02]
	Non-home based trips (NHB)	~Civt for HBW trips
	Home-based other trip (HBO)	~0.1 to 0.5*Civt HBW trips
Ratio: Covt/Civt	All	[2, 3]
Nest Coefficient, θ	All	[0, 0.7]

Notes: Civt = coefficient of *IVTT* (in-vehicle travel time). Covt = coefficient of *OVTT* (out-of-vehicle travel time).

Table 2.4: CTPS mode choice model parameters

	Impedance Variables				Socioeconomic Variables				
Home-Based Work	Nest Coefficient	IVTT	OVTT[1]	Terminal Time[2]	COST[3]	Vehicles per Worker	PEV[4]	Sq-Rt Emp Density[5]	Walk Access Fraction[6]
DA or SOV	1	-0.0199		-0.269	-0.111	1.25			
SR2 or HOV2	0.69	-0.0199		-0.269	-0.111				
SR3+ or HOV3+	0.69	-0.0199		-0.269	-0.111				
Walk	0.69		-0.0599				-0.0663	0.0016	
Bike	0.69		-0.0599				-0.0663	0.0016	1.84
WAT+CR	0.50	-0.0199	-0.0599		-0.111		-0.0663	0.0016	1.84
WAT+ RT	0.50	-0.0199	-0.0599		-0.111		-0.0663	0.0016	1.84
WAT+B	0.50	-0.0199	-0.0599		-0.111		-0.0663	0.0016	1.84
WAT+LB	0.50	-0.0199	-0.0599		-0.111		-0.0663	0.0016	1.84
DAT+CR	0.69	-0.0199	-0.0599	-0.269	-0.111	1.59		0.0016	1.46
DAT+RT	0.69	-0.0199	-0.0599	-0.269	-0.111	1.59		0.0016	1.46
DAT+B	0.69	-0.0199	-0.0599	-0.269	-0.111	1.59		0.0016	1.46
DAT+LB	0.69	-0.0199	-0.0599	-0.269	-0.111	1.59		0.0016	1.46

[1] Walk (access, egress, transfer), initial wait, transfer penalty time.

[2] Auto terminal time = production + attraction terminal time; DAT Terminal Time = Production end terminal time.

[3] All Costs: fare, parking, auto operating cost and toll.

[4] PEV: Pedestrian environmental variable—availability of walking features, vehicle volume, and speeds; truck routes are a negative (the larger the PEV, the less friendly to pedestrians).

[5] Square root of the employment density at the attraction zone in employees per acre.

[6] Walk Access Fraction (0 to 1)—0: No stops within 1 mile of Traffic Analysis Zone (TAZ) centroid (airline distance); 1: entire zone within 1 mile of stops.

Table 2.5: CTPS mode choice model alternative-specific constants

Nest and Modes	Nest Coefficient	ASC
Drive Alone	0.000	0.000
Shared Ride	-0.770	
SR2 or HOV2		0.000
SR3+ or HOV3+		-0.852
Non-Motorized:	0.494	
Walk		0.000
Bike		-2.920
Transit-Walk Access:	-1.540	
Commuter Rail		0.174
Rapid Transit		0.000
Local Bus		-0.543
Boat/Ferry		-0.515
Transit-Drive Access:	-4.440	
Commuter Rail		0.992
Rapid Transit		0.000
Local Bus		-0.916
Boat/Ferry		0.135

2.1.2 CTPS Network

The CTPS network is composed of 2,727 Traffic Analysis Zones (TAZs) in the Greater Boston area. The Greater Boston area represents the eastern third of Massachusetts, an area of approximately 2,830 square miles surrounding Boston. The TAZs are areas that roughly follow the U.S. Census Bureau's census boundaries, but are smaller than census tracts and larger than census blocks. The exact size and population of each TAZ varies by population density. Denser areas can have much smaller TAZs around the size of just a few city blocks, whereas less dense areas are much larger. The average number of people who live within each TAZ is approximately 1,600 people. The boundaries of CTPS's network were provided in Geographic Information System (GIS) files in a shapefile format. This allowed for analysis and visualization to be conducted on the network using the shapefiles.

In addition to the physical network, the following 2,727 by 2,727 matrices were provided in TransCAD format by CTPS:

- Total AM peak and PM peak OD flows
- AM peak and PM peak OD flows by mode:
    1. Drive alone (SOV)
    2. Shared ride (HOV)
    3. Walk
    4. Bike
    5. Drive access boat (DAT+B)
    6. Drive access commuter rail (DAT+CR)
    7. Drive access rapid transit (DAT+RT)
    8. Drive access local bus (DAT+LB)
    9. Walk access boat (WAT+B)
    10. Walk access commuter rail (WAT+CR)
    11. Walk access rapid transit (WAT+RT)
    12. Walk access local bus (WAT+LB)

As shown in the list above, the Share Ride data were not provided separately for shared rides with two riders (HOV 2) or three or more (HOV 3+).

2.1.3 CTPS Travel Time Skims

Travel time skims are matrices of travel times for each OD pair given a particular mode. CTPS used TransCAD's path building and skimming abilities to create travel time skim data for the Greater Boston area.

The travel time skims were generated for four different daily time periods, AM peak (6:00 a.m.–9:00 a.m.), PM peak (3:00 p.m.–6:00 p.m.), midday (9:00 a.m.–3:00 p.m.), and night time (9:00 p.m.–6:00 a.m.). This was done in order to reflect typical traffic congestion and transit headways that would be expected during these different time periods. In total, there are 36 travel time skim matrices generated by the CTPS model, one for each of the eight transit modes and the driving travel times. Each of the skim matrices then contains elements for both travel time and travel cost. Examples of the available times and costs for the drive alone (SOV) and drive to boat (DAT+B) modes are shown as follows.

From the drive to boat skim matrix:

- Generalized cost
- Fare
- In-vehicle time
- Initial wait time
- Transfer wait time
- Transfer penalty time
- Transfer, access, and egress walk time
- Access and egress drive time
- Dwell time
- Transfer penalty cost
- Number of transfers
- Access drive distance
- Walk time
- Park and ride parking cost
- Boat
- Total IVTT
- Total OVTT
- Total cost

From the drive alone matrix:

- Car toll
- Length
- Congested time
- Total cost

For this project, in-vehicle travel time (IVTT) for each mode was provided by CTPS, with the exception of walk and bike. In addition, out-of-vehicle travel time (OVTT) for each mode was provided, except drive alone, shared ride, and walk and bike. Finally, total cost was provided for each mode, except walk and bike; the value for walk and bike was expressed in units of minutes based on a value of time of $10.75/hour.

2.1.4 Existing Commuter Bus Routes

Commuter bus routes used in the model for the Greater Boston area were provided to the research team by MassDOT in General Transit Feed Specification (GTFS) format. The Merrimack Valley Regional Transit Authority (MVRTA) and the MetroWest Regional Transit Authority (MWRTA) operate 9 routes each, and the four private companies (Coach Co, DATTCO, Boston Express, and Bloom) operate a combined 26 routes in the Greater Boston area. These routes were already included in the CTPS model, and therefore, no changes needed to be made in that regard.

2.1.5 Greenhouse Gas Emission Estimation Models

Due to a global concern over human-induced climate change, there has been a growing body of research related to GHG emissions. Historically, emission modeling had been pollutant-based, stemming from the environmental and air quality concerns of the 1960s to 1970s (*3*,*4*), largely coinciding with the Clean Air Act of 1963 and the National Environmental Policy Act of 1969. Since that time, emission modeling has been expanded to include GHG as well as airborne pollutants emitted from automobiles (*5*).

Transportation emission modeling itself has been predominantly tied to traffic modeling and simulation methods (*6*). Existing emission models fall between two ends of a spectrum, with the extremes being microscopic and macroscopic models. Macroscopic models rely on aggregate data sources and average values. Microscopic models, in contrast, provide instantaneous emission estimates based on the detailed operating conditions of individual vehicles (*7*). Between microscopic and macroscopic models is a third, though less common, category called mesoscopic models (*8*,*9*). For transit emissions modeling, the different modeling scales can be adapted for heavy-duty transit vehicles by making use of transit vehicle emissions data, trajectory data, or vehicle specific power (VSP) models (*10*,*11*).

Microscopic models rely on very detailed data inputs, such as vehicle trajectories and powertrain data, which are then often coupled with microsimulation. These microsimulation models then require further calibration and relevant data (e.g., traffic counts) to create the specific scenario being modeled. Some commonly used microscopic models are the Virginia Tech Microscopic Emissions (VT-Micro) model (*12*), the Comprehensive Modal Emissions model (CMEM) (*13*), and the U.S. Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES) project-level tool (*14*). These models require second-by-second speeds as inputs to produce vehicle emissions estimates. Though extremely useful, the data requirements, computation time, and time-consuming setup required for microscopic models limit their practical use to mainly small-scale projects.

Macroscopic models require much fewer data inputs and are effective at making larger regional-scale emission estimates. These models are often based on distance traveled (e.g., vehicle miles traveled (VMT)), average network speed, or total number of vehicles. Commonly used macroscopic emissions models include the California Air Resources Board's Emission Factors model (EMFAC) (*15*) and MOVES county-level tool (*14*). The limitation of macroscopic models is that they do not account for vehicle drive cycles, such as acceleration and deceleration. This can be important when considering traffic conditions in a network, because different patterns of stop-and-go traffic can greatly affect emissions.

A third modeling technique, called mesoscopic models, attempts to address the drive cycle issue in macroscopic models by making use of simpler network-wide traffic flow models, rather than second-by-second vehicle trajectories. Several examples of mesoscopic models are the Virginia Tech Mesoscopic (VT-Meso) model (*16*), the Akcelik model (*17*,*18*), and the Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE) model (*19*). Mesoscopic models can improve the accuracy of regional emission estimates, but still require the additional input of aggregated traffic data.

2.1.6 Transit System Models

Transit systems can be modeled to account for all the physical components of the passengers' trips and the vehicles' operations in order to quantify the cost of the system for users and the agency. For example, the cost to a user consists of accessing the transit stop, waiting for the vehicle, riding onboard the vehicle, accessing the destination after alighting at a stop, and paying the fare. The cost to the agency depends on the number of vehicles required and the details of operation, such as number of stops and operating speed, which are consequences of the route design and schedule of service. Since the design of a transit service affects the cost for both users and agencies, both must be considered when optimizing planned services. Transit networks in regions similar to that of the Greater Boston area have been studied in great detail (*20*–*23*). In particular, a systematic accounting of the components of a transit service that contribute to user and agency cost has been used to design systems that are competitive with travel by private car (*20*). The following subsections summarize the agency cost, user cost, and generalized cost equations that have been developed in previous research efforts and are adjusted for the purposes of this project.

Agency Cost (AC)

The agency cost, *AC*, during a time period is modeled as a function of the amortized capital cost for that period that is required to purchase the vehicles, c_v [\$/time period], the operating cost per vehicle-hour traveled, c_t [\$/vehicle-time traveled], and/or monetary cost per vehicle-mile traveled, c_d [\$/distance traveled], to capture different types of costs that incur for the distance and time over which the vehicles are used. Costs that are related to distance operated include fuel, maintenance on the engine, replacement of tires and brakes, etc. These costs are assumed to be roughly proportional to the distance that vehicles travel to provide the service. The main cost that is related to operating time is labor, because drivers are paid for the duration of time that they are working rather than the distance that the bus travels. As a result, the total agency cost can be expressed as:

$$AC = c_v \frac{1}{H} + c_t d \frac{1}{H} + c_t IVTT \frac{1}{H} \qquad (1)$$

where H [1/time] is the headway of the transit service within the time period of interest, $IVTT$ [time] is the in-vehicle travel time (including moving time and time lost for stopping at bus stops, and d [distance] is the distance traveled by each transit vehicle. $1/H$ represents the frequency of the bus service within the time period of interest. The important planning decision is to choose an appropriate value of H, with the agency benefiting from long headways that require the fewest resources to operate.

User Cost (UC)

The user cost, *UC*, is modeled per passenger as a function of both in-vehicle and out-of-vehicle cost. The out-of-vehicle cost includes access cost, AT (e.g., walking time, time to drive to a bus stop, etc.), waiting time at the bus stop or between scheduled departures, WT, in-vehicle-travel time, $IVTT$ (including moving time and time lost for stopping at bus stops), and fare expressed in units of travel time for consistency, F/β:

$$UC = AT + WT + IVTT + F/\beta \qquad (2)$$

where β is the value of time (VOT) factor [\$/time]. For a user traveling a distance l, the access time is the access distance d_a divided by the speed v_a; the person may wait as much as a full headway between bus departures and then sits in the vehicle for the duration of the trip before experiencing egress time (egress distance d_e divided by egress speed v_e) at the destination. Thus, equation (2) can be expressed as follows:

$$UC = \frac{d_a}{v_a} + H + \frac{l}{v} + \frac{d_e}{v_e} + F/\beta \qquad (3)$$

The access distance depends on the size of the catchment area for the stop, and the access speed depends on whether the access mode is by walking, cycling, driving, and parking, or some other type of mode.

The benefit of these formulae is that they are flexible to include different types of variables based on the available information for each system. Similar formulae have been developed and used for other studies, including a bus network redesign for Barcelona (*21*) and one that investigated the effect of mixing transit with automobile traffic in cities (*24*).

2.2 Data Processing

Due to the granularity and limitations of the data that were provided by CTPS, certain assumptions and data processing had to be made.

2.2.1 Definition of Commuting Corridors

The TAZs in the CTPS model represent too fine a geographic resolution that would increase computational complexity and also result in very small OD flows. Based on this, it was necessary to aggregate the TAZ-level data to a less granular resolution. The team’s first consideration was to use CTPS’s neighborhood aggregations, but these aggregations are focused on defining neighborhoods within the region’s urban core (primarily Boston, Brookline, Cambridge, and Somerville). A more realistic geographic scale for considering commuter bus services is the scale of cities or towns across the region and special consideration of the Boston Business District (as defined by CTPS), which includes the Financial District, North End, West End, Beacon Hill, Back Bay, and the South Boston Waterfront. ArcGIS software was used to define the aggregations of TAZs into 165 zones representing cities, towns, and the Boston Business District, as shown in Figure 2.3. This is the spatial scale that is used for the rest of the project.

Figure 2.3: Map of 165 cities, towns, and Boston Central Business District

Each of the data fields provided by CTPS is a 2,727 by 2,727 TAZ matrix, but it was aggregated to the resolution of 165 towns, forming 165 by 165 town matrices. The aggregation of flows consisted of a simple summation of component values. The aggregation of travel times and costs was done by taking an average of component values from the CTPS skim matrices. This aggregation procedure is a built-in capability of TransCAD, based on the TAZs constituting each town. The result is data that is aggregated to 27,225 OD pairs rather than 7,436,529 OD pairs.

Following the aggregation of TAZs to towns, the distance between each town was determined in order to provide data to support the estimation of GHG emissions as well as walk and bike travel times. Using the network data layers for the Boston metropolitan area from MassGIS online, the road network was imported into TransCAD, and the software identified shortest path network distance between every OD pair, using zone centroids and Road Classes 1–4. The classes represent the main highways and routes in the Commonwealth, and these are roads most likely used by commuters and express buses. The result is a 165 by 165 zone-to-zone distance matrix at the same spatial resolution as the flow, travel time, and cost data.

2.2.2 Other Data Processing

As mentioned earlier, the mode choice model is defined for separate categories of shared ride with two occupants and shared ride with three or more occupants. However, the data from CTPS presents only a single mode for shared ride trips, and that is what was modeled to obtain the necessary mode split estimates. In addition, the missing data from the CTPS model included travel times associated with walk and bike trips. These missing travel times were calculated using the network distances between OD pairs and average walking speed of 3 mph and bicycling speed of 10 mph as specified in the CTPS Regional Travel Demand Modeling Methodology and Assumptions document (*25*). It was assumed that the cost of travel by walk or bike is free, so no attempt was made to substitute those missing values. The terminal time associated with access to and from automobile trips was also not provided. Additionally, it was assumed the data field labeled “Cong. Time” drive alone and shared ride modes represent the in-vehicle travel time, including peak period congestion.

2.3 Status Quo Mode Share for Commuting Corridors

The objective of the Status Quo Model was to determine the existing demand levels by mode for the corridors of interest. The multinomial logit model developed by CTPS for home-based work trips was used to estimate the current mode share based on the available trip characteristics such as travel time and cost by mode for every OD pair for the two peak periods, AM (6:00 a.m.–9:00 a.m.) and PM (3:00 p.m.–6:00 p.m.). Certain assumptions and data processing had to be performed as described in the previous section to alter the aggregation from TAZs to towns and account for limitations of the data that were provided. In addition, the socioeconomic characteristics were not provided, so the corresponding coefficients presented in Table 2.4 are not included in the model.

In order to estimate the mode share demand for commuting corridors, the aggregated data was exported from TransCAD in .csv format so that it could be imported into a mode choice model implemented in MATLAB. The following types of data provided by CTPS were used as inputs to the mode choice model, each indexed by origin zone i, destination zone j, and mode m (the 12 numbered modes accounting for the fact that HOVs were grouped in one mode type as defined in Table 2.6):

Table 2.6: Implemented mode choice model

- $\boldsymbol{IVTTAM(i,j,m)}$: In-vehicle travel time from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the morning peak, expressed in units of minutes.
- $\boldsymbol{IVTTPM(i,j,m)}$: In-vehicle travel time from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the afternoon peak, expressed in units of minutes.
- $\boldsymbol{OVTTAM(i,j,m)}$: Out-of-vehicle travel time from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the morning peak, expressed in units of minutes.
- $\boldsymbol{OVTTPM(i,j,m)}$: Out-of-vehicle travel time from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the afternoon peak, expressed in units of minutes.
- $\boldsymbol{COSTAM(i,j,m)}$: Total cost of a trip from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the morning peak, expressed in units of minutes (value of time \$10.75/hour).
- $\boldsymbol{COSTPM(i,j,m)}$: Total cost of a trip from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the afternoon peak, expressed in units of minutes (value of time \$10.75/hour).
- $\boldsymbol{ODAM(i,j,m)}$: Flow of home-based work trips from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the morning peak.
- $\boldsymbol{ODPM(i,j,m)}$: Flow of home-based work trips from $\boldsymbol{i}$ to $\boldsymbol{j}$ by mode $\boldsymbol{m}$ in the afternoon peak.

A simplified version of the CTPS mode choice model, including only 12 modes and aggregation of TAZs, was coded and run in MATLAB to provide the probabilities for each mode choice for each OD pair and peak period. This simplified model makes use only of the available data and is implemented at the resolution of the 165 by 165 town pairs rather than each pair of TAZs. Therefore, the utility of each mode and the corresponding choice probabilities are calculated based on the impedance variables but not considering socioeconomic variables.

Table 2.6 summarizes the parameters of the mode choice model for each mode m and nest n.

Table 2.6: Implemented mode choice model

Mode, m		Nest Coef., $\theta(n)$	Nest Const., $V(n)$	$\beta_{ASC}(m)$	β_{IVTT}	β_{OVTT}	β_{COST}
Nest 1: Drive Alone (SOV)		1.00	0.00				
1	Drive Alone			0.00	-0.0199		-0.111
Nest 2: Shared Ride (HOV)		1.00	0.00				
2	Shared Ride			-0.77	-0.0199		-0.111
Nest 3: Non-Motorized (NM)		0.69	0.494				
3	Walk			0.00		-0.0599	
4	Bike			-2.92		-0.0599	
Nest 4: Drive + Transit (DAT)		0.69	-4.40				
5	Drive + B			0.135	-0.0199	-0.0599	-0.111
6	Drive + CR			0.992	-0.0199	-0.0599	-0.111
7	Drive + RT			0.000	-0.0199	-0.0599	-0.111
8	Drive + LB			-0.916	-0.0199	-0.0599	-0.111
Nest 5: Walk + Transit (WAT)		0.50	-1.54				
9	Walk + B			-0.515	-0.0199	-0.0599	-0.111
10	Walk + CR			0.174	-0.0199	-0.0599	-0.111
11	Walk + RT			0.000	-0.0199	-0.0599	-0.111
12	Walk + LB			-0.543	-0.0199	-0.0599	-0.111

For each mode, the utility, $V(i,j,m)$, is calculated based on the β parameters and the observed IVTT, OVTT, and COST.

$$V(i,j,m) = \beta_{ASC}(m) + \beta_{IVTT}IVTT(i,j,m) + \beta_{OVTT}OVTT(i,j,m) + \beta_{COST}COST(i,j,m) \quad (4)$$

Then, a logsum term, $\Gamma(i,j,n)$, is calculated for each nest to represent the combined utility of all modes in the nest.

$$\Gamma(i,j,n) = \ln\left(\sum_{m\in n} e^{\frac{V(i,j,m)}{\theta(n)}}\right) \quad (5)$$

Note that the logsum term simplifies to the calculated utility expression for nests that contain only one mode. Based on the logsum term and the nest-specific utility, $V(n)$, the probability associated with each nest is calculated as:

$$P(i,j,n) = \frac{e^{V(n)+\theta(n)\Gamma(i,j,n)}}{\sum_{k\in N} e^{V(k)+\theta(k)\Gamma(i,j,k)}} \quad (6)$$

where N is the set of all nests. Finally, the probability associated with each individual mode, $P(i,j,m)$, is expressed as the product of the conditional probability of the mode being chosen given that the nest is chosen and the probability of choosing said nest. This probability is calculated as follows.

$$P(i,j,m) = \frac{e^{V(i,j,m)/\theta(n)}}{\sum_{m\in n} e^{V(i,j,m)/\theta(n)}} P(i,j,n) \quad (7)$$

All of these calculations are made using the matrix computation features of MATLAB. The result is a 165 by 165 by 12 matrix representing predicted mode shares for each OD pair during the morning and afternoon peak periods.

A final manipulation of the data is to generate estimated mode flows. The total OD flows are represented by 165 by 165 matrices, $TODAM$ for the morning peak and $TODPM$ for the evening peak. The modeled OD flow by mode is given by multiplying the mode share (probability) values by the total OD flows reported by CTPS.

$$PODAM(i,j,m) = TODAM(i,j,m)P(i,j,m) \tag{8}$$

The same calculation method is used to estimate model flows using PM peak data.

2.3.1 Calibration of Status Quo Model

Given that the model implemented in MATLAB is a simplification of the full CTPS travel model, it results in discrepancies. More specifically, the MATLAB mode flow estimates do not exactly match the CTPS reported mode flows. A calibration parameter was fitted to each OD pair in order to correct for errors associated with aggregation, omitted socioeconomic parameters, and assumptions about missing information. The matrix of calibration parameters is calculated by:

$$CODAM(i,j,m) = \frac{ODAM(i,j,m)}{PODAM(i,j,m)} \tag{9}$$

A calibration parameter equal to 1 indicates a perfect match between the MATLAB model and CTPS value. A calibration parameter value less than 1 indicates that the MATLAB model overpredicts trips and must be factored down. A calibration parameter value greater than 1 indicates that the MATLAB model underpredicts trips and must be factored up.

2.4 GHG Emission Estimation for Commuting Corridors

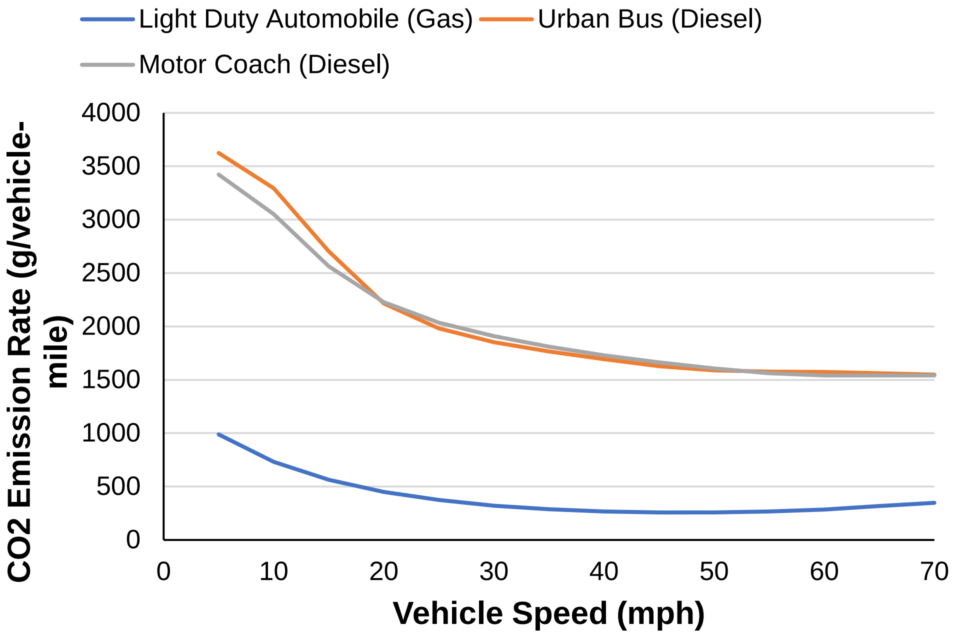
GHG emission estimation was performed with the use of the California Air Resources Board (CARB) EMFAC model for both cars and buses. The Project Team assumed that all current transit services will continue to operate, so emissions associated with existing bus and train operations will not change. The potential for new car trips to be induced as a result of new commuter bus service is also not included in the model. As a result, a new commuter bus service will affect GHG emissions in two ways:

1. Adding GHG emissions from new bus operations.
2. Reducing GHG emissions from vehicles taken off the road by attracting commuters that currently drive alone (SOV) or share a ride (HOV).

A commuter service is beneficial from a GHG perspective if the first value is less than the second. Therefore, the emission model for making this comparison requires only that the team quantify the emissions associated with private car trips (SOV and HOV) and new commuter bus transit operations.

For this project, the most appropriate approach for estimating emissions is a macroscopic model based on average vehicle speed, because the resolution of network data for cars and transit operations provides distance and travel time but not the detailed second-by-second vehicle trajectories that would be produced by a microsimulation of traffic. For a particular OD pair, the average speed can be calculated from the distance and travel time from CTPS's modeled travel-time skims and the distance for each route. For example, Figure 2.4 shows the macroscopic emissions profile for three kinds of vehicles based on average speed: light duty automobile powered by gasoline, urban bus powered by diesel, and motor coach powered by diesel.

In this project, the team made the simplifying assumption that all car drivers use gasoline-powered light duty automobiles, and commuter bus services are likely to be operated with diesel-powered motor coaches. Then from the new estimated number of riders attracted to the proposed bus service away from driving alone, the net change in emissions can be estimated by reducing the corresponding vehicle miles traveled by cars and accounting for the emissions associated with the new bus operations.



Source: U.S. Environmental Protection Agency, *MOVES User Guide*, 2010 *(14)*.

Figure 2.4: Emission factors for light duty automobiles and buses from EMFAC2014 model

2.4.1 GHG Emission Estimation for private vehicles

In order to estimate GHG emissions from private vehicles, the team assumed that each commute trip travels the distance of the shortest path between the centroid of the origin town i and the centroid of the destination town j, $d(i,j)$. Although this assumption may introduce some aggregation errors for very short trips between adjacent towns, the team was primarily interested in commute corridors over longer distances in which this approximation is likely to be close to the actual travel distance.

Without running a detailed traffic model of the entire region, the team made use of macroscopic emission models to estimate the emission rate per distance traveled associated with the average speed of traffic. In particular, the EMFAC model was used, which represents emission of CO_2-equivalent per vehicle-mile driven. Table 2.7 shows the emission factors for a typical fleet mix of private cars for speeds from 5 mph to 70 mph.

Table 2.7: Emission factors from EMFAC2014 model for gasoline cars

Vehicle Speed, mph	Emission, gCO_2/mile
5	988.30
10	731.07
15	565.02
20	450.95
25	373.63
30	321.25
35	287.72
40	267.56
45	257.73
50	257.95
55	266.93
60	285.01
65	317.62
70	347.48

In order to calculate emissions rapidly in the MATLAB model, it is useful to fit a polynomial curve to these points so that the emission factor for any speed can be evaluated as a function rather than a lookup table. This polynomial curve for the emission factor for cars, e_{car}, is as follows:

$$e_{car}(v) = e_4 v^4 + e_3 v^3 + e_2 v^2 + e_1 v + e_0 \tag{10}$$

The coefficient values as shown in Table 2.8 are fitted by a regression with $R^2 = 0.9994$. The emission model is implemented with four significant digits, as presented in the table, because rounding errors cause large errors, especially for higher speeds. Figure 2.5 shows the points from the EMFAC model and the fitted curve. The errors introduced by using this fitted curve were less than 2.3% for each observation.

Table 2.8: Emission coefficients from regression

Coefficient	Value	p-statistic
e_0	1307	1.0 E-14
e_1	-74.76	1.9 E-10
e_2	2.0727	4.7 E-08
e_3	-0.02685	1.8 E-06
e_4	0.0001389	1.4 E-05

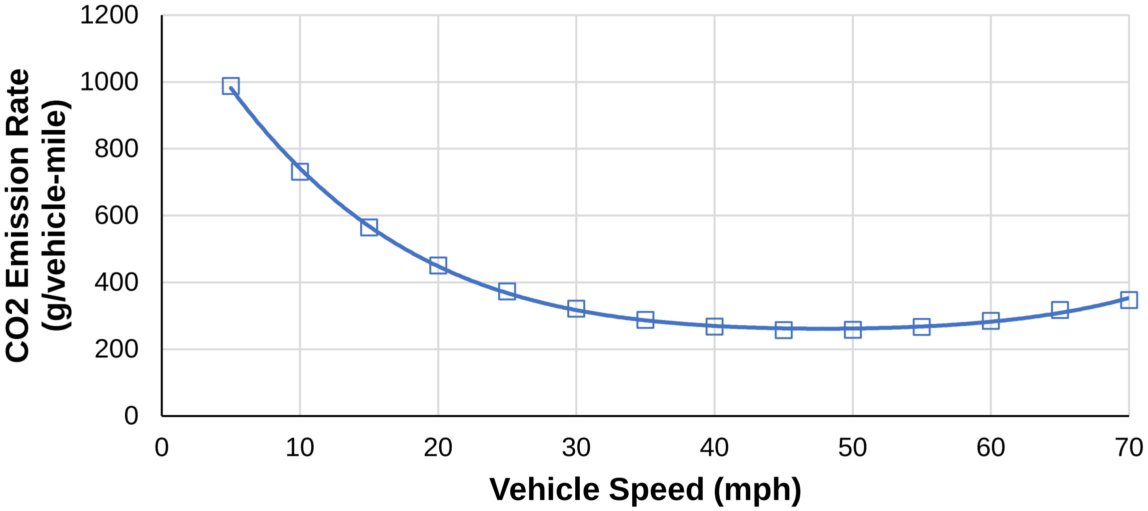


Figure 2.5: Emission rates for gasoline car fleet from EMFAC2014 model

The emission rate associated with each OD pair, e, is estimated based on the average speed associated with car travel as shown in Figure 2.5. For each OD pair, this emission rate is calculated as a function of the in-vehicle travel time, $IVTT(i,j,m)$, and the distance, $d(i,j)$. The total emissions associated with car traffic between each OD pair are the product of the emission rate, trip distance, and vehicle flow. The expression for emissions associated with private cars in the morning peak, ${E_{car}}^{AM}(i,j)$ is a function of the number of single-occupant vehicle trips ($m = 1$) and high-occupancy vehicles ($m = 2$), as well as the emission factor associated with the average speed of the trip:

$$ {E_{car}}^{AM}(i,j) = \sum_{m=1}^{2} \frac{CODAM(i,j,m)PODAM(i,j,m)}{Occ(m)} d(i,j) e_{car}\left(\frac{d(i,j)}{IVTT(i,j,m)}\right) \qquad (11) $$

where $Occ(m)$ is the average vehicle occupancy. The value for drive alone (SOV) is $Occ(1) = 1$ passenger per vehicle. The average occupancy for shared ride (HOV) trips was calculated from the data in the CTPS model documentation as $Occ(2) = 2.35$ passengers per vehicle. The flow of passenger trips is converted to vehicle trips by dividing the passenger flow by the number of vehicle occupants. The emission calculation for evening peak emissions, ${E_{car}}^{PM}(i,j)$, takes the same form.

2.4.2 GHG Emission Estimation for Commuter Buses

A macroscopic emission model for diesel buses is used, which has the same characteristics as the emission model applied to cars in this study. In particular, CARB has produced EMFAC model parameters for diesel buses. Diesel buses are considered, because these are the most common vehicles used for commuter bus services. Table 2.9 shows the emission factors for a typical diesel bus for speeds from 5 mph to 70 mph.

Table 2.9: Emission factors from EMFAC2014 model for diesel buses

Vehicle Speed, mph	Emission, gCO_2/mile
5	3523.55
10	3172.54
15	2632.58
20	2221.70
25	2007.88
30	1880.31
35	1787.02
40	1710.90
45	1644.85
50	1597.26
55	1568.85
60	1556.90
65	1551.30
70	1544.85

Like the model for cars, a polynomial curve is fitted to these points so the emission rate associated with any speed can be rapidly calculated in the MATLAB model the team developed. The function for the emission factor for buses, e_{bus}, has the same 4th order polynomial as the one used for cars:

$$e_{bus}(v) = e_4 v^4 + e_3 v^3 + e_2 v^2 + e_1 v + e_0 \tag{12}$$

The coefficient values in Table 2.10 are fitted by a regression with $R^2 = 0.9971$. The emission model is implemented with four significant digits, as presented in Table 2.10, because rounding errors cause large errors in emissions estimates, especially at higher speeds. Figure 2.6 shows the points from the EMFAC model and the fitted curve. The errors introduced by using the fitted curve were less than 4% for each observation, and less than 2% for speeds above 25 mph.

Table 2.10: Emission coefficients from regression

Coefficient	Value	p-statistic
$\boldsymbol{e_0}$	4264	9.5 E-11
$\boldsymbol{e_1}$	-150.1	7.2 E-05
$\boldsymbol{e_2}$	3.1079	0.022
$\boldsymbol{e_3}$*	-0.02762	0.245
$\boldsymbol{e_4}$*	0.00008431	0.581

*Coefficients are not statistically significant, but necessary to fit the EMFAC datapoints with minimal error.

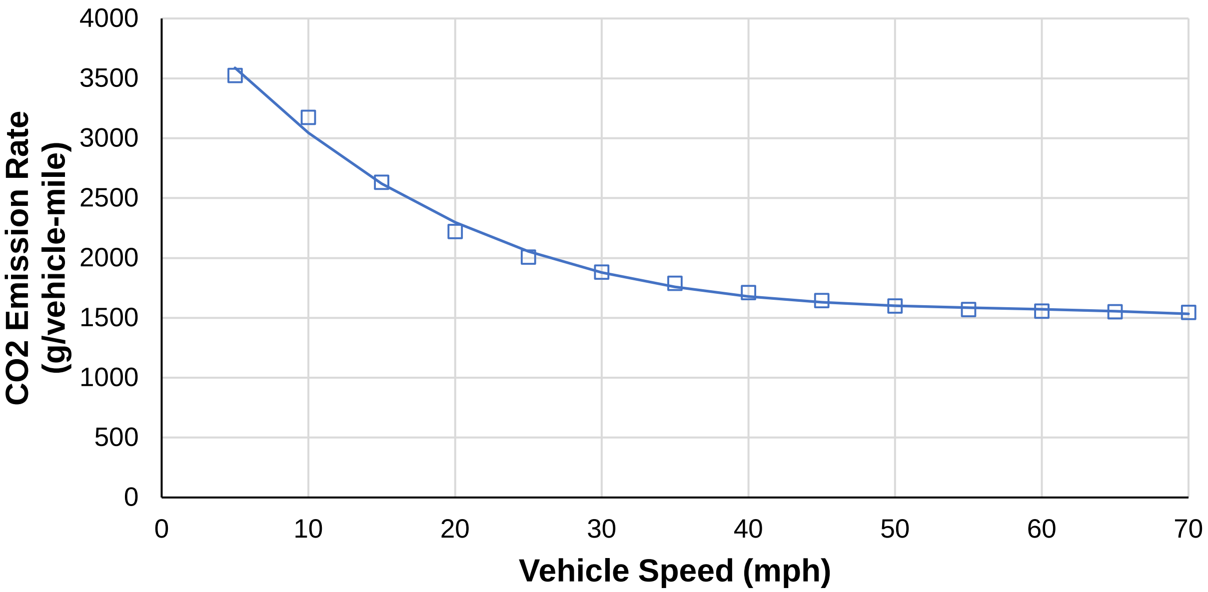


Figure 2.6: Emission rates for diesel bus fleet from EMFAC2014 model

The calculation of total emissions from buses for each OD pair, $E_{bus}(i,j)$, is simply the product of the emission factor, distance, and number of buses dispatched and can be expressed as follows:

$$E_{bus}(i,j) = e_{bus}(v(i,j)d(i,j)N(i,j)) \tag{13}$$

where the speed is given by $v(i,j) = d(i,j)/IVTT(i,j,1)$ where $m = 1$ corresponds to the drive alone mode under the assumption that the bus will have the same in-vehicle travel time as a private vehicle in the absence of any preferential treatments and $N(i,j)$ is the number of commuter buses during the period of interest. Note that unlike the emissions from cars, the estimated emissions from buses does not depend on the number of passengers using the service. This is because the number of buses is determined by the choice of $N(i,j)$, whereas the number of cars is proportional to the number of people who choose to drive.

2.5 Commuter Bus Service Model

New commuter bus services are considered for individual OD pairs. For each OD pair, a new commuter bus service can be characterized by the number of buses dispatched per peak period from origin i to destination j, $N(i,j)$ and the fare charged per customer, $F(i,j)$. The costs that a user will experience, the costs that an operator incurs, and the corresponding GHG emissions from buses are modeled based on these two design variables. By updating the cost parameters of the simplified CTPS model to correspond to the proposed commuter bus, the forecasted origin-destination flows of passengers by mode are compared against the status quo in order to quantify the anticipated ridership and change in number of trips by car. For this project, the relevant metric for the proposed commuter bus service was the ratio of the cost of providing service to the quantity of GHG emissions reduced. For each OD pair, the values of $N(i,j)$ and $F(i,j)$ were jointly determined to minimize the cost per unit of GHG reduced. Then, the OD pairs were ranked by the same metric (i.e., cost per unit of GHG reduced) to create a prioritized list of potential commuter bus services.

2.5.1 User Cost of Commuter Buses

There are three cost components that contribute to the utility associated with each mode in the nested logit mode choice model: in-vehicle travel time (IVTT), out-of-vehicle travel time (OVTT), and cost (COST). Each of the following sections describes the model and assumptions for estimating these values based on the number of buses dispatched per peak period, $N(i,j)$, and the fare charged per passenger, $F(i,j)$.

The implementation of commuter bus service adds two new transit modes to the available choices for commuters: drive-access commuter bus ($m = 13$) and walk-access commuter bus ($m = 14$). It is assumed that in-vehicle travel time (referring to travel time onboard commuter buses) and fares are the same for both cases, but the out-of-vehicle time is affected by how passengers get to the commuter bus service, and some additional charges may be associated with parking when driving is used as the access mode.

In-Vehicle Travel Time

The travel time for a proposed express commuter bus for an OD pair is assumed to be the same as the travel time for a single-occupant vehicle. This means that once passengers board the bus, the vehicle is assumed to follow a similar route as cars, making no additional stops for passengers until the destination. Therefore, the in-vehicle travel time for buses is defined as equal to the in-vehicle travel time for cars:

$$IVTT(i,j,13) = IVTT(i,j,1) \tag{14}$$

$$IVTT(i,j,14) = IVTT(i,j,1) \tag{15}$$

As defined, this travel time implies that buses are susceptible to the same traffic congestion as cars, so the potential effects of preferential treatments to speed up bus services is not considered. Defining in-vehicle travel time this way represents a faster service than the current bus service, because the current bus service makes stops along the route.

Out-of-Vehicle Travel Time

The out-of-vehicle travel time for a commuter bus trip consists of three components: access from the origin to the bus stop, waiting time for the service, and egress from the bus stop to the final destination. These components depend on the access mode, so drive-access (in which the passenger drives, parks, and then rides) is associated with a different travel time than someone who walks. The waiting time, however, is the same for drive-access and walk-access, because passengers are assumed to have access to the same scheduled services.

Drive-Access Time

It is assumed that passengers who drive to access transit only use a car for the beginning portion of their trip in the morning and the end portion of their trip in the evening, because it is most likely that a car is used to drive between home and a park-and-ride location. At the other end of the trip, it is assumed that they use walk as the access mode.

To calculate an estimated access distance within an origin town, the locations of specific trip origins are assumed to be uniformly distributed within roughly circular-shaped towns. With these assumptions, the average access distance can be calculated using principles of geometric probability: Note that the average distance from a point within a circle to the center of the circle is 2/3 of the radius. As a result, the estimated access time by driving in town i is:

$$t_d(i) = k\frac{2}{3v_d}\sqrt{\frac{A_i}{\pi}} \qquad (16)$$

where A_i is the area of town i in square miles, v_d is the average speed of driving across the straight line distance to the centroid of the town in miles per hour, and π is the ratio of the circumference to the diameter of the circle. Note that the estimated distance is the straight-line distance from origins to the center of the town. The real driving trip would likely be more circuitous in following the road network and involve stopping for traffic. Therefore, the driving speed used in this model is much slower than a typical speed limit, and it is intended to reflect the speed of cars traversing distance using the network. The actual access time in many cases will be less than this average, because development tends to be clustered near town centers. A factor, k, is introduced as a constant that can be calibrated to adjust the access time. If $k = 1$, this time is associated with uniformly distributed origin and destination locations within a circular town. Evidence from the CTPS skims is that access distances to the modes like commuter rail are significantly lower than this raw calculation. The access time estimates for commuter bus in a town with a rail station are comparable to access times to commuter rail when a value of $k = 0.25$ is used.

Walk-Access Time

For passengers who access transit by walking, an alternative travel time calculation is required. Furthermore, all trips are assumed to include egress by walking from the bus to the final destination, because commuters who drive to transit leave their cars behind when they board. The expression for walking time is similar to the expression for driving time as presented in equation (3), with the speed changed to reflect the walking speed, v_w.

$$t_w(i) = k\frac{2}{3v_w}\sqrt{\frac{A_i}{\pi}} \qquad (17)$$

Waiting Time

All passengers experience some time waiting for the vehicle, which depends in part on the frequency of service and in part on how early passengers arrive at bus stops prior to the scheduled departure. A simplistic assumption is that all passengers consider the published schedule and arrange their activities so that they only wait a minimal time w_{min} at the bus stop to ensure that they are early enough not to miss it. A more complete representation of the waiting time accounts for the time that passengers have to wait for the next bus departure. Longer headways require passengers to make bigger adjustments to their schedule in order to use the commuter bus, which is effectively a longer waiting time.

The waiting time, $w(i,j)$, is modeled as the maximum of two possible values: the 5-minute time people arrive early to ensure they catch a scheduled departure, and a weighted measure of the time between bus departures that are assumed to be uniformly distributed across the peak period.

$$w(i,j) = \max\left\{w_{min}, \frac{\phi T}{N(i,j)}\right\} \tag{18}$$

In this expression, ϕ represents the perceived cost of the scheduled headway relative to travel time, and T is the duration of the peak period. For services with long headways that passengers plan their daily schedule for in advance, ϕ is likely to be less than 1 (perhaps much less), because people can plan productive uses for their time until their bus is scheduled to depart.

Combined Out-of-Vehicle Cost

The total out-of-vehicle travel time is a combination of the access time, waiting time, and egress time components defined above. The documentation of the CTPS Travel Demand Modeling Methodology (*25*) specifies path-building parameters for each of these components. These parameters are weighting factors that are multiplied by each component of the travel time to construct the total out-of-vehicle travel time for use in the mode choice model.

The expression for the out-of-vehicle travel time for drive-access commuters is:

$$OVTT(i,j,13) = 2.65t_d(i) + 1.1w(i,j) + 1.6t_w(j) \tag{19}$$

because commuters are assumed to drive to the bus stop, wait for the bus, and then walk from the bus to their final destination.

The expression for out-of-vehicle travel time for walk-access commuters is similar to equation (19), except that the initial access component is also by walking.

$$OVTT(i,j,14) = 1.6t_d(i) + 1.1w(i,j) + 1.6t_w(j) \tag{20}$$

As specified by the CTPS Travel Demand Modeling Methodology, the walking speed is assumed to be $v_w = 3$ mph.

Money Cost

In addition to travel time, users experience the monetary costs associated with their choice of mode. For drive-access to transit, these costs include the costs of owning and operating a car, costs for parking, and transit fare. For walk-access to transit, the only monetary cost is assumed to be the fare.

There are two ways that fare can be specified in the proposed mode choice model. First, the cost can be simply defined as a dollar amount, $F(i,j)$, which would represent the published fare for the service or the average price per trip for a passholder. To keep this part of the analysis simple, the additional costs of driving and parking are assumed to be unchanged. Therefore, the cost for a drive-access commuter bus trip is given by:

$$COST(i,j,13) = COSTAM(i,j,8) - COSTAM(i,j,12) + \frac{F(i,j)}{VOT} \tag{21}$$

where *COSTAM*(*i*,*j*,8) is the cost of drive-access transit and *COSTAM*(*i*,*j*,12) the cost of walk-access transit with the existing model, while *COSTAM*(*i*,*j*,13) is the cost of drive-access commuter bus that is introduced. The first term includes the existing cost of driving and parking as well as fare. The second term subtracts the cost of walk-access transit, which is the existing fare. The third adds back the new fare in units of travel time based on the value of time, which is $VOT = \$10.75$/hour, based on the CTPS model documentation. The cost for a walk-access commuter bus trip is given by the following equation:

$$COST(i,j,14) = \frac{F(i,j)}{VOT} \tag{22}$$

An alternative way to express the fare is in terms of the difference from the existing cost of a bus trip from origin i to destination j. In this case, the existing cost data is simply adjusted by a change in fare, $\Delta F(i,j)$.

$$COST(i,j,13) = COSTAM(i,j,8) + \frac{\Delta F(i,j)}{VOT} \tag{23}$$

$$COST(i,j,14) = COSTAM(i,j,12) + \frac{\Delta F(i,j)}{VOT} \tag{24}$$

2.5.2 Agency Costs of Commuter Bus

The costs to an agency or operator for running a commuter bus service, $COST_{agency}(i,j)$, can be categorized in two parts. There are capital costs associated with purchasing vehicles that will be used to operate the service, and operating costs that are incurred for the distance and time over which the vehicles are used.

$$COST_{agency}(i,j) = COST_{capital}(i,j) + COST_{operations}(i,j) \tag{25}$$

For this study, conventional diesel motor coaches were considered, because these are the most common vehicles used for commuter bus services. Vehicles that are powered by alternative fuels may lead to reduced GHG emissions in exchange for increased cost.

Capital Cost

The capital cost of vehicles depends on the cost of purchasing a new vehicle and the anticipated life span of the vehicle. If the amortized cost of each bus in a weekday peak period is c_v, then the capital cost associated with the operations in a peak period is the number of required vehicles multiplied by this cost per vehicle. The number of required vehicles depends on how many dispatches are scheduled during the rush period and the length of the trip. The total capital cost for walk-access commuter bus, which is the same as for drive-access commuter bus, is given by:

$$COST_{capital}(i,j) = c_v \left(\min\{IVTT(i,j,14) + IVTT(j,i,14) + t_T, T\} \frac{N(i,j)}{T}\right) \tag{26}$$

where *IVTT*(*i*,*j*,14) and IVTT(*j*,*i*,14) are the in-vehicle travel time for transit from *i* to *j* and *j* to *i* respectively, t_T is the terminal time, *N*(*i*,*j*) is the number of bus dispatches in the peak period, and *T* is the duration of the peak period. In equation (26), the cycle time for a bus to return to the start of its route at i and serve a second trip is the sum of the travel times in each direction and an additional terminal time, t_T, to load and unload passengers and turn around at the end of the line. This terminal time is assumed to be approximately $t_T = 30$ minutes. For short enough trips, a bus can carry a load of passengers from i to j and then return back to the start to carry another load before the end of the peak period, T. For longer trips, this is not possible, and an additional vehicle is needed for each subsequent dispatch. The total number of vehicles required for the peak service is the minimum of either the cycle time or the peak period duration by the rate of bus dispatches per time ($N(i,j)/T$).

A new motor coach costs approximately $445,000 (*26*) and is expected to last at least 12 years (*27*). Amortizing this cost across 260 weekdays per year and two peak periods of operation per weekday, this implies a capital cost of approximately $c_v = 71$ $/veh in a peak period. The estimate is conservative, because buses could be used for other productive purposes during the rest of the day or on weekends, and the vehicle may have some productive value at the end of the planned service life.

If a fleet of buses is available for use to provide commuter services, it is possible that the capital costs are not a deciding factor for considering whether or not to operate the service. In this case, the capital costs can be omitted from the calculations altogether, and the analysis can focus on the operating costs.

Operating Costs

Operating costs for commuter buses are associated with two important components: costs that accrue per vehicle mile, c_d, and costs that accrue per vehicle time, c_t. As a result, the operating cost for the scheduled runs in a peak period are given by the following expression.

$$COST_{operations}(i,j) = \left(c_d d(i,j) + c_t IVTT(i,j,12)\right) \cdot N(i,j) \qquad (27)$$

For diesel buses, the operating cost per distance is approximately $c_d =$ \$1.56/mile, including approximately \$0.90/mile for fuel (*28*) and \$0.66/mile for maintenance (*29*).

Operating costs per time were estimated from cost records reported in the National Transit Database (*30*) by the following bus operators in Massachusetts:

- Massachusetts Bay Transportation Authority
- Boston Express
- Brockton Area Transit Authority
- Lowell Area Regional Transit Authority
- Southeastern Regional Transit Authority
- Worcester Regional Transit Authority
- Pioneer Valley Transit Authority

Based on the average of reported costs from these agencies, the cost per revenue hour of operations is estimated to be $c_t = \$105$/hour.

2.6 Introduction of Commuter Bus Service

The objective of this study is to identify potential commuter bus services that could be provided to reduce GHG emissions associated with transportation in the Greater Boston area. From an operator's or agency's perspective, there are two relevant performance measures that should be considered for potential services: the total expected reduction in system GHG emissions associated with a new commuter bus service, and the cost of operating the new service. The total quantity of GHG reduction is a measure of the effectiveness of a proposed commuter bus service. However, the cost of achieving these reductions is important for making efficient use of financial resources. Therefore, the two measures can be combined in a single cost-efficiency metric as the dollar cost per unit of GHG reduced. Each OD pair can then be ranked by cost-efficiency in order to identify the services that would reduce the most GHG emissions per dollar expended.

2.6.1 Change in GHG Emissions

As mentioned earlier, the effect of a new commuter bus service on GHG emissions is a combination of the effect on emissions from car trips and additional emissions from the new bus operations. For the purposes of this study, it is assumed that all other transit operations in the region will not be changed, so emissions from existing bus, rail, and ferry services are unchanged.

The change in GHG emissions is estimated by first running the mode choice model for the existing conditions to estimate current emissions from cars using equation (11). Then, the mode choice model is run again with the mode characteristics for drive-access bus and walk-access bus revised as described through equations (14) and (15) for in-vehicle travel time, equations (19) and (20) for out-of-vehicle travel time, and either (21) and (22) or (23) and (24) for cost. The new calibrated flows for each OD pair by mode are denoted by $NPCODAM(i,j,m)$, and these are used to calculate the emissions from cars after the introduction of commuter bus service.

The change in GHG emissions, $\Delta GHG(i,j)$, is then calculated as the sum of the car and bus emissions with the proposed commuter bus minus the car emissions from the initial case.

$$\Delta GHG(i,j) = [E_{bus}(i,j) + E_{car}(i,j)]_{new} - [E_{car}(i,j)]_{initial} \tag{28}$$

2.6.2 Change in Cost

The change in cost associated with a new commuter bus service has two components. First, there are the new capital and operating agency costs presented in equations (26) and (27). There is also an effect of changing fare revenues, which can increase or decrease the net effect to the agency depending on fare and the change in the number of riders. The change in revenue is calculated by subtracting the total initial revenue from the total final revenue as follows:

$$REV(i,j) = COST(i,j,14)[NCPODAM(i,j,13) + NCPODAM(i,j,14)] \tag{29}$$

where fare is represented by the cost paid by walk-access transit users, $COST(i,j,13) = COST(i,j,14)$, as described in equations (21) to (24).

The change in cost associated with new commuter bus service from i to j, $\Delta Cost(i,j)$, is given by:

$$\Delta Cost(i,j) = COST_{capital}(i,j) + COST_{operations}(i,j) - REV(i,j) \qquad (30)$$

where positive change in cost indicates net increase in expenditures for service, and a negative value indicates a profit for the agency.

2.6.3 Cost Efficiency of GHG Reduction

Although ranking OD pairs to minimize equation (30) would reveal the single route that would achieve the greatest reduction (i.e., most negative change) in GHG emissions, this would not account for the costs of achieving this reduction. Therefore, a more useful metric for decision making is to consider the cost per unit of GHG emissions reduced.

$$Efficiency(i,j) = \frac{\Delta Cost(i,j)}{\Delta GHG(i,j)} \qquad (31)$$

This efficiency metric is maximized, subject to the constraint that $\Delta GHG(i,j) < 0$. The constraint is necessary to ensure that only new services that actually reduce GHG emissions are considered, because any corridor in which new bus service increases emissions should not be prioritized in this analysis, no matter how profitable it may be. Considering only negative values in the denominator, minimizing the cost in the numerator results in maximizing the value of $Efficiency(i,j)$.

Additional constraints include a vehicle capacity constraint to ensure that the number of passengers assigned to each bus is less than the bus capacity. In situations that buses are overcrowded, either more buses are needed or fares need to be raised to manage demand. In addition, a constraint to consider only trips longer than 8 miles is imposed to filter out short trips that are unrealistic for commuter buses.

In cases that a proposed commuter bus service may be profitable, the change in cost is negative, and the efficiency measure is greater than 0. In cases that costs exceed any possible gains in revenue, the efficiency metric will be negative. In ranking OD pairs by this metric, those services (i.e., OD pairs) that most cost-effectively reduce GHG emissions are identified and prioritized.

3.0 Results

The modeling methods described in the previous section were applied to the towns in Eastern Massachusetts that are included in the CTPS travel demand model. In this section, the results of the model calibration are presented to show how the simplified travel demand model compares with the OD flows by mode predicted by the regional travel demand model. Then, the status quo GHG emissions are estimated by using the travel time, distance, and mode flow data. Finally, the transit model is implemented and optimized in order to identify the OD pairs for which GHG emissions can be reduced by shifting commuters away from driving.

3.1 Model Calibration

The simplified mode choice model utilizes the data inputs to generate estimated origin-destination flows by mode for each combination of the 165 towns in the Greater Boston area. In order to calibrate these modeled values to the reported OD mode flows from CTPS, each model estimate is compared to the corresponding reported value; $PODAM$ and $ODAM$ for the morning peak, $PODPM$ and $ODPM$ for the evening peak.

One way to visualize the fit of the uncalibrated model is to plot values predicted with the MATLAB model against values provided by CTPS, as shown in Figure 3.1 and Figure 3.2. A perfect model would generate points that lie exactly along the line of unit slope (slope = 1), shown in black. Figure 3.1 shows the data for the AM peak and reveals some scatter in the data, especially for the various transit modes. This indicates the need to calibrate each origin-destination mode flow estimate in order to account for variations that are not adequately described in the simplified model. Figure 3.2 shows the data for the PM peak, with a similar pattern of scatter. A calibration factor for each OD pair and mode is calculated using equation (9).

Table 3.1 presents the total trips by mode across all OD pairs from the uncalibrated model and the reported values from CTPS. Generally, the model does well for predicting car trips, which account for the vast majority of home-based work trips in the Greater Boston area. Calibration is more critical for accounting for the correct number of trips completed by the various transit modes.

Although the simplified mode choice model requires that a calibration factor be used to adjust the mode flows for each OD pair, on average the clustering of points along the line of unit slope indicates a generally unbiased estimate. The more important result for this project is that this provides an implementation of the mode choice model for every OD pair in the Greater Boston area that is responsive to changes in transit travel time. In the subsequent tasks to optimize and model the impact of new commuter bus services, new commuter services will reduce the travel time by bus transit and the resulting effect on mode share will be quantified for comparison directly against the status quo.

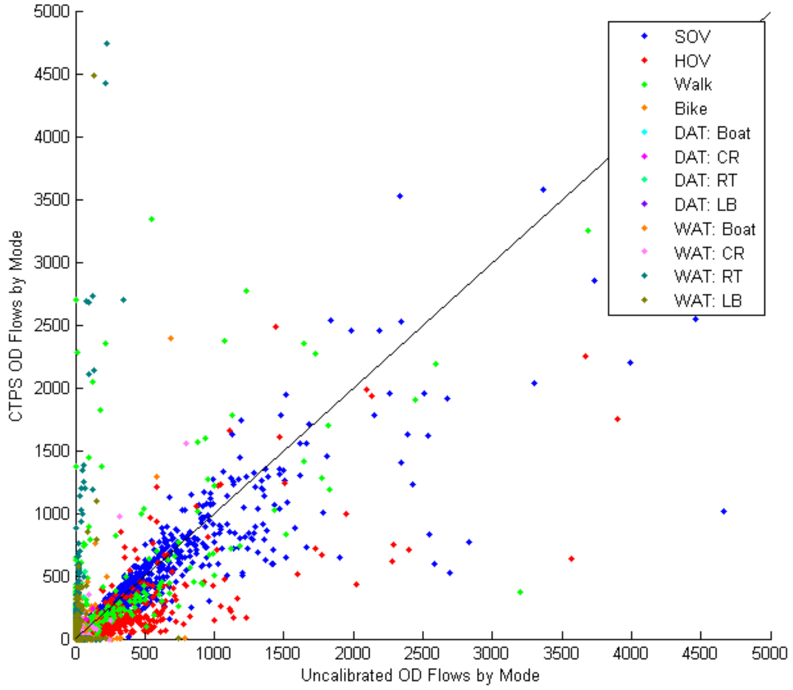


Figure 3.1: Comparison of uncalibrated mode flows and CTPS mode flows (AM peak)

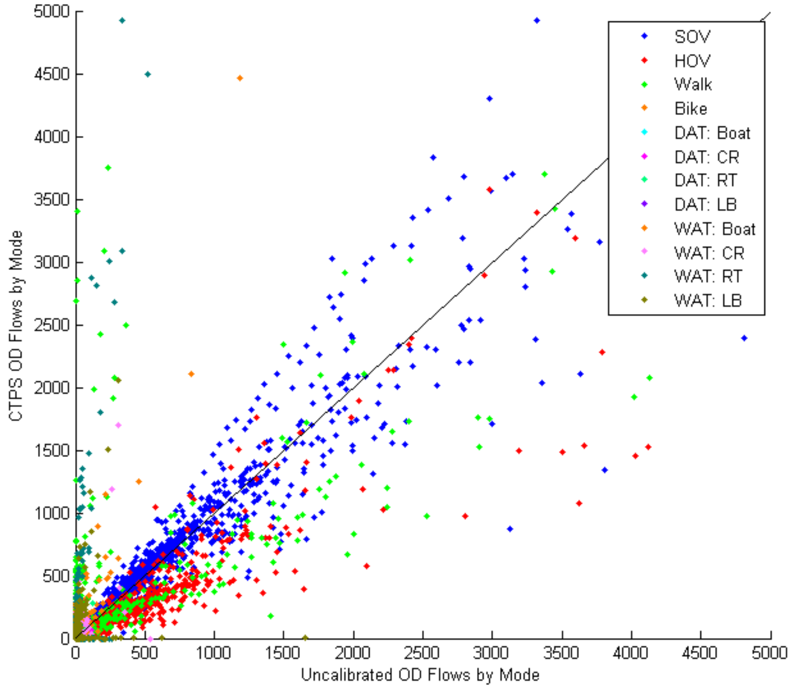


Figure 3.2: Comparison of uncalibrated mode flows and CTPS mode flows (PM peak)

Table 3.1: Comparison of uncalibrated mode flows (trips per time period)

	AM Peak		PM Peak	
Mode	Uncalibrated	CTPS Flow	Uncalibrated	CTPS Flow
SOV	885,611	797,935	1,447,558	1,418,369
HOV	377,378	203,958	619,094	383,491
Walk	133,633	213,838	276,641	348,937
Bike	10,016	35,893	19,163	56,172
DAT Boat	174	836	166	104
DAT Commuter Rail	2,249	14,157	2,811	3,568
DAT Rapid Transit	819	14,718	1,184	4,266
DAT Local Bus	172	1,695	246	529
WAT Boat	7,314	435	1,937	700
WAT Commuter Rail	6,678	15,703	8,060	17,118
WAT Rapid Transit	10,505	115,488	16,178	134,715
WAT Local Bus	5,851	25,746	11,128	36,195

3.2 Status Quo GHG Emissions

The GHG emissions associated with status quo conditions are estimated using the reported number of car trips from CTPS for each OD pair, along with speeds estimated from calculated distances and reported travel times. Using the EMFAC model as shown in equation (11), the GHG from single-occupant vehicles and high-occupant passenger cars was calculated for each OD pair. Table 3.2 presents a comparison of the total number of modeled private vehicle trips in the morning and evening peak, as well as the corresponding GHG emissions. These values represent the status quo private vehicle emissions against which changes resulting from new or expanded commuter bus services will be compared.

Table 3.2: Status quo trip flows and emission estimates

	AM Peak	PM Peak
SOV Trips	797,930	1,418,400
HOV Trips	203,960	383,490
Total Private Vehicle Trips	1,001,890	1,801,890
SOV Emissions (tons CO_2)	2792	3956
HOV Emissions (tons CO_2)	263	444
Total Private Vehicle Emissions (tons CO_2)	3055	4400

A more detailed view of the status quo conditions is to consider the emissions associated with individual OD pairs. Since the GHG emission calculation methodology produces an emission estimate for every OD pair, these pairs can be ranked to identify the top-polluting corridors in the Greater Boston area. Table 3.3 shows the top 15 OD pairs for GHG emissions in the morning peak, and Table 3.4 shows the top 15 OD pairs for the evening peak. The emissions depend on the number of car trips as well as the distance and speed. These corridors are also illustrated in Figure 3.3. The highest emitting OD pairs are associated with the congested center of the Greater Boston area, but several longer commuting corridors also make the list. This view of current emissions provides some insights into the OD pairs that are likely to be contenders for commuter bus service that reduces emissions. OD pairs where the distance is long and the current mode share for cars (i.e., SOV and HOV) is high offer the greatest opportunity for attracting riders to a commuter bus.

Table 3.3: Top 15 GHG emitting OD pairs in Greater Boston area (AM peak)

Origin	Destination	Distance (miles)	Car Trips	SOV & HOV Mode Share	GHG Emissions (gCO$_2$e)
NEWTON	BOSTON	7.42	4567	87.4%	11,789,589
BOSTON	BOSTON CBD	3.51	7933	91.0%	11,611,560
QUINCY	BOSTON	6.86	3370	97.4%	8,961,595
BOSTON	NEWTON	7.42	3647	97.9%	8,543,393
BROCKTON	BOSTON	17.70	1296	80.4%	8,007,398
WEYMOUTH	BOSTON	13.00	1552	99.2%	7,300,223
BOSTON	CAMBRIDGE	5.51	3641	96.0%	7,088,483
NORWOOD	BOSTON	11.92	1454	83.7%	6,933,825
WEYMOUTH	BOSTON CBD	14.56	1283	98.3%	6,490,117
FRAMINGHAM	BOSTON	20.14	968	99.2%	6,144,623
NEWTON	BOSTON CBD	8.10	2083	96.8%	5,874,515
FRAMINGHAM	BOSTON CBD	20.46	888	98.1%	5,846,970
DEDHAM	BOSTON	7.55	2049	87.0%	5,739,800
PLYMOUTH	BOSTON	41.81	483	99.6%	5,609,677
BOSTON	QUINCY	6.86	2436	96.1%	5,564,657

Table 3.4: Top 15 GHG emitting OD pairs in Greater Boston area (PM peak)

Origin	Destination	Distance (miles)	Car Trips	SOV & HOV Mode Share	GHG Emissions (gCO$_2$e)
BOSTON CBD	BOSTON	3.51	13644	92.8%	21,234,945
BOSTON	NEWTON	7.42	7830	98.1%	20,638,414
NEWTON	BOSTON	7.42	7259	98.2%	18,190,662
CAMBRIDGE	BOSTON	5.51	7998	96.2%	16,486,384
BOSTON	QUINCY	6.86	5314	96.8%	15,142,310
BOSTON	BOSTON CBD	3.51	9818	92.0%	13,833,542
BOSTON	CAMBRIDGE	5.51	6429	96.0%	12,052,520
BOSTON	DEDHAM	7.55	3826	97.5%	11,676,113
BROOKLINE	BOSTON	3.53	7169	94.4%	11,337,594
BOSTON	BROOKLINE	3.53	7060	94.1%	10,670,498
BOSTON	NORWOOD	11.92	2104	97.7%	10,596,252
BOSTON	BROCKTON	17.70	1514	97.9%	10,320,104
BOSTON	WEYMOUTH	13.00	1858	98.7%	9,938,695
QUINCY	BOSTON	6.86	4034	97.8%	9,332,897
BOSTON	MILTON	5.58	4153	97.2%	9,266,110

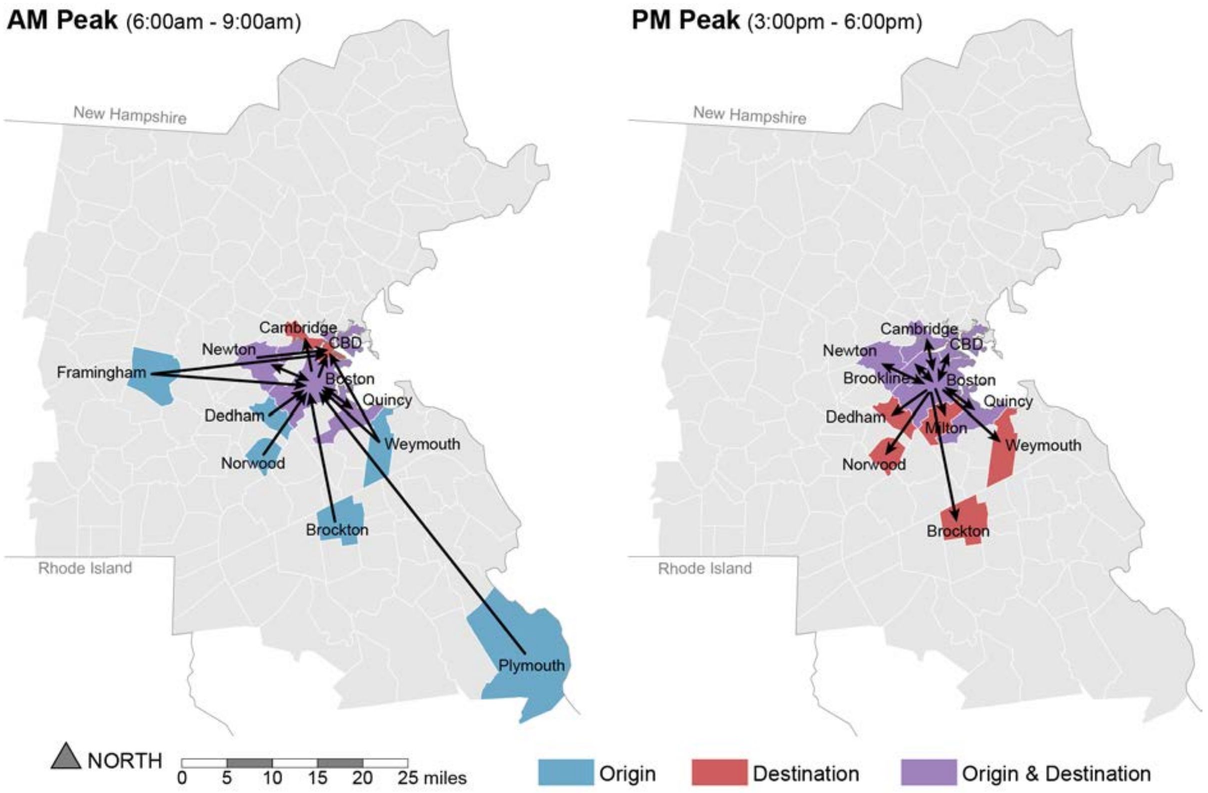


Figure 3.3: Top 15 GHG emitting OD pairs in the AM and PM peaks

3.3 Introduction of Commuter Bus Services

The model, as described in the preceding sections, has been implemented for the 165 towns and central business district in the Greater Boston area covered by the CTPS travel demand model. The model has been implemented across all OD pairs to identify the optimal number of vehicles to dispatch per peak period, $N(i, j)$, and the corresponding fare that maximizes efficiency, $F(i, j)$. A number of fare and cost scenarios were evaluated with the model in order to compare results under different operating assumptions and to identify which OD pairs (if any) appear consistently in the rankings.

Five fare scenarios are considered:

1. No Fare Charged ($F = 0$ \$/ride)—This scenario identifies the practical limit of what can be achieved if fares are totally subsidized, which should maximize the incentive for commuters to change modes.
2. Flat Fare Charged ($F = 8$ \$/ride)—This scenario considers the effect of travel time when a typical express commuter bus fare is charged.
3. Optimized Fare ($F \in [0, 20]$ \$/ride)—This scenario is the most general, and considers the possibility of setting the fare differently for each OD pair at a level from \$0 to \$20/ride. Specifically, the model is evaluated for values of $F \in \{0, 4, 6, 8, 10, 12, 14, 16, 18, 20\}$ \$/ride.

4. Optimized Fare, with Minimum ($F \in [6, 20]$ \$/ride)—This scenario also considers the possibility of setting the fare differently for each OD pair, but restricts the minimum fare to \$6/ride. Specifically, the model is evaluated for values of $F \in \{6, 8, 10, 12, 14, 16, 18, 20\}$ \$/ride.
5. Existing Fares Not Change ($\Delta F = 0$)—This scenario isolates the effect of changing in-vehicle travel time and out-of-vehicle travel time on emissions.

Two cost scenarios are considered:

A. Capital and Operating Costs ($c_v = 71$ \$/veh per day)—This scenario considers that vehicles must be procured for the new commuter bus service, and therefore the capital costs are considered in the cost efficiency calculation.
B. Only Operating Costs ($c_v = 0$ \$/veh per day)—This scenario considers that a fleet of vehicles is already available for use, so the only additional costs to an agency for providing new commuter bus service are those associated with operations.

For each OD pair, the ridership, agency costs, and emissions were calculated for $N \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ buses per peak period. In scenarios with a fixed fare assumption, these eight cases were compared to identify which yields the greatest efficiency in reducing GHG per dollar of expenditure. In scenarios 3 and 4, which consider a range of possible fares, each combination of F and N was evaluated to identify the optimal combination of values for the OD pair.

For each scenario, only OD pairs for which GHG can be reduced by some choice N are ultimately considered for ranking. For many OD pairs, the number of commuters is so small that even with free fares, there would not be enough commuter bus riders for the emissions of the bus itself to offset reductions from reduced car trips. The number of candidate commuter bus corridors under each scenario is summarized in Table 3.5. There are many more candidate OD pairs in the evening because there are greater total numbers of trips being made during that time period of the day.

Table 3.5: Number of OD pairs for which GHG is reduced with commuter buses

Scenario	AM Peak		PM Peak	
	Case A: $c_v = 71$	Case B: $c_v = 0$	Case A: $c_v = 71$	Case B: $c_v = 0$
Case 1: $F = 0$	69	69	311	311
Case 2: $F = 8$	40	40	223	223
Case 3: $F \in [0,20]$	70	70	314	314
Case 4: $F \in [6,20]$	47	47	241	241
Case 5: $\Delta F = 0$	49	49	228	228

The most general results are associated with cases 3A and 3B. These are the results that consider the greatest range of combinations of number of buses dispatched per peak period and possibility of charging no fare or as much as \$20/ride. This flexibility is also why these cases are associated with the greatest number of possible OD pairs in Table 3.5. If passengers must be charged a fare, this discourages some commuters from using the commuter bus, making it less effective at reducing emissions.

A complete set of tables listing ranked OD pairs under each scenario is included in the Appendix of this report. In this section, the team focuses on the results for Cases 3A and 3B, which provide the most general insights.

3.3.1 Including Capital and Operating Costs

First, the results are shown when capital costs for vehicles are included in the calculation of agency costs. Table 3.6 and Table 3.7 show the top commuting corridors ranked by quantity of GHG emissions reduced per day. These OD pairs are also mapped in Figure 3.4. The OD pairs have been filtered to only consider distances that are greater than 8 miles, because express commuter buses are designed to serve longer distance trips. Short transit trips are more suitable for local bus or rail services. The number of buses and fares have been optimized for each OD pair in order to maximize efficiency, so some fares are high in order to balance the demand for the commuter bus with the capacity of vehicles and the cost of providing the service. For many OD pairs, the fares are low in order to attract riders from driving.

Table 3.6: OD pairs ranked by reduction of GHG (Case 3A, AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare (\$)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost (\$)	Efficiency (\$/gCO$_2$e)
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	229.88	-0.016
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	309.35	-0.065
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	337.95	-0.109
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	558.70	-0.263
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	68.77	-0.049
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	297.47	-0.226
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
WALTHAM	BURLINGTON	9.64	1	0	8	-469	-0.03%	189.03	-0.403
GLOUCESTER	BEVERLY	10.14	2	0	57	-247	-0.01%	55.29	-0.224
NORWOOD	BOSTON CBD	14.70	4	4	231	-183	0.00%	440.80	-2.408

Table 3.7: OD pairs ranked by reduction of GHG (Case 3A, PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare (\$)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost (\$)	Efficiency (\$/gCO$_2$e)
BOSTON CBD	RANDOLPH	12.63	2	0	97	-44945.2	-0.93%	320.32	-0.007
BOSTON CBD	FRAMINGHAM	20.46	2	0	103	-39010.7	-0.66%	319.89	-0.008
BOSTON CBD	BRAINTREE	11.92	4	12	221	-30145.5	-0.47%	269.18	-0.009
PEABODY	BEVERLY	8.34	2	0	29	-18725.5	-0.70%	155.69	-0.008
BOSTON CBD	MILTON	8.55	2	0	92	-13933.1	-0.48%	227.74	-0.016
BEVERLY	GLOUCESTER	10.14	2	0	65	-12635.0	-0.31%	261.35	-0.021
BOSTON CBD	MILFORD	31.16	1	0	8	-11562.0	-0.36%	215.30	-0.019
BURLINGTON	WALTHAM	9.64	1	0	11	-10562.6	-0.42%	158.36	-0.015
BEVERLY	PEABODY	8.34	1	10	18	-10045.0	-0.35%	47.75	-0.005
BOSTON	WINTHROP	9.36	2	4	108	-9998.8	-0.27%	144.50	-0.014
CAMBRIDGE	WOBURN	9.18	2	0	73	-9468.3	-0.45%	196.10	-0.021
BOSTON CBD	ROCKLAND	20.40	1	0	10	-8974.1	-0.33%	247.22	-0.028
BOSTON CBD	LAWRENCE	25.86	2	0	32	-8679.1	-0.23%	394.71	-0.045
BOSTON CBD	WILMINGTON	17.19	2	0	48	-8203.2	-0.28%	311.50	-0.038
BOSTON CBD	BILLERICA	19.34	1	0	16	-7169.0	-0.20%	188.44	-0.026

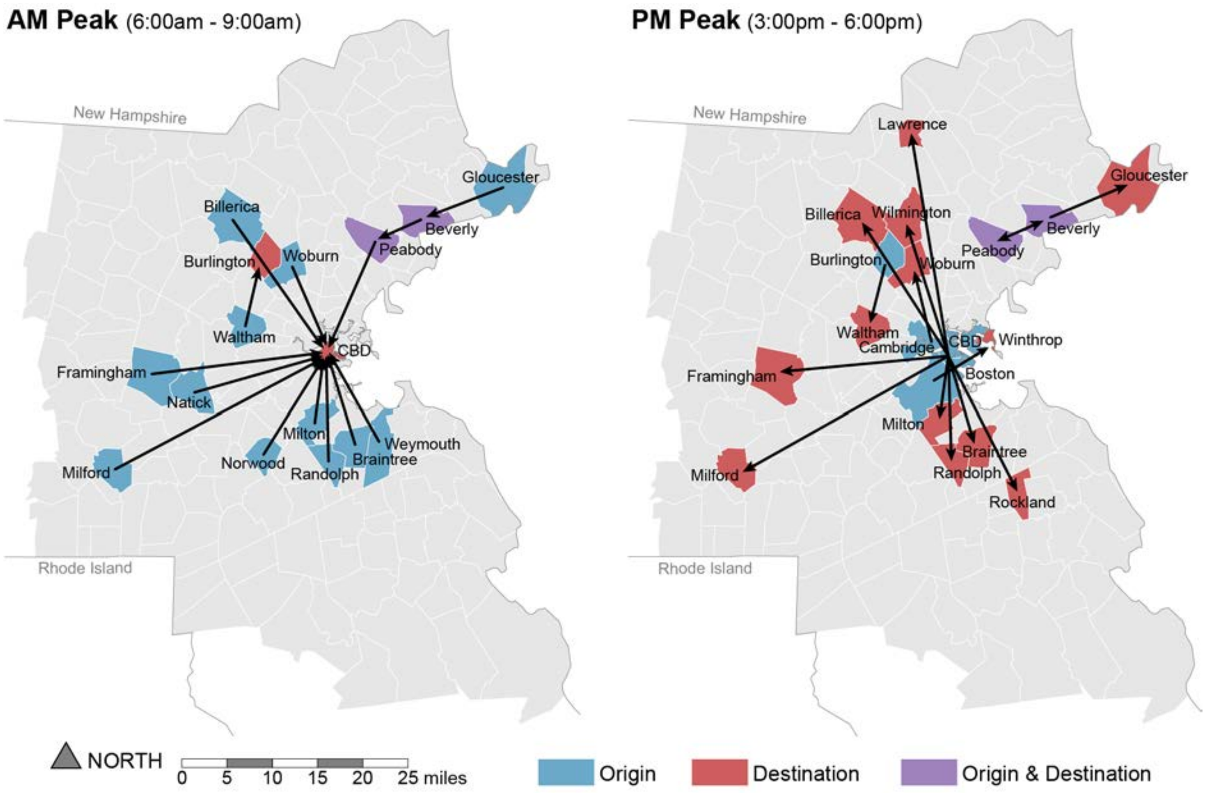


Figure 3.4: Top OD pairs for GHG emission reduction with commuter buses

Next, the OD pairs are ranked by efficiency to identify which OD pairs reduce GHG at the lowest cost per unit of GHG reduced. This is the ranking that would be of interest if scarce financial resources are being allocated to achieve GHG reductions. Table 3.8 and Table 3.9 show these rankings. In the morning peak, there are only 14 candidate OD pairs that are longer than 8 miles and exhibit reduced GHG emissions, so Table 3.8 is a reordering of the same rows as Table 3.6. In the evening, there are more candidate OD pairs, and there are some differences in their ranking. These OD pairs are also illustrated in Figure 3.5.

Table 3.8: OD pairs ranked by efficiency (Case 3A, AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	229.88	-0.016
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	68.77	-0.049
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	309.35	-0.065
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	337.95	-0.109
GLOUCESTER	BEVERLY	10.14	2	0	57	-247	-0.01%	55.29	-0.224
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	297.47	-0.226
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	558.70	-0.263
WALTHAM	BURLINGTON	9.64	1	0	8	-469	-0.03%	189.03	-0.403
NORWOOD	BOSTON CBD	14.70	4	4	231	-183	0.00%	440.80	-2.408

Table 3.9: OD pairs ranked by efficiency (Case 3A, PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
LAWRENCE	HAVERHILL	8.50	3	8	76	-115.1	0.00%	-30.85	0.268
BOSTON CBD	WOBURN	11.50	1	14	56	-1409.2	-0.04%	-54.79	0.039
ASHLAND	FRAMINGHAM	9.19	2	20	19	-4835.6	-0.16%	-16.56	0.003
BOSTON CBD	WEYMOUTH	14.56	1	20	57	-220.4	0.00%	-0.71	0.003
FRAMINGHAM	ASHLAND	9.19	1	20	10	-3134.8	-0.09%	-9.39	0.003
FRAMINGHAM	MARLBORO.	9.72	1	20	9	-6005.4	-0.13%	-4.61	0.001
BOSTON CBD	NORWOOD	14.70	3	16	156	-2399.0	-0.04%	0.22	0.000
WESTBORO.	MARLBORO.	8.73	1	0	10	-6679.7	-0.28%	25.45	-0.004
BEVERLY	PEABODY	8.34	1	10	18	-10045.0	-0.35%	47.75	-0.005
BOSTON CBD	RANDOLPH	12.63	2	0	97	-44945.2	-0.93%	320.32	-0.007
BOSTON CBD	FRAMINGHAM	20.46	2	0	103	-39010.7	-0.66%	319.89	-0.008
PEABODY	BEVERLY	8.34	2	0	29	-18725.5	-0.70%	155.69	-0.008
BOSTON CBD	BRAINTREE	11.92	4	12	221	-30145.5	-0.47%	269.18	-0.009
BOSTON	WINTHROP	9.36	2	4	108	-9998.8	-0.27%	144.50	-0.014
BURLINGTON	WALTHAM	9.64	1	0	11	-10562.6	-0.42%	158.36	-0.015

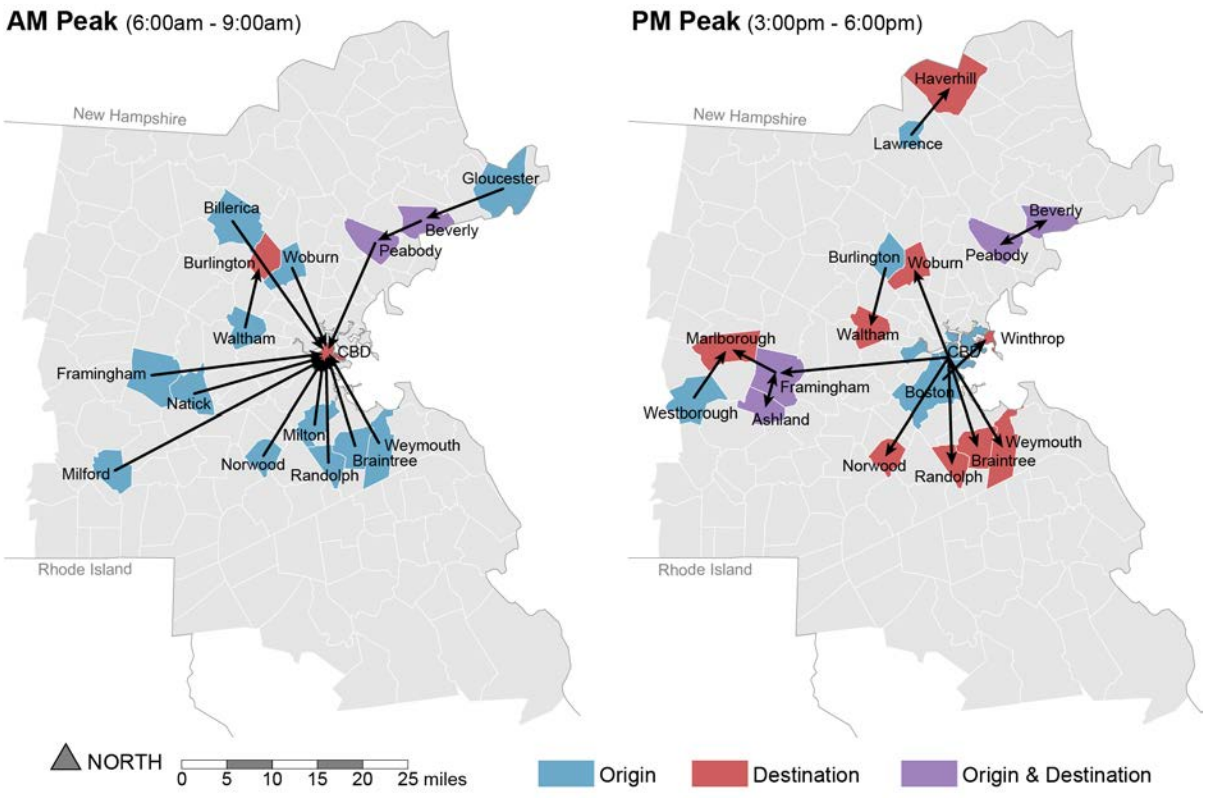


Figure 3.5: Top OD pairs for cost-efficient reduction of GHG

3.3.2 Only Operating Costs Considered

In cases that vehicles are available for additional commuter bus operations, the costs of providing new commuter bus service would only be associated with the operations. The same analyses as presented in the preceding section were also conducted for this scenario to evaluate the effect of capital costs on the performance of various corridors. Table 3.10 and

Table 3.11 show the top commuting corridors ranked by quantity of GHG emissions reduced per day. The rankings are the same in the morning peak, but the cost efficiency is improved, because less money needs to be spent on acquiring vehicles. In the evening, the rankings change only slightly.

Table 3.10: OD pairs ranked by reduction of GHG (Case 3B, AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/g$CO_2$e)
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	134.77	-0.009
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	177.17	-0.012
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	202.86	-0.019
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	150.86	-0.017
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	213.05	-0.045
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	220.80	-0.071
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	326.92	-0.154
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-275.83	0.170
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	39.73	-0.028
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	201.10	-0.153
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-143.47	0.168
WALTHAM	BURLINGTON	9.64	1	0	8	-469	-0.03%	130.33	-0.278
GLOUCESTER	BEVERLY	10.14	2	0	57	-247	-0.01%	31.63	-0.128
NORWOOD	BOSTON CBD	14.70	4	4	231	-183	0.00%	249.99	-1.366

Table 3.11: OD pairs ranked by reduction of GHG (Case 3B, PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/g$CO_2$e)
PEABODY	BEVERLY	8.34	2	0	29	-18726	-0.70%	98.68	-0.005
BEVERLY	GLOUCESTER	10.14	2	0	65	-12635	-0.31%	175.59	-0.014
BOSTON CBD	MILFORD	31.16	1	0	8	-11562	-0.36%	155.90	-0.013
BOSTON CBD	FRAMINGHAM	20.46	2	10	89	-11536	-0.20%	64.36	-0.006
BURLINGTON	WALTHAM	9.64	1	0	11	-10563	-0.42%	101.19	-0.010
CAMBRIDGE	WOBURN	9.18	2	0	73	-9468	-0.45%	128.33	-0.014
BOSTON CBD	ROCKLAND	20.40	1	0	10	-8974	-0.33%	176.22	-0.020
BOSTON CBD	LAWRENCE	25.86	2	0	32	-8679	-0.23%	252.71	-0.029
BOSTON CBD	MILTON	8.55	2	4	85	-8261	-0.29%	87.94	-0.011
BOSTON CBD	WILMINGTON	17.19	2	0	48	-8203	-0.28%	217.62	-0.027
BOSTON CBD	BILLERICA	19.34	1	0	16	-7169	-0.20%	132.57	-0.018
BOSTON CBD	NEEDHAM	11.87	2	0	92	-6897	-0.29%	179.90	-0.026
BOSTON	BRAINTREE	10.36	3	0	158	-6509	-0.07%	326.50	-0.050
BOSTON CBD	STONEHAM	9.83	2	0	79	-6350	-0.39%	79.24	-0.012
BOSTON	CANTON	10.31	2	0	51	-6067	-0.09%	234.23	-0.039

Ranking the ODs by efficiency, Table 3.12 and Table 3.13 show that the biggest change is an improvement in efficiency compared to Case 3A. In some cases, the calculation of efficiency comes out positive, because the model estimates that it would be possible to bring in more fare revenues than operating expenses (turning a profit) while simultaneously reducing GHG emissions by attracting commuters from their cars. Despite opportunities for high efficiency scores, some of these potentially profitable routes yield very small reductions of GHG emissions (e.g., Lawrence to Haverhill in the PM peak would reduce only 115 grams per peak period). Therefore, it is worth considering both the magnitude of savings and the cost efficiency together when interpreting the results.

Table 3.12: OD pairs ranked by efficiency (Case 3B, AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-275.83	0.170
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-143.47	0.168
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	134.77	-0.009
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	177.17	-0.012
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	150.86	-0.017
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	202.86	-0.019
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	39.73	-0.028
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	213.05	-0.045
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	220.80	-0.071
GLOUCESTER	BEVERLY	10.14	2	0	57	-247	-0.01%	31.63	-0.128
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	201.10	-0.153
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	326.92	-0.154
WALTHAM	BURLINGTON	9.64	1	0	8	-469	-0.03%	130.33	-0.278
NORWOOD	BOSTON CBD	14.70	4	4	231	-183	0.00%	249.99	-1.366

Table 3.13: OD pairs ranked by efficiency (Case 3B, PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-69.12	0.601
BOSTON CBD	WEYMOUTH	14.56	1	20	57	-220	0.00%	-60.87	0.276
BOSTON	WINTHROP	9.36	2	12	99	-581	-0.02%	-63.01	0.108
BOSTON CBD	BRAINTREE	11.92	4	20	195	-3168	-0.05%	-194.29	0.061
BOSTON CBD	WOBURN	11.50	1	14	56	-1409	-0.04%	-85.49	0.061
BOSTON CBD	NORWOOD	14.70	3	16	156	-2399	-0.04%	-141.72	0.059
FRAMINGHAM	ASHLAND	9.19	3	18	25	-1979	-0.06%	-38.63	0.020
ASHLAND	FRAMINGHAM	9.19	3	16	26	-1744	-0.06%	-30.79	0.018
WESTBORO.	MARLBORO.	8.73	1	16	7	-536	-0.02%	-6.19	0.012
FRAMINGHAM	MARLBORO.	9.72	3	18	21	-2241	-0.05%	-22.06	0.010
BEVERLY	PEABODY	8.34	1	20	15	-5116	-0.18%	-2.16	0.000
WALTHAM	BOSTON	10.82	3	8	177	-3292	-0.04%	-1.30	0.000
BOSTON CBD	RANDOLPH	12.63	2	18	68	-1915	-0.04%	-0.32	0.000
PEABODY	BEVERLY	8.34	2	0	29	-18726	-0.70%	98.68	-0.005
BOSTON CBD	FRAMINGHAM	20.46	2	10	89	-11536	-0.20%	64.36	-0.006

4.0 Conclusion

This study has presented a data-based method for quantifying the potential of commuter bus service to reduce GHG emissions from the transportation sector in the Greater Boston area. The approach builds on the regional travel demand model that is developed and maintained by CTPS. CTPS defines travel between 2,727 TAZs, includes socioeconomic characteristics about each TAZ, and includes traffic assignment components to estimate traffic conditions. As a result, it requires extensive data, calibration, and computational resources to evaluate the effect of changes to the transportation system.

This study has focused on identifying the effect that investments in commuter bus services can have on GHG emissions from the transportation sector. In order to conduct a comprehensive comparison of potential OD pairs to serve with commuter buses, a simplified nested logit travel demand model based on the CTPS model was developed. This simplified model defines travel between 164 towns in the Greater Boston area as well as the Boston CBD, thus creating a spatial aggregation of 165 zones. Furthermore, the model explicitly considers mode characteristics associated with in-vehicle travel time, out-of-vehicle travel time, and cost, but the effects of socioeconomic characteristics are accounted for with calibration factors. This specification is suitable for the purposes of this project, because the Project Team is interested in the isolated effect of adding commuter bus services.

In addition to modeling the potential mode shift toward new commuter bus services, this study involved estimation of GHG emissions from car traffic within the Greater Boston area and the additional GHG emissions that would be associated with new commuter bus operations. In order to reduce emissions, enough commuters must stop driving for the net effect of new bus operations to result in reduced GHG emissions. Importantly, if commuters are only attracted from other transit modes, a reduction in GHG emissions will not be achieved, because existing transit operations are likely to continue running anyway.

Finally, a model to estimate the capital and operating costs of commuter bus services was developed so the cost of implementing commuter bus services that reduce GHG emissions can be quantified. This allows for development of a cost-efficiency metric that represents the dollars of expenditure required to reduce a unit of GHG emissions. Cost parameters were estimated from other New England transit agencies, and the corridors in which commuter buses have the potential to reduce emissions have been ranked by cost efficiency.

4.1 Summary of Findings

The results of the study show that there are OD pairs for which GHG emissions can likely be reduced through the introduction of commuter bus services. The magnitude of potential reduction in a corridor depends on the total number of commuters, the distance between the origin and destination, and the current mode share for cars versus transit. For high-emitting OD pairs where the vast majority of commuters currently drive, there tends to be an opportunity for express commuter bus service to attract some riders. In other corridors, where a substantial number of commuters already use transit, commuter bus service is less likely to be effective at reducing GHG emissions.

In the case that no fare is charged for commuter buses (Case 1), an assumption that maximizes potential ridership, the total emission reduction across all potential OD pairs added up to 452 kg CO_2e/day in the morning peak and 3,948 kg CO_2e/day in the evening peak. The magnitude of GHG reductions was typically less than 1% of the emissions in a corridor. In part, this is due to the difficulty of attracting large numbers of riders to transit. It is also a consequence of the fact that diesel-powered buses emit GHG themselves. Using buses powered by alternative fuels would improve the GHG reduction performance, but such vehicles typically cost more to purchase and operate.

A number of assumptions have been made that can affect the magnitude of commuter bus ridership, the reduction in GHG emissions, and the cost of operating service. The most important of these assumptions are related to the constructing of the travel time and cost functions that commuters experience when choosing among available modes. The assumptions going into three factors affect the results most significantly:

1. **Access Distance.** A fit parameter, k, was introduced in equations (16) and (17) to adjust the average distance calculation based on uniform distribution of origins within a town. From out-of-vehicle travel time skims provided by CTPS, the access times for commuter rail in towns with commuter rail stations were used to calibrate this value. On average distances are shortened with $k = 0.25$, which makes sense for towns in which there is a cluster of housing and activities nearer the center.
2. **Waiting Time.** For infrequent commuter services that may run only a couple of times per day, customers do not experience the whole headway between departures as waiting time because they can plan their day and activities around the published commuter bus schedule. In equation (18), the ϕ parameter discounts the headway to represent the time that customers perceive waiting. A value of $\phi = 0.1$ was used in this model, and a minimum waiting time of 5 minutes associated with arriving early enough to catch the bus was included.
3. **Alternative Specific Constant (ASC).** In the nested logit model, a utility function is constructed for each possible mode that a commuter can choose. The relative values of these utilities determine the share of demand that chooses each mode. In the CTPS model, a constant term for each mode is specified as the ASC, as shown in Table 2.6. For the commuter bus model in this study, an assumed value of $ASC = 0$ was used, which implies that commuters' preference for commuter buses is similar to rapid transit, all else being equal. This places commuter buses about midway between local buses and commuter rail. Perhaps some of the attractive features of motor coaches (e.g., comfortable seating, Wi-Fi access, etc.) would actually make this mode more appealing.

Overall, the most promising OD pairs for reducing GHG emissions tend to be to or from Boston and the Boston CBD. This is not surprising, because the Boston CBD is the economic and employment center of the region. Consistently high-ranking OD pairs include

Framingham, Weymouth, Woburn, and Norwood. However, there are some outlying OD pairs that arise, which indicates some opportunity to design commuter routes to support suburb-to-suburb travel. Specifically, trips between Peabody and Beverly and trips between Waltham and Burlington appear in both the AM and PM peak periods.

With the exception of OD pairs that appear to be profitable on their own, the cost of reducing GHG emissions by subsidizing commuter bus services is high relative to other methods of GHG reduction. The efficiency values reported in the ranked tables are presented in units of \$/gCO_2e. This value can be compared against the cost of other GHG abatement strategies. Many of the OD pairs that fall near the top of the list in Table 3.8, Table 3.9, Table 3.12, and Table 3.13 cost on the order of \$0.001 per gCO_2e reduced. This equates to \$1,000 per metric ton CO_2e. By comparison, the U.S. Environmental Protection Agency estimates the social cost of carbon to be as much as \$212 per ton CO_2e (*31*), and many technologies for alternative energy production can reduce GHG emissions for 1/10 the cost (*32*). Although it may be difficult to justify large investments in commuter buses on the basis of GHG reduction alone, there are many other benefits that help justify supporting these services. For example, commuter bus service provides more choices to travelers, allows greater numbers of people to access employment centers (thus supporting the vitality of Boston's CBD as a dense, vibrant, and competitive economic engine), and provides a means to reduce traffic congestion. For these reasons, the OD pairs that are identified and ranked in this study are most valuable if considered in the context of other transportation goals. In this way, the GHG reduction potential can be used to prioritize commuter bus investments that also satisfy other objectives or to tip the balance in choosing between two otherwise similar investments.

4.2 Direction for Future Work

There are a number of ways in which the model and analyses developed in this study may be extended to gain further insights about the potential effectiveness of commuter bus services to attract riders and reduce GHG emissions.

1. **Potential to transfer in Boston CBD to MBTA Rapid Transit to access neighboring towns and communities.** Current commuter bus, commuter rail, and rapid transit services are centered on the Boston CBD zone, which is not showing up at the top of this analysis because it is already well served. It would be of value to look at how trips to locations elsewhere in Boston are treated, because the walk-access assumption may not be representing out-of-vehicle travel time in an accurate way for these trips. The result is that the team is seeing many candidate corridors to/from Boston's non-CBD neighborhoods.
2. **Potential of dedicated bus lanes or HOV lanes to offer faster commuter bus service.** The current model considered that an express bus would travel the same speed as a single-occupant vehicle, meaning that it would be subject to the same delays from traffic congestion. If dedicated lanes for buses were implemented on certain parts of the network, or commuter buses were allowed to run on highway shoulders where space is available, the travel time for a commuter bus may be closer to the travel time of an off-peak car trip. Speeding up buses would have two

beneficial effects: (1) faster service is more attractive to commuters, encouraging more to switch from driving; and (2) buses that are not stuck in congestion will have fewer GHG emissions, thereby supporting greater GHG reductions.

3. **Potential of routing commuter buses to make stops in multiple towns rather than serving a single OD pair.** Many of the OD pairs that show potential for reducing GHG emissions are near one another or fall roughly in a line. There are certainly opportunities to increase the market size for new routes by stopping in more than one community. The key tradeoff is that each additional stop adds travel time for commuters already onboard the bus. It is likely that the most effective routes will add only one or two extra stops, thereby doubling or tripling the potential market size for ridership while adding minimal travel time. Analyzing the effectiveness of commuter bus routes with multiple stops may include design of new services and modifications of existing express commuter routes to include an additional stop for passengers.

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6.0 Appendices

6.1 Appendix A: Detailed Results for OD Pairs in the AM Peak

Table 6.1: Case 1A ($F = 0, c_v = 71$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WEYMOUTH	BOSTON CBD	14.56	5	0	283	-42241	-0.65%	855.39	-0.020
WINTHROP	BOSTON CBD	5.93	4	0	224	-22796	-1.19%	238.91	-0.010
WALTHAM	NEWTON	5.21	2	0	95	-20149	-0.74%	149.74	-0.007
WOBURN	BOSTON CBD	11.50	3	0	147	-19998	-0.65%	258.78	-0.013
WEYMOUTH	BRAINTREE	3.82	2	0	35	-19610	-0.88%	116.24	-0.006
NEWTON	CAMBRIDGE	6.98	4	0	207	-18248	-0.52%	340.95	-0.019
FRAMINGHAM	BOSTON CBD	20.46	3	0	146	-17919	-0.31%	472.88	-0.026
METHUEN	LAWRENCE	3.14	1	0	35	-16443	-0.80%	16.74	-0.001
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
WEYMOUTH	QUINCY	6.14	2	0	102	-13039	-0.52%	118.04	-0.009
WOBURN	BURLINGTON	3.61	2	0	33	-10757	-0.88%	104.83	-0.010
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
CHELMSFORD	LOWELL	4.63	1	0	21	-10248	-0.51%	19.80	-0.002
LAWRENCE	METHUEN	3.14	1	0	26	-9964	-0.63%	16.74	-0.002
LYNN	PEABODY	5.29	2	0	115	-9298	-0.62%	139.81	-0.015
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
BEVERLY	DANVERS	5.51	1	0	15	-8623	-0.53%	56.34	-0.007
ATTLEBORO	N. ATTLEBOR.	6.19	2	0	25	-8596	-0.37%	42.98	-0.005
DANVERS	BEVERLY	5.51	1	0	17	-7599	-0.48%	48.46	-0.006
WALTHAM	WATERTOWN	4.46	2	0	76	-7309	-0.57%	118.80	-0.016
LEXINGTON	WALTHAM	4.18	1	0	16	-7252	-0.47%	64.87	-0.009
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	230.57	-0.032
NEWTON	WATERTOWN	3.80	2	0	42	-7142	-0.62%	105.03	-0.015
N. ATTLEBOR.	ATTLEBORO	6.19	1	0	17	-6318	-0.30%	21.49	-0.003
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	65.44	-0.010
SALEM	PEABODY	5.22	1	0	35	-6242	-0.50%	55.95	-0.009
PEABODY	DANVERS	4.85	1	0	34	-6115	-0.46%	42.68	-0.007
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	66.62	-0.011
NEEDHAM	NEWTON	4.49	2	0	73	-5469	-0.34%	124.53	-0.023
WHITMAN	BROCKTON	4.46	2	0	20	-5366	-0.41%	73.91	-0.014
PEABODY	SALEM	5.22	2	0	83	-5332	-0.45%	127.93	-0.024
LAWRENCE	N. ANDOVER	4.46	2	0	27	-5261	-0.40%	37.57	-0.007
WEYMOUTH	HINGHAM	4.65	1	0	20	-4831	-0.29%	49.23	-0.010
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	309.35	-0.065
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	77.89	-0.017
BURLINGTON	WOBURN	3.61	1	0	14	-4334	-0.38%	60.30	-0.014
HUDSON	MARLBORO.	4.02	1	0	10	-4225	-0.38%	18.10	-0.004
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	103.79	-0.025
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	60.02	-0.015
CAMBRIDGE	WATERTOWN	3.43	2	0	117	-3956	-0.44%	111.41	-0.028
MEDFORD	SOMERVILLE	2.45	2	0	105	-3796	-0.50%	78.06	-0.021
BELMONT	WATERTOWN	3.23	2	0	43	-3716	-0.74%	64.02	-0.017
BELMONT	WALTHAM	3.91	2	0	79	-3645	-0.41%	110.04	-0.030
DANVERS	PEABODY	4.85	1	0	18	-3318	-0.31%	39.76	-0.012
NEEDHAM	WELLESLEY	3.48	2	0	26	-3248	-0.39%	59.53	-0.018
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	337.95	-0.109
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	82.98	-0.033
ARLINGTON	WATERTOWN	5.75	2	0	19	-2163	-0.26%	165.39	-0.076
MALDEN	MEDFORD	2.94	2	0	62	-2158	-0.28%	95.31	-0.044
MARBLEHEAD	SALEM	3.75	2	0	104	-2114	-0.34%	122.06	-0.058

Table 6.2: Case 1A ($F = 0, c_v = 71$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
METHUEN	LAWRENCE	3.14	1	0	35	-16443	-0.80%	16.74	-0.001
LAWRENCE	METHUEN	3.14	1	0	26	-9964	-0.63%	16.74	-0.002
CHELMSFORD	LOWELL	4.63	1	0	21	-10248	-0.51%	19.80	-0.002
N. ATTLEBOR.	ATTLEBORO	6.19	1	0	17	-6318	-0.30%	21.49	-0.003
HUDSON	MARLBORO.	4.02	1	0	10	-4225	-0.38%	18.10	-0.004
ATTLEBORO	N. ATTLEBOR.	6.19	2	0	25	-8596	-0.37%	42.98	-0.005
WEYMOUTH	BRAINTREE	3.82	2	0	35	-19610	-0.88%	116.24	-0.006
DANVERS	BEVERLY	5.51	1	0	17	-7599	-0.48%	48.46	-0.006
BEVERLY	DANVERS	5.51	1	0	15	-8623	-0.53%	56.34	-0.007
PEABODY	DANVERS	4.85	1	0	34	-6115	-0.46%	42.68	-0.007
LAWRENCE	N. ANDOVER	4.46	2	0	27	-5261	-0.40%	37.57	-0.007
WALTHAM	NEWTON	5.21	2	0	95	-20149	-0.74%	149.74	-0.007
LEXINGTON	WALTHAM	4.18	1	0	16	-7252	-0.47%	64.87	-0.009
SALEM	PEABODY	5.22	1	0	35	-6242	-0.50%	55.95	-0.009
WEYMOUTH	QUINCY	6.14	2	0	102	-13039	-0.52%	118.04	-0.009
WOBURN	BURLINGTON	3.61	2	0	33	-10757	-0.88%	104.83	-0.010
WEYMOUTH	HINGHAM	4.65	1	0	20	-4831	-0.29%	49.23	-0.010
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	65.44	-0.010
WINTHROP	BOSTON CBD	5.93	4	0	224	-22796	-1.19%	238.91	-0.010
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	66.62	-0.011
DANVERS	PEABODY	4.85	1	0	18	-3318	-0.31%	39.76	-0.012
WOBURN	BOSTON CBD	11.50	3	0	147	-19998	-0.65%	258.78	-0.013
WHITMAN	BROCKTON	4.46	2	0	20	-5366	-0.41%	73.91	-0.014
N. ANDOVER	LAWRENCE	4.46	1	0	14	-1360	-0.13%	18.79	-0.014
BURLINGTON	WOBURN	3.61	1	0	14	-4334	-0.38%	60.30	-0.014
NEWTON	WATERTOWN	3.80	2	0	42	-7142	-0.62%	105.03	-0.015
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	60.02	-0.015
LYNN	PEABODY	5.29	2	0	115	-9298	-0.62%	139.81	-0.015
WALTHAM	WATERTOWN	4.46	2	0	76	-7309	-0.57%	118.80	-0.016
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	77.89	-0.017
BELMONT	WATERTOWN	3.23	2	0	43	-3716	-0.74%	64.02	-0.017
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
NEEDHAM	WELLESLEY	3.48	2	0	26	-3248	-0.39%	59.53	-0.018
NEWTON	CAMBRIDGE	6.98	4	0	207	-18248	-0.52%	340.95	-0.019
WEYMOUTH	BOSTON CBD	14.56	5	0	283	-42241	-0.65%	855.39	-0.020
MEDFORD	SOMERVILLE	2.45	2	0	105	-3796	-0.50%	78.06	-0.021
NEEDHAM	NEWTON	4.49	2	0	73	-5469	-0.34%	124.53	-0.023
PEABODY	SALEM	5.22	2	0	83	-5332	-0.45%	127.93	-0.024
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	103.79	-0.025
FRAMINGHAM	BOSTON CBD	20.46	3	0	146	-17919	-0.31%	472.88	-0.026
CAMBRIDGE	WATERTOWN	3.43	2	0	117	-3956	-0.44%	111.41	-0.028
NORWOOD	WESTWOOD	2.22	1	0	27	-968	-0.15%	27.87	-0.029
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
BELMONT	WALTHAM	3.91	2	0	79	-3645	-0.41%	110.04	-0.030
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	230.57	-0.032
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	82.98	-0.033
BROCKTON	W. BRIDGEW.	4.77	1	0	9	-1512	-0.13%	59.10	-0.039
MALDEN	MEDFORD	2.94	2	0	62	-2158	-0.28%	95.31	-0.044
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	68.77	-0.049

Table 6.3: Case 2A ($F = 8, c_v = 71$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare (\$)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost (\$)	Efficiency (\$/gCO$_2$e)
METHUEN	LAWRENCE	3.14	1	8	29	-12908	-0.63%	-25.32	0.002
NEWTON	CAMBRIDGE	6.98	3	8	171	-11943	-0.34%	10.37	-0.001
WOBURN	BOSTON CBD	11.50	2	8	113	-9397	-0.31%	10.73	-0.001
WINTHROP	BOSTON CBD	5.93	4	8	198	-7933	-0.41%	-44.28	0.006
WEYMOUTH	BOSTON CBD	14.56	5	8	257	-7762	-0.12%	486.48	-0.063
CHELMSFORD	LOWELL	4.63	1	8	18	-7317	-0.36%	-5.54	0.001
LAWRENCE	METHUEN	3.14	1	8	22	-7274	-0.46%	-14.43	0.002
WOBURN	BURLINGTON	3.61	2	8	28	-6528	-0.53%	64.31	-0.010
WEYMOUTH	QUINCY	6.14	2	8	95	-6186	-0.25%	-18.36	0.003
WEYMOUTH	BRAINTREE	3.82	1	8	18	-6025	-0.27%	32.41	-0.005
BEVERLY	DANVERS	5.51	1	8	13	-5707	-0.35%	38.16	-0.007
DANVERS	BEVERLY	5.51	1	8	14	-4889	-0.31%	27.85	-0.006
BURLINGTON	WOBURN	3.61	2	8	23	-4705	-0.42%	88.00	-0.019
LEXINGTON	WALTHAM	4.18	1	8	14	-4616	-0.30%	45.26	-0.010
LYNN	PEABODY	5.29	2	8	109	-4414	-0.29%	-16.45	0.004
FRAMINGHAM	BOSTON CBD	20.46	2	8	112	-4397	-0.08%	155.34	-0.035
PEABODY	DANVERS	4.85	1	8	32	-3862	-0.29%	-2.63	0.001
SALEM	PEABODY	5.22	1	8	33	-3758	-0.30%	9.23	-0.002
N. ATTLEBOR.	ATTLEBORO	6.19	1	8	14	-3679	-0.17%	1.33	0.000
WALTHAM	NEWTON	5.21	1	8	50	-3659	-0.13%	3.11	-0.001
BROCKTON	EASTON	5.95	1	8	12	-3608	-0.16%	48.84	-0.014
ATTLEBORO	N. ATTLEBOR.	6.19	2	8	21	-3438	-0.15%	13.13	-0.004
BILLERICA	BURLINGTON	5.81	1	8	8	-2914	-0.14%	55.82	-0.019
NEWTON	WATERTOWN	3.80	2	8	37	-2802	-0.24%	52.54	-0.019
WEYMOUTH	HINGHAM	4.65	1	8	18	-2554	-0.15%	22.97	-0.009
HUDSON	MARLBORO.	4.02	1	8	9	-2431	-0.22%	5.59	-0.002
WALTHAM	WATERTOWN	4.46	2	8	66	-2278	-0.18%	23.94	-0.011
WALTHAM	LEXINGTON	4.18	1	8	11	-1940	-0.16%	44.96	-0.023
ACTON	CONCORD	4.33	1	8	9	-1786	-0.10%	90.75	-0.051
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	17.30	-0.012
LAWRENCE	N. ANDOVER	4.46	2	8	23	-1454	-0.11%	5.14	-0.004
ARLINGTON	WALTHAM	6.44	2	8	37	-1277	-0.09%	178.06	-0.139
WHITMAN	BROCKTON	4.46	2	8	17	-1109	-0.08%	49.62	-0.045
BELMONT	WATERTOWN	3.23	2	8	37	-1060	-0.21%	10.55	-0.010
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	29.52	-0.037
MEDFORD	SOMERVILLE	2.45	2	8	90	-768	-0.10%	-51.25	0.067
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	27.02	-0.080
WALPOLE	NORWOOD	5.16	2	8	23	-123	-0.01%	44.32	-0.360
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	6.78	-0.123
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-11.18	0.468

Table 6.4: Case 2A ($F = 8, c_v = 71$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-11.18	0.468
MEDFORD	SOMERVILLE	2.45	2	8	90	-768	-0.10%	-51.25	0.067
WINTHROP	BOSTON CBD	5.93	4	8	198	-7933	-0.41%	-44.28	0.006
LYNN	PEABODY	5.29	2	8	109	-4414	-0.29%	-16.45	0.004
WEYMOUTH	QUINCY	6.14	2	8	95	-6186	-0.25%	-18.36	0.003
LAWRENCE	METHUEN	3.14	1	8	22	-7274	-0.46%	-14.43	0.002
METHUEN	LAWRENCE	3.14	1	8	29	-12908	-0.63%	-25.32	0.002
CHELMSFORD	LOWELL	4.63	1	8	18	-7317	-0.36%	-5.54	0.001
PEABODY	DANVERS	4.85	1	8	32	-3862	-0.29%	-2.63	0.001
N. ATTLEBOR.	ATTLEBORO	6.19	1	8	14	-3679	-0.17%	1.33	0.000
WALTHAM	NEWTON	5.21	1	8	50	-3659	-0.13%	3.11	-0.001
NEWTON	CAMBRIDGE	6.98	3	8	171	-11943	-0.34%	10.37	-0.001
WOBURN	BOSTON CBD	11.50	2	8	113	-9397	-0.31%	10.73	-0.001
HUDSON	MARLBORO.	4.02	1	8	9	-2431	-0.22%	5.59	-0.002
SALEM	PEABODY	5.22	1	8	33	-3758	-0.30%	9.23	-0.002
LAWRENCE	N. ANDOVER	4.46	2	8	23	-1454	-0.11%	5.14	-0.004
ATTLEBORO	N. ATTLEBOR.	6.19	2	8	21	-3438	-0.15%	13.13	-0.004
WEYMOUTH	BRAINTREE	3.82	1	8	18	-6025	-0.27%	32.41	-0.005
DANVERS	BEVERLY	5.51	1	8	14	-4889	-0.31%	27.85	-0.006
BEVERLY	DANVERS	5.51	1	8	13	-5707	-0.35%	38.16	-0.007
WEYMOUTH	HINGHAM	4.65	1	8	18	-2554	-0.15%	22.97	-0.009
LEXINGTON	WALTHAM	4.18	1	8	14	-4616	-0.30%	45.26	-0.010
WOBURN	BURLINGTON	3.61	2	8	28	-6528	-0.53%	64.31	-0.010
BELMONT	WATERTOWN	3.23	2	8	37	-1060	-0.21%	10.55	-0.010
WALTHAM	WATERTOWN	4.46	2	8	66	-2278	-0.18%	23.94	-0.011
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	17.30	-0.012
BROCKTON	EASTON	5.95	1	8	12	-3608	-0.16%	48.84	-0.014
BURLINGTON	WOBURN	3.61	2	8	23	-4705	-0.42%	88.00	-0.019
NEWTON	WATERTOWN	3.80	2	8	37	-2802	-0.24%	52.54	-0.019
BILLERICA	BURLINGTON	5.81	1	8	8	-2914	-0.14%	55.82	-0.019
WALTHAM	LEXINGTON	4.18	1	8	11	-1940	-0.16%	44.96	-0.023
FRAMINGHAM	BOSTON CBD	20.46	2	8	112	-4397	-0.08%	155.34	-0.035
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	29.52	-0.037
WHITMAN	BROCKTON	4.46	2	8	17	-1109	-0.08%	49.62	-0.045
ACTON	CONCORD	4.33	1	8	9	-1786	-0.10%	90.75	-0.051
WEYMOUTH	BOSTON CBD	14.56	5	8	257	-7762	-0.12%	486.48	-0.063
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	27.02	-0.080
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	6.78	-0.123
ARLINGTON	WALTHAM	6.44	2	8	37	-1277	-0.09%	178.06	-0.139
WALPOLE	NORWOOD	5.16	2	8	23	-123	-0.01%	44.32	-0.360

Table 6.5: Case 3A ($F \leq 20, c_v = 71$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG ($gCO_{2}e$)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_{2}e$)
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	229.88	-0.016
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
BEVERLY	DANVERS	5.51	1	0	15	-8623	-0.53%	56.34	-0.007
WOBURN	BURLINGTON	3.61	2	4	30	-8560	-0.70%	83.01	-0.010
LEXINGTON	WALTHAM	4.18	1	0	16	-7252	-0.47%	64.87	-0.009
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	230.57	-0.032
NEWTON	WATERTOWN	3.80	2	0	42	-7142	-0.62%	105.03	-0.015
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	65.44	-0.010
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	66.62	-0.011
NEEDHAM	NEWTON	4.49	2	0	73	-5469	-0.34%	124.53	-0.023
WHITMAN	BROCKTON	4.46	2	0	20	-5366	-0.41%	73.91	-0.014
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	309.35	-0.065
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	77.89	-0.017
BURLINGTON	WOBURN	3.61	1	0	14	-4334	-0.38%	60.30	-0.014
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	103.79	-0.025
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	60.02	-0.015
BELMONT	WALTHAM	3.91	2	0	79	-3645	-0.41%	110.04	-0.030
NEEDHAM	WELLESLEY	3.48	2	0	26	-3248	-0.39%	59.53	-0.018
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	337.95	-0.109
DANVERS	BEVERLY	5.51	1	16	12	-2576	-0.16%	13.75	-0.005
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	82.98	-0.033
ARLINGTON	WATERTOWN	5.75	2	0	19	-2163	-0.26%	165.39	-0.076
MALDEN	MEDFORD	2.94	2	0	62	-2158	-0.28%	95.31	-0.044
CHELMSFORD	LOWELL	4.63	3	20	32	-2129	-0.11%	-53.63	0.025
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	558.70	-0.263
MARBLEHEAD	SALEM	3.75	2	0	104	-2114	-0.34%	122.06	-0.058
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	6.97	-0.004
BRAINTREE	QUINCY	4.05	2	0	80	-1820	-0.11%	109.06	-0.060
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-321.73	0.199
BROCKTON	W. BRIDGEW.	4.77	1	0	9	-1512	-0.13%	59.10	-0.039
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	17.30	-0.012
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	68.77	-0.049
WATERTOWN	NEWTON	3.80	2	0	44	-1385	-0.11%	105.28	-0.076
N. ANDOVER	LAWRENCE	4.46	1	0	14	-1360	-0.13%	18.79	-0.014
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	297.47	-0.226
SALEM	DANVERS	5.97	1	0	23	-1210	-0.13%	62.43	-0.052
HINGHAM	WEYMOUTH	4.65	2	0	19	-1120	-0.08%	136.60	-0.122
PEABODY	DANVERS	4.85	1	20	28	-1084	-0.08%	-58.91	0.054
MILTON	BOSTON	5.58	3	0	153	-1005	-0.02%	259.79	-0.258
NORWOOD	WESTWOOD	2.22	1	0	27	-968	-0.15%	27.87	-0.029
NEWTON	WALTHAM	5.21	2	0	50	-948	-0.03%	148.00	-0.156
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-1.54	0.002
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-81.53	0.090
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
ABINGTON	BROCKTON	5.29	1	0	9	-773	-0.06%	51.49	-0.067
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-47.58	0.068
WELLESLEY	NEWTON	4.88	2	0	51	-594	-0.04%	117.11	-0.197

Table 6.6: Case 3A ($F \leq 20, c_v = 71$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
MEDFORD	SOMERVILLE	2.45	2	10	87	-98	-0.01%	-77.35	0.786
LYNN	PEABODY	5.29	2	16	103	-237	-0.02%	-156.83	0.663
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-11.18	0.468
METHUEN	LAWRENCE	3.14	6	16	61	-190	-0.01%	-73.22	0.385
WALTHAM	NEWTON	5.21	3	20	82	-181	-0.01%	-69.44	0.383
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-134.83	0.363
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-165.58	0.362
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-321.73	0.199
WALTHAM	WATERTOWN	4.46	2	12	61	-94	-0.01%	-13.26	0.142
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-81.53	0.090
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-25.26	0.078
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-47.58	0.068
PEABODY	DANVERS	4.85	1	20	28	-1084	-0.08%	-58.91	0.054
HUDSON	MARLBORO.	4.02	2	16	13	-68	-0.01%	-2.34	0.034
ATTLEBORO	N. ATTLEBOR.	6.19	2	14	18	-88	0.00%	-2.67	0.030
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
CHELMSFORD	LOWELL	4.63	3	20	32	-2129	-0.11%	-53.63	0.025
WEYMOUTH	HINGHAM	4.65	1	18	16	-178	-0.01%	-2.82	0.016
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-1.34	0.002
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-1.54	0.002
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-0.51	0.001
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	6.97	-0.004
DANVERS	BEVERLY	5.51	1	16	12	-2576	-0.16%	13.75	-0.005
BEVERLY	DANVERS	5.51	1	0	15	-8623	-0.53%	56.34	-0.007
LEXINGTON	WALTHAM	4.18	1	0	16	-7252	-0.47%	64.87	-0.009
WOBURN	BURLINGTON	3.61	2	4	30	-8560	-0.70%	83.01	-0.010
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	65.44	-0.010
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	66.62	-0.011
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	17.30	-0.012
WHITMAN	BROCKTON	4.46	2	0	20	-5366	-0.41%	73.91	-0.014
N. ANDOVER	LAWRENCE	4.46	1	0	14	-1360	-0.13%	18.79	-0.014
BURLINGTON	WOBURN	3.61	1	0	14	-4334	-0.38%	60.30	-0.014
NEWTON	WATERTOWN	3.80	2	0	42	-7142	-0.62%	105.03	-0.015
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	60.02	-0.015
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	229.88	-0.016
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	77.89	-0.017
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	257.22	-0.018
NEEDHAM	WELLESLEY	3.48	2	0	26	-3248	-0.39%	59.53	-0.018
NEEDHAM	NEWTON	4.49	2	0	73	-5469	-0.34%	124.53	-0.023
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	209.96	-0.024
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	103.79	-0.025
NORWOOD	WESTWOOD	2.22	1	0	27	-968	-0.15%	27.87	-0.029
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	303.76	-0.029
BELMONT	WALTHAM	3.91	2	0	79	-3645	-0.41%	110.04	-0.030
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	230.57	-0.032
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	82.98	-0.033
BROCKTON	W. BRIDGEW.	4.77	1	0	9	-1512	-0.13%	59.10	-0.039
MALDEN	MEDFORD	2.94	2	0	62	-2158	-0.28%	95.31	-0.044
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	68.77	-0.049

Table 6.7: Case 4A ($F \in [6,20], c_v = 71$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
FRAMINGHAM	BOSTON CBD	20.46	2	6	115	-9366	-0.16%	191.27	-0.020
WOBURN	BURLINGTON	3.61	2	6	29	-7524	-0.61%	73.29	-0.010
BEVERLY	DANVERS	5.51	1	6	13	-6394	-0.39%	42.11	-0.007
BURLINGTON	WOBURN	3.61	2	6	24	-5616	-0.50%	95.14	-0.017
LEXINGTON	WALTHAM	4.18	1	6	14	-5236	-0.34%	49.61	-0.009
BROCKTON	EASTON	5.95	1	6	12	-4241	-0.19%	52.54	-0.012
NEWTON	WATERTOWN	3.80	2	6	38	-3818	-0.33%	64.17	-0.017
BILLERICA	BURLINGTON	5.81	1	6	8	-3664	-0.18%	58.15	-0.016
ARLINGTON	WALTHAM	6.44	2	6	38	-2655	-0.18%	189.83	-0.072
DANVERS	BEVERLY	5.51	1	16	12	-2576	-0.16%	13.75	-0.005
WALTHAM	LEXINGTON	4.18	1	6	11	-2428	-0.20%	48.27	-0.020
ACTON	CONCORD	4.33	1	6	9	-2333	-0.13%	93.64	-0.040
CHELMSFORD	LOWELL	4.63	3	20	32	-2129	-0.11%	-53.63	0.025
WHITMAN	BROCKTON	4.46	2	6	18	-2110	-0.16%	54.81	-0.026
NEEDHAM	NEWTON	4.49	2	6	68	-1889	-0.12%	51.45	-0.027
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	6.97	-0.004
NATICK	BOSTON CBD	16.37	2	6	72	-1852	-0.05%	180.30	-0.097
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-321.73	0.199
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	17.30	-0.012
WALPOLE	NORWOOD	5.16	2	6	24	-1164	-0.08%	51.74	-0.044
PEABODY	DANVERS	4.85	1	20	28	-1084	-0.08%	-58.91	0.054
NEEDHAM	WELLESLEY	3.48	2	6	24	-1024	-0.12%	34.19	-0.033
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-1.54	0.002
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-81.53	0.090
BELMONT	WALTHAM	3.91	2	6	74	-898	-0.10%	30.79	-0.034
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
MILFORD	BOSTON CBD	31.16	1	6	10	-762	-0.02%	198.82	-0.261
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-47.58	0.068
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-1.34	0.002
BILLERICA	LOWELL	6.58	1	6	20	-576	-0.03%	61.30	-0.106
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-0.51	0.001
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-165.58	0.362
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-134.83	0.363
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-25.26	0.078
LYNN	PEABODY	5.29	2	16	103	-237	-0.02%	-156.83	0.663
METHUEN	LAWRENCE	3.14	6	16	61	-190	-0.01%	-73.22	0.385
WALTHAM	NEWTON	5.21	3	20	82	-181	-0.01%	-69.44	0.383
WEYMOUTH	HINGHAM	4.65	1	18	16	-178	-0.01%	-2.82	0.016
BROCKTON	W. BRIDGEW.	4.77	1	6	8	-176	-0.02%	50.97	-0.290
N. ANDOVER	LAWRENCE	4.46	1	6	12	-115	-0.01%	5.76	-0.050
MEDFORD	SOMERVILLE	2.45	2	10	87	-98	-0.01%	-77.35	0.786
WALTHAM	WATERTOWN	4.46	2	12	61	-94	-0.01%	-13.26	0.142
ATTLEBORO	N. ATTLEBOR.	6.19	2	14	18	-88	0.00%	-2.67	0.030
HUDSON	MARLBORO.	4.02	2	16	13	-68	-0.01%	-2.34	0.034
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-11.18	0.468
NORWOOD	WESTWOOD	2.22	1	6	25	-23	0.00%	1.08	-0.047

Table 6.8: Case 4A ($F \in [6, 20], c_v = 71$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
MEDFORD	SOMERVILLE	2.45	2	10	87	-98	-0.01%	-77.35	0.786
LYNN	PEABODY	5.29	2	16	103	-237	-0.02%	-156.83	0.663
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-11.18	0.468
METHUEN	LAWRENCE	3.14	6	16	61	-190	-0.01%	-73.22	0.385
WALTHAM	NEWTON	5.21	3	20	82	-181	-0.01%	-69.44	0.383
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-134.83	0.363
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-165.58	0.362
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-321.73	0.199
WALTHAM	WATERTOWN	4.46	2	12	61	-94	-0.01%	-13.26	0.142
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-83.85	0.098
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-81.53	0.090
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-25.26	0.078
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-47.58	0.068
PEABODY	DANVERS	4.85	1	20	28	-1084	-0.08%	-58.91	0.054
HUDSON	MARLBORO.	4.02	2	16	13	-68	-0.01%	-2.34	0.034
ATTLEBORO	N. ATTLEBOR.	6.19	2	14	18	-88	0.00%	-2.67	0.030
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-45.04	0.028
CHELMSFORD	LOWELL	4.63	3	20	32	-2129	-0.11%	-53.63	0.025
WEYMOUTH	HINGHAM	4.65	1	18	16	-178	-0.01%	-2.82	0.016
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-1.34	0.002
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-1.54	0.002
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-0.51	0.001
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	6.97	-0.004
DANVERS	BEVERLY	5.51	1	16	12	-2576	-0.16%	13.75	-0.005
BEVERLY	DANVERS	5.51	1	6	13	-6394	-0.39%	42.11	-0.007
LEXINGTON	WALTHAM	4.18	1	6	14	-5236	-0.34%	49.61	-0.009
WOBURN	BURLINGTON	3.61	2	6	29	-7524	-0.61%	73.29	-0.010
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	17.30	-0.012
BROCKTON	EASTON	5.95	1	6	12	-4241	-0.19%	52.54	-0.012
BILLERICA	BURLINGTON	5.81	1	6	8	-3664	-0.18%	58.15	-0.016
NEWTON	WATERTOWN	3.80	2	6	38	-3818	-0.33%	64.17	-0.017
BURLINGTON	WOBURN	3.61	2	6	24	-5616	-0.50%	95.14	-0.017
WALTHAM	LEXINGTON	4.18	1	6	11	-2428	-0.20%	48.27	-0.020
FRAMINGHAM	BOSTON CBD	20.46	2	6	115	-9366	-0.16%	191.27	-0.020
WHITMAN	BROCKTON	4.46	2	6	18	-2110	-0.16%	54.81	-0.026
NEEDHAM	NEWTON	4.49	2	6	68	-1889	-0.12%	51.45	-0.027
NEEDHAM	WELLESLEY	3.48	2	6	24	-1024	-0.12%	34.19	-0.033
BELMONT	WALTHAM	3.91	2	6	74	-898	-0.10%	30.79	-0.034
ACTON	CONCORD	4.33	1	6	9	-2333	-0.13%	93.64	-0.040
WALPOLE	NORWOOD	5.16	2	6	24	-1164	-0.08%	51.74	-0.044
NORWOOD	WESTWOOD	2.22	1	6	25	-23	0.00%	1.08	-0.047
N. ANDOVER	LAWRENCE	4.46	1	6	12	-115	-0.01%	5.76	-0.050
ARLINGTON	WALTHAM	6.44	2	6	38	-2655	-0.18%	189.83	-0.072
NATICK	BOSTON CBD	16.37	2	6	72	-1852	-0.05%	180.30	-0.097
BILLERICA	LOWELL	6.58	1	6	20	-576	-0.03%	61.30	-0.106
MILFORD	BOSTON CBD	31.16	1	6	10	-762	-0.02%	198.82	-0.261
BROCKTON	W. BRIDGEW.	4.77	1	6	8	-176	-0.02%	50.97	-0.290

Table 6.9: Case 5A ($\Delta F = 0, c_v = 71$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WINTHROP	BOSTON CBD	5.93	4	0.41	217	-18323	-0.96%	151.03	-0.008
METHUEN	LAWRENCE	3.14	1	0.00	35	-16443	-0.80%	16.74	-0.001
WEYMOUTH	BRAINTREE	3.82	2	0.80	33	-15941	-0.72%	90.20	-0.006
WALTHAM	NEWTON	5.21	2	1.03	88	-14457	-0.53%	59.90	-0.004
NEWTON	CAMBRIDGE	6.98	3	1.44	172	-11963	-0.34%	8.26	-0.001
WOBURN	BOSTON CBD	11.50	2	1.25	115	-10999	-0.36%	29.39	-0.003
CHELMSFORD	LOWELL	4.63	1	0.00	21	-10248	-0.51%	19.80	-0.002
LAWRENCE	METHUEN	3.14	1	0.00	26	-9964	-0.63%	16.74	-0.002
WOBURN	BURLINGTON	3.61	2	0.64	31	-8772	-0.71%	85.05	-0.010
WEYMOUTH	QUINCY	6.14	2	0.87	98	-8763	-0.35%	33.15	-0.004
ATTLEBORO	N. ATTLEBOR.	6.19	2	0.00	25	-8596	-0.37%	42.98	-0.005
BEVERLY	DANVERS	5.51	1	0.89	14	-6762	-0.41%	44.32	-0.007
WALTHAM	WATERTOWN	4.46	2	0.18	75	-6619	-0.52%	105.19	-0.016
LYNN	PEABODY	5.29	2	0.76	112	-6610	-0.44%	54.84	-0.008
BURLINGTON	WOBURN	3.61	2	0.71	25	-6588	-0.58%	103.13	-0.016
DANVERS	BEVERLY	5.51	1	0.57	16	-6462	-0.41%	39.31	-0.006
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	17	-6318	-0.30%	21.49	-0.003
LEXINGTON	WALTHAM	4.18	1	0.67	15	-5966	-0.39%	54.95	-0.009
PEABODY	DANVERS	4.85	1	0.30	34	-5616	-0.43%	32.66	-0.006
LAWRENCE	N. ANDOVER	4.46	2	0.00	27	-5261	-0.40%	37.57	-0.007
NEWTON	WATERTOWN	3.80	2	0.60	40	-5232	-0.45%	81.04	-0.015
SALEM	PEABODY	5.22	1	0.92	34	-4605	-0.37%	25.12	-0.005
NEEDHAM	NEWTON	4.49	2	0.27	72	-4513	-0.28%	104.85	-0.023
HUDSON	MARLBORO.	4.02	1	0.00	10	-4225	-0.38%	18.10	-0.004
WHITMAN	BROCKTON	4.46	2	0.39	19	-4146	-0.31%	66.36	-0.016
BILLERICA	BURLINGTON	5.81	1	0.87	8	-4106	-0.20%	59.58	-0.015
WALPOLE	NORWOOD	5.16	2	0.16	27	-4032	-0.27%	73.64	-0.018
BROCKTON	EASTON	5.95	1	1.28	12	-3884	-0.17%	50.44	-0.013
PEABODY	SALEM	5.22	2	0.55	80	-3684	-0.31%	83.63	-0.023
WEYMOUTH	HINGHAM	4.65	1	0.72	19	-3639	-0.22%	35.32	-0.010
MEDFORD	SOMERVILLE	2.45	2	0.21	102	-3324	-0.44%	56.89	-0.017
WALTHAM	LEXINGTON	4.18	1	0.63	11	-3066	-0.26%	52.83	-0.017
BELMONT	WATERTOWN	3.23	2	0.33	41	-3057	-0.61%	50.14	-0.016
DANVERS	PEABODY	4.85	1	0.37	17	-2817	-0.26%	33.49	-0.012
NEEDHAM	WELLESLEY	3.48	2	0.31	26	-2572	-0.31%	51.52	-0.020
BELMONT	WALTHAM	3.91	2	0.57	76	-2139	-0.24%	66.44	-0.031
ACTON	CONCORD	4.33	1	1.24	9	-2076	-0.11%	92.27	-0.044
ARLINGTON	WALTHAM	6.44	2	1.38	37	-1567	-0.11%	179.32	-0.114
N. ANDOVER	LAWRENCE	4.46	1	0.00	14	-1360	-0.13%	18.79	-0.014
CAMBRIDGE	WATERTOWN	3.43	2	0.93	107	-1281	-0.14%	11.92	-0.009
NORWOOD	WESTWOOD	2.22	1	0.20	26	-785	-0.12%	22.70	-0.029
WEYMOUTH	BOSTON CBD	14.56	4	3.32	227	-769	-0.01%	-69.65	0.091
MALDEN	MEDFORD	2.94	2	0.66	58	-640	-0.08%	57.24	-0.089
BEVERLY	PEABODY	8.34	1	0.54	10	-456	-0.03%	63.29	-0.139
MARBLEHEAD	SALEM	3.75	2	0.88	99	-268	-0.04%	35.09	-0.131
FRAMINGHAM	BOSTON CBD	20.46	2	1.75	108	-266	0.00%	124.86	-0.470
GLOUCESTER	BEVERLY	10.14	2	0.00	57	-247	-0.01%	55.29	-0.224
BILLERICA	LOWELL	6.58	1	1.29	20	-228	-0.01%	57.40	-0.252
LAWRENCE	ANDOVER	4.80	2	0.00	29	-95	-0.01%	56.91	-0.598

Table 6.10: Case 5A ($\Delta F = 0, c_v = 71$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WEYMOUTH	BOSTON CBD	14.56	4	3.32	227	-769	-0.01%	-69.65	0.091
NEWTON	CAMBRIDGE	6.98	3	1.44	172	-11963	-0.34%	8.26	-0.001
METHUEN	LAWRENCE	3.14	1	0.00	35	-16443	-0.80%	16.74	-0.001
LAWRENCE	METHUEN	3.14	1	0.00	26	-9964	-0.63%	16.74	-0.002
CHELMSFORD	LOWELL	4.63	1	0.00	21	-10248	-0.51%	19.80	-0.002
WOBURN	BOSTON CBD	11.50	2	1.25	115	-10999	-0.36%	29.39	-0.003
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	17	-6318	-0.30%	21.49	-0.003
WEYMOUTH	QUINCY	6.14	2	0.87	98	-8763	-0.35%	33.15	-0.004
WALTHAM	NEWTON	5.21	2	1.03	88	-14457	-0.53%	59.90	-0.004
HUDSON	MARLBORO.	4.02	1	0.00	10	-4225	-0.38%	18.10	-0.004
ATTLEBORO	N. ATTLEBOR.	6.19	2	0.00	25	-8596	-0.37%	42.98	-0.005
SALEM	PEABODY	5.22	1	0.92	34	-4605	-0.37%	25.12	-0.005
WEYMOUTH	BRAINTREE	3.82	2	0.80	33	-15941	-0.72%	90.20	-0.006
PEABODY	DANVERS	4.85	1	0.30	34	-5616	-0.43%	32.66	-0.006
DANVERS	BEVERLY	5.51	1	0.57	16	-6462	-0.41%	39.31	-0.006
BEVERLY	DANVERS	5.51	1	0.89	14	-6762	-0.41%	44.32	-0.007
LAWRENCE	N. ANDOVER	4.46	2	0.00	27	-5261	-0.40%	37.57	-0.007
WINTHROP	BOSTON CBD	5.93	4	0.41	217	-18323	-0.96%	151.03	-0.008
LYNN	PEABODY	5.29	2	0.76	112	-6610	-0.44%	54.84	-0.008
LEXINGTON	WALTHAM	4.18	1	0.67	15	-5966	-0.39%	54.95	-0.009
CAMBRIDGE	WATERTOWN	3.43	2	0.93	107	-1281	-0.14%	11.92	-0.009
WOBURN	BURLINGTON	3.61	2	0.64	31	-8772	-0.71%	85.05	-0.010
WEYMOUTH	HINGHAM	4.65	1	0.72	19	-3639	-0.22%	35.32	-0.010
DANVERS	PEABODY	4.85	1	0.37	17	-2817	-0.26%	33.49	-0.012
BROCKTON	EASTON	5.95	1	1.28	12	-3884	-0.17%	50.44	-0.013
N. ANDOVER	LAWRENCE	4.46	1	0.00	14	-1360	-0.13%	18.79	-0.014
BILLERICA	BURLINGTON	5.81	1	0.87	8	-4106	-0.20%	59.58	-0.015
NEWTON	WATERTOWN	3.80	2	0.60	40	-5232	-0.45%	81.04	-0.015
BURLINGTON	WOBURN	3.61	2	0.71	25	-6588	-0.58%	103.13	-0.016
WALTHAM	WATERTOWN	4.46	2	0.18	75	-6619	-0.52%	105.19	-0.016
WHITMAN	BROCKTON	4.46	2	0.39	19	-4146	-0.31%	66.36	-0.016
BELMONT	WATERTOWN	3.23	2	0.33	41	-3057	-0.61%	50.14	-0.016
MEDFORD	SOMERVILLE	2.45	2	0.21	102	-3324	-0.44%	56.89	-0.017
WALTHAM	LEXINGTON	4.18	1	0.63	11	-3066	-0.26%	52.83	-0.017
WALPOLE	NORWOOD	5.16	2	0.16	27	-4032	-0.27%	73.64	-0.018
NEEDHAM	WELLESLEY	3.48	2	0.31	26	-2572	-0.31%	51.52	-0.020
PEABODY	SALEM	5.22	2	0.55	80	-3684	-0.31%	83.63	-0.023
NEEDHAM	NEWTON	4.49	2	0.27	72	-4513	-0.28%	104.85	-0.023
NORWOOD	WESTWOOD	2.22	1	0.20	26	-785	-0.12%	22.70	-0.029
BELMONT	WALTHAM	3.91	2	0.57	76	-2139	-0.24%	66.44	-0.031
ACTON	CONCORD	4.33	1	1.24	9	-2076	-0.11%	92.27	-0.044
MALDEN	MEDFORD	2.94	2	0.66	58	-640	-0.08%	57.24	-0.089
ARLINGTON	WALTHAM	6.44	2	1.38	37	-1567	-0.11%	179.32	-0.114
MARBLEHEAD	SALEM	3.75	2	0.88	99	-268	-0.04%	35.09	-0.131
BEVERLY	PEABODY	8.34	1	0.54	10	-456	-0.03%	63.29	-0.139
GLOUCESTER	BEVERLY	10.14	2	0.00	57	-247	-0.01%	55.29	-0.224
BILLERICA	LOWELL	6.58	1	1.29	20	-228	-0.01%	57.40	-0.252
FRAMINGHAM	BOSTON CBD	20.46	2	1.75	108	-266	0.00%	124.86	-0.470
LAWRENCE	ANDOVER	4.80	2	0.00	29	-95	-0.01%	56.91	-0.598

Table 6.11: Case 1B ($F = 0, c_v = 0$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
WEYMOUTH	BOSTON CBD	14.56	5	0	283	-42241	-0.65%	566.90	-0.013
WINTHROP	BOSTON CBD	5.93	4	0	224	-22796	-1.19%	139.95	-0.006
WALTHAM	NEWTON	5.21	2	0	95	-20149	-0.74%	92.22	-0.005
WOBURN	BOSTON CBD	11.50	3	0	147	-19998	-0.65%	169.36	-0.008
WEYMOUTH	BRAINTREE	3.82	2	0	35	-19610	-0.88%	61.52	-0.003
NEWTON	CAMBRIDGE	6.98	4	0	207	-18248	-0.52%	212.94	-0.012
FRAMINGHAM	BOSTON CBD	20.46	3	0	146	-17919	-0.31%	330.22	-0.018
METHUEN	LAWRENCE	3.14	1	0	35	-16443	-0.80%	4.90	0.000
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	177.17	-0.012
WEYMOUTH	QUINCY	6.14	2	0	102	-13039	-0.52%	68.00	-0.005
WOBURN	BURLINGTON	3.61	2	0	33	-10757	-0.88%	56.99	-0.005
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	202.86	-0.019
CHELMSFORD	LOWELL	4.63	1	0	21	-10248	-0.51%	7.22	-0.001
LAWRENCE	METHUEN	3.14	1	0	26	-9964	-0.63%	4.90	0.000
LYNN	PEABODY	5.29	2	0	115	-9298	-0.62%	86.02	-0.009
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	150.86	-0.017
BEVERLY	DANVERS	5.51	1	0	15	-8623	-0.53%	34.57	-0.004
ATTLEBORO	N. ATTLEBOR.	6.19	2	0	25	-8596	-0.37%	19.31	-0.002
DANVERS	BEVERLY	5.51	1	0	17	-7599	-0.48%	26.69	-0.004
WALTHAM	WATERTOWN	4.46	2	0	76	-7309	-0.57%	69.94	-0.010
LEXINGTON	WALTHAM	4.18	1	0	16	-7252	-0.47%	39.34	-0.005
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	149.65	-0.021
NEWTON	WATERTOWN	3.80	2	0	42	-7142	-0.62%	59.73	-0.008
N. ATTLEBOR.	ATTLEBORO	6.19	1	0	17	-6318	-0.30%	9.65	-0.002
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	44.06	-0.007
SALEM	PEABODY	5.22	1	0	35	-6242	-0.50%	31.69	-0.005
PEABODY	DANVERS	4.85	1	0	34	-6115	-0.46%	24.06	-0.004
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	42.55	-0.007
NEEDHAM	NEWTON	4.49	2	0	73	-5469	-0.34%	73.95	-0.014
WHITMAN	BROCKTON	4.46	2	0	20	-5366	-0.41%	32.19	-0.006
PEABODY	SALEM	5.22	2	0	83	-5332	-0.45%	79.42	-0.015
LAWRENCE	N. ANDOVER	4.46	2	0	27	-5261	-0.40%	13.91	-0.003
WEYMOUTH	HINGHAM	4.65	1	0	20	-4831	-0.29%	25.07	-0.005
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	213.05	-0.045
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	42.44	-0.009
BURLINGTON	WOBURN	3.61	1	0	14	-4334	-0.38%	36.38	-0.008
HUDSON	MARLBORO.	4.02	1	0	10	-4225	-0.38%	6.27	-0.001
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	66.62	-0.016
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	34.48	-0.009
CAMBRIDGE	WATERTOWN	3.43	2	0	117	-3956	-0.44%	65.01	-0.016
MEDFORD	SOMERVILLE	2.45	2	0	105	-3796	-0.50%	39.65	-0.010
BELMONT	WATERTOWN	3.23	2	0	43	-3716	-0.74%	30.53	-0.008
BELMONT	WALTHAM	3.91	2	0	79	-3645	-0.41%	62.54	-0.017
DANVERS	PEABODY	4.85	1	0	18	-3318	-0.31%	21.14	-0.006
NEEDHAM	WELLESLEY	3.48	2	0	26	-3248	-0.39%	27.73	-0.009
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	220.80	-0.071
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	56.51	-0.023
ARLINGTON	WATERTOWN	5.75	2	0	19	-2163	-0.26%	102.04	-0.047
MALDEN	MEDFORD	2.94	2	0	62	-2158	-0.28%	51.81	-0.024
MARBLEHEAD	SALEM	3.75	2	0	104	-2114	-0.34%	71.26	-0.034

Table 6.12: Case 1B ($F = 0, c_v = 0$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
METHUEN	LAWRENCE	3.14	1	0	35	-16443	-0.80%	4.90	0.000
LAWRENCE	METHUEN	3.14	1	0	26	-9964	-0.63%	4.90	0.000
CHELMSFORD	LOWELL	4.63	1	0	21	-10248	-0.51%	7.22	-0.001
HUDSON	MARLBORO.	4.02	1	0	10	-4225	-0.38%	6.27	-0.001
N. ATTLEBOR.	ATTLEBORO	6.19	1	0	17	-6318	-0.30%	9.65	-0.002
ATTLEBORO	N. ATTLEBOR.	6.19	2	0	25	-8596	-0.37%	19.31	-0.002
LAWRENCE	N. ANDOVER	4.46	2	0	27	-5261	-0.40%	13.91	-0.003
WEYMOUTH	BRAINTREE	3.82	2	0	35	-19610	-0.88%	61.52	-0.003
DANVERS	BEVERLY	5.51	1	0	17	-7599	-0.48%	26.69	-0.004
PEABODY	DANVERS	4.85	1	0	34	-6115	-0.46%	24.06	-0.004
BEVERLY	DANVERS	5.51	1	0	15	-8623	-0.53%	34.57	-0.004
WALTHAM	NEWTON	5.21	2	0	95	-20149	-0.74%	92.22	-0.005
SALEM	PEABODY	5.22	1	0	35	-6242	-0.50%	31.69	-0.005
N. ANDOVER	LAWRENCE	4.46	1	0	14	-1360	-0.13%	6.95	-0.005
WEYMOUTH	HINGHAM	4.65	1	0	20	-4831	-0.29%	25.07	-0.005
WEYMOUTH	QUINCY	6.14	2	0	102	-13039	-0.52%	68.00	-0.005
WOBURN	BURLINGTON	3.61	2	0	33	-10757	-0.88%	56.99	-0.005
LEXINGTON	WALTHAM	4.18	1	0	16	-7252	-0.47%	39.34	-0.005
WHITMAN	BROCKTON	4.46	2	0	20	-5366	-0.41%	32.19	-0.006
WINTHROP	BOSTON CBD	5.93	4	0	224	-22796	-1.19%	139.95	-0.006
DANVERS	PEABODY	4.85	1	0	18	-3318	-0.31%	21.14	-0.006
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	42.55	-0.007
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	44.06	-0.007
BELMONT	WATERTOWN	3.23	2	0	43	-3716	-0.74%	30.53	-0.008
NEWTON	WATERTOWN	3.80	2	0	42	-7142	-0.62%	59.73	-0.008
BURLINGTON	WOBURN	3.61	1	0	14	-4334	-0.38%	36.38	-0.008
WOBURN	BOSTON CBD	11.50	3	0	147	-19998	-0.65%	169.36	-0.008
NEEDHAM	WELLESLEY	3.48	2	0	26	-3248	-0.39%	27.73	-0.009
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	34.48	-0.009
LYNN	PEABODY	5.29	2	0	115	-9298	-0.62%	86.02	-0.009
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	42.44	-0.009
WALTHAM	WATERTOWN	4.46	2	0	76	-7309	-0.57%	69.94	-0.010
MEDFORD	SOMERVILLE	2.45	2	0	105	-3796	-0.50%	39.65	-0.010
NEWTON	CAMBRIDGE	6.98	4	0	207	-18248	-0.52%	212.94	-0.012
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	177.17	-0.012
NORWOOD	WESTWOOD	2.22	1	0	27	-968	-0.15%	12.02	-0.012
WEYMOUTH	BOSTON CBD	14.56	5	0	283	-42241	-0.65%	566.90	-0.013
NEEDHAM	NEWTON	4.49	2	0	73	-5469	-0.34%	73.95	-0.014
PEABODY	SALEM	5.22	2	0	83	-5332	-0.45%	79.42	-0.015
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	66.62	-0.016
CAMBRIDGE	WATERTOWN	3.43	2	0	117	-3956	-0.44%	65.01	-0.016
BELMONT	WALTHAM	3.91	2	0	79	-3645	-0.41%	62.54	-0.017
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	150.86	-0.017
FRAMINGHAM	BOSTON CBD	20.46	3	0	146	-17919	-0.31%	330.22	-0.018
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	202.86	-0.019
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	149.65	-0.021
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	56.51	-0.023
MALDEN	MEDFORD	2.94	2	0	62	-2158	-0.28%	51.81	-0.024
BROCKTON	W. BRIDGEW.	4.77	1	0	9	-1512	-0.13%	39.17	-0.026
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	39.73	-0.028

Table 6.13: Case 2B ($F = 8, c_v = 0$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WINTHROP	BOSTON CBD	5.93	4	8	198	-7933	-0.41%	-143.24	0.018
WEYMOUTH	BOSTON CBD	14.56	5	8	257	-7762	-0.12%	197.99	-0.026
WEYMOUTH	BRAINTREE	3.82	1	8	18	-6025	-0.27%	5.05	-0.001
BEVERLY	DANVERS	5.51	1	8	13	-5707	-0.35%	16.39	-0.003
DANVERS	BEVERLY	5.51	1	8	14	-4889	-0.31%	6.08	-0.001
BURLINGTON	WOBURN	3.61	2	8	23	-4705	-0.42%	40.17	-0.009
LEXINGTON	WALTHAM	4.18	1	8	14	-4616	-0.30%	19.73	-0.004
FRAMINGHAM	BOSTON CBD	20.46	2	8	112	-4397	-0.08%	60.23	-0.014
PEABODY	DANVERS	4.85	1	8	32	-3862	-0.29%	-21.24	0.006
SALEM	PEABODY	5.22	1	8	33	-3758	-0.30%	-15.03	0.004
CHELMSFORD	LOWELL	4.63	4	8	43	-3728	-0.19%	-32.92	0.009
WALTHAM	NEWTON	5.21	1	8	50	-3659	-0.13%	-25.65	0.007
BROCKTON	EASTON	5.95	1	8	12	-3608	-0.16%	27.46	-0.008
WOBURN	BOSTON CBD	11.50	3	8	131	-3490	-0.11%	-18.94	0.005
NEWTON	CAMBRIDGE	6.98	4	8	182	-3242	-0.09%	-47.31	0.015
BILLERICA	BURLINGTON	5.81	1	8	8	-2914	-0.14%	31.76	-0.011
WOBURN	BURLINGTON	3.61	1	8	16	-2913	-0.24%	5.52	-0.002
HUDSON	MARLBORO.	4.02	2	8	16	-2811	-0.25%	-10.03	0.004
NEWTON	WATERTOWN	3.80	2	8	37	-2802	-0.24%	7.24	-0.003
WEYMOUTH	HINGHAM	4.65	1	8	18	-2554	-0.15%	-1.19	0.000
WALTHAM	WATERTOWN	4.46	2	8	66	-2278	-0.18%	-24.92	0.011
LAWRENCE	METHUEN	3.14	5	8	53	-2063	-0.13%	-51.16	0.025
WALTHAM	LEXINGTON	4.18	1	8	11	-1940	-0.16%	19.42	-0.010
ACTON	CONCORD	4.33	1	8	9	-1786	-0.10%	53.57	-0.030
WEYMOUTH	QUINCY	6.14	3	8	104	-1676	-0.07%	-47.08	0.028
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	-1.32	0.001
ARLINGTON	WALTHAM	6.44	2	8	37	-1277	-0.09%	97.15	-0.076
WHITMAN	BROCKTON	4.46	2	8	17	-1109	-0.08%	7.91	-0.007
BELMONT	WATERTOWN	3.23	2	8	37	-1060	-0.21%	-22.95	0.022
ATTLEBORO	N. ATTLEBOR.	6.19	1	8	10	-1043	-0.05%	-5.22	0.005
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	-21.06	0.027
MEDFORD	SOMERVILLE	2.45	2	8	90	-768	-0.10%	-89.66	0.117
N. ATTLEBOR.	ATTLEBORO	6.19	3	8	32	-614	-0.03%	-16.55	0.027
METHUEN	LAWRENCE	3.14	7	8	71	-548	-0.03%	-67.61	0.123
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	-4.78	0.014
LAWRENCE	N. ANDOVER	4.46	1	8	12	-310	-0.02%	-10.15	0.033
LYNN	PEABODY	5.29	3	8	116	-169	-0.01%	-37.43	0.221
WALPOLE	NORWOOD	5.16	2	8	23	-123	-0.01%	8.88	-0.072
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	-40.72	0.738
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-35.44	1.483

Table 6.14: Case 2B ($F = 8, c_v = 0$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-35.44	1.483
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	-40.72	0.738
LYNN	PEABODY	5.29	3	8	116	-169	-0.01%	-37.43	0.221
METHUEN	LAWRENCE	3.14	7	8	71	-548	-0.03%	-67.61	0.123
MEDFORD	SOMERVILLE	2.45	2	8	90	-768	-0.10%	-89.66	0.117
LAWRENCE	N. ANDOVER	4.46	1	8	12	-310	-0.02%	-10.15	0.033
WEYMOUTH	QUINCY	6.14	3	8	104	-1676	-0.07%	-47.08	0.028
N. ATTLEBOR.	ATTLEBORO	6.19	3	8	32	-614	-0.03%	-16.55	0.027
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	-21.06	0.027
LAWRENCE	METHUEN	3.14	5	8	53	-2063	-0.13%	-51.16	0.025
BELMONT	WATERTOWN	3.23	2	8	37	-1060	-0.21%	-22.95	0.022
WINTHROP	BOSTON CBD	5.93	4	8	198	-7933	-0.41%	-143.24	0.018
NEWTON	CAMBRIDGE	6.98	4	8	182	-3242	-0.09%	-47.31	0.015
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	-4.78	0.014
WALTHAM	WATERTOWN	4.46	2	8	66	-2278	-0.18%	-24.92	0.011
CHELMSFORD	LOWELL	4.63	4	8	43	-3728	-0.19%	-32.92	0.009
WALTHAM	NEWTON	5.21	1	8	50	-3659	-0.13%	-25.65	0.007
PEABODY	DANVERS	4.85	1	8	32	-3862	-0.29%	-21.24	0.006
WOBURN	BOSTON CBD	11.50	3	8	131	-3490	-0.11%	-18.94	0.005
ATTLEBORO	N. ATTLEBOR.	6.19	1	8	10	-1043	-0.05%	-5.22	0.005
SALEM	PEABODY	5.22	1	8	33	-3758	-0.30%	-15.03	0.004
HUDSON	MARLBORO.	4.02	2	8	16	-2811	-0.25%	-10.03	0.004
DANVERS	PEABODY	4.85	1	8	16	-1472	-0.14%	-1.32	0.001
WEYMOUTH	HINGHAM	4.65	1	8	18	-2554	-0.15%	-1.19	0.000
WEYMOUTH	BRAINTREE	3.82	1	8	18	-6025	-0.27%	5.05	-0.001
DANVERS	BEVERLY	5.51	1	8	14	-4889	-0.31%	6.08	-0.001
WOBURN	BURLINGTON	3.61	1	8	16	-2913	-0.24%	5.52	-0.002
NEWTON	WATERTOWN	3.80	2	8	37	-2802	-0.24%	7.24	-0.003
BEVERLY	DANVERS	5.51	1	8	13	-5707	-0.35%	16.39	-0.003
LEXINGTON	WALTHAM	4.18	1	8	14	-4616	-0.30%	19.73	-0.004
WHITMAN	BROCKTON	4.46	2	8	17	-1109	-0.08%	7.91	-0.007
BROCKTON	EASTON	5.95	1	8	12	-3608	-0.16%	27.46	-0.008
BURLINGTON	WOBURN	3.61	2	8	23	-4705	-0.42%	40.17	-0.009
WALTHAM	LEXINGTON	4.18	1	8	11	-1940	-0.16%	19.42	-0.010
BILLERICA	BURLINGTON	5.81	1	8	8	-2914	-0.14%	31.76	-0.011
FRAMINGHAM	BOSTON CBD	20.46	2	8	112	-4397	-0.08%	60.23	-0.014
WEYMOUTH	BOSTON CBD	14.56	5	8	257	-7762	-0.12%	197.99	-0.026
ACTON	CONCORD	4.33	1	8	9	-1786	-0.10%	53.57	-0.030
WALPOLE	NORWOOD	5.16	2	8	23	-123	-0.01%	8.88	-0.072
ARLINGTON	WALTHAM	6.44	2	8	37	-1277	-0.09%	97.15	-0.076

Table 6.15: Case 3B ($F \leq 20, c_v = 0$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare (\$)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost (\$)	Efficiency (\$/gCO$_2$e)
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	134.77	-0.009
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	177.17	-0.012
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	202.86	-0.019
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	150.86	-0.017
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	149.65	-0.021
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	44.06	-0.007
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	42.55	-0.007
PEABODY	BOSTON CBD	15.24	2	0	61	-4786	-0.19%	213.05	-0.045
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	42.44	-0.009
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	66.62	-0.016
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	34.48	-0.009
BURLINGTON	WOBURN	3.61	1	4	13	-3230	-0.29%	26.93	-0.008
WHITMAN	BROCKTON	4.46	2	4	19	-3152	-0.24%	18.84	-0.006
MILTON	BOSTON CBD	8.55	3	0	159	-3107	-0.14%	220.80	-0.071
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	56.51	-0.023
ARLINGTON	WATERTOWN	5.75	2	0	19	-2163	-0.26%	102.04	-0.047
BRAINTREE	BOSTON CBD	11.92	4	4	225	-2125	-0.05%	326.92	-0.154
BEVERLY	DANVERS	5.51	1	20	10	-2115	-0.13%	-0.50	0.000
DANVERS	BEVERLY	5.51	2	20	21	-1904	-0.12%	-21.90	0.012
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	-20.39	0.011
BRAINTREE	QUINCY	4.05	2	0	80	-1820	-0.11%	61.95	-0.034
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-275.83	0.170
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-395.95	0.245
BROCKTON	W. BRIDGEW.	4.77	1	0	9	-1512	-0.13%	39.17	-0.026
BEVERLY	PEABODY	8.34	1	0	11	-1408	-0.10%	39.73	-0.028
WATERTOWN	NEWTON	3.80	2	0	44	-1385	-0.11%	59.98	-0.043
LEXINGTON	WALTHAM	4.18	1	20	11	-1375	-0.09%	0.00	0.000
BILLERICA	BOSTON CBD	19.34	2	0	32	-1318	-0.04%	201.10	-0.153
SALEM	DANVERS	5.97	1	0	23	-1210	-0.13%	37.48	-0.031
HINGHAM	WEYMOUTH	4.65	2	0	19	-1120	-0.08%	88.28	-0.079
PEABODY	DANVERS	4.85	2	20	38	-1081	-0.08%	-87.12	0.081
MILTON	BOSTON	5.58	3	0	153	-1005	-0.02%	161.34	-0.160
NEWTON	WALTHAM	5.21	2	0	50	-948	-0.03%	90.48	-0.095
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-47.95	0.053
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-128.87	0.143
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-143.47	0.168
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	-21.06	0.027
ABINGTON	BROCKTON	5.29	1	0	9	-773	-0.06%	29.17	-0.038
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-71.84	0.103
CHELMSFORD	LOWELL	4.63	4	12	40	-691	-0.03%	-56.60	0.082
WELLESLEY	NEWTON	4.88	2	0	51	-594	-0.04%	67.89	-0.114
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-25.01	0.042
MARBLEHEAD	SALEM	3.75	2	4	100	-589	-0.09%	-0.56	0.001
MALDEN	MEDFORD	2.94	2	4	57	-521	-0.07%	10.84	-0.021
WALTHAM	BURLINGTON	9.64	1	0	8	-469	-0.03%	130.33	-0.278
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-34.01	0.074
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-261.58	0.572
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-184.87	0.497
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	-4.78	0.014
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-48.92	0.152

Table 6.16: Case 3B ($F \leq 20, c_v = 0$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
NEWTON	WATERTOWN	3.80	2	14	33	-5	0.00%	-22.20	4.833
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-35.44	1.483
MEDFORD	SOMERVILLE	2.45	2	10	87	-98	-0.01%	-115.76	1.176
LYNN	PEABODY	5.29	2	16	103	-237	-0.02%	-210.62	0.890
WALTHAM	NEWTON	5.21	3	20	82	-181	-0.01%	-155.71	0.860
METHUEN	LAWRENCE	3.14	6	16	61	-190	-0.01%	-144.22	0.758
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	-40.72	0.738
WALTHAM	WATERTOWN	4.46	2	12	61	-94	-0.01%	-62.12	0.663
NORWOOD	WESTWOOD	2.22	1	6	25	-23	0.00%	-14.76	0.644
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-261.58	0.572
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-184.87	0.497
HUDSON	MARLBORO.	4.02	2	16	13	-68	-0.01%	-26.00	0.382
ATTLEBORO	N. ATTLEBOR.	6.19	2	14	18	-88	0.00%	-26.34	0.299
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-395.95	0.245
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-275.83	0.170
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-143.47	0.168
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-48.92	0.152
WEYMOUTH	HINGHAM	4.65	1	18	16	-178	-0.01%	-26.98	0.152
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-128.87	0.143
WOBURN	BURLINGTON	3.61	1	20	13	-124	-0.01%	-16.57	0.134
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-71.84	0.103
CHELMSFORD	LOWELL	4.63	4	12	40	-691	-0.03%	-56.60	0.082
PEABODY	DANVERS	4.85	2	20	38	-1081	-0.08%	-87.12	0.081
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-34.01	0.074
DANVERS	PEABODY	4.85	2	12	23	-115	-0.01%	-6.93	0.060
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-47.95	0.053
N. ANDOVER	LAWRENCE	4.46	1	6	12	-115	-0.01%	-6.08	0.053
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-25.01	0.042
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	-21.06	0.027
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	-4.78	0.014
DANVERS	BEVERLY	5.51	2	20	21	-1904	-0.12%	-21.90	0.012
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	-20.39	0.011
MARBLEHEAD	SALEM	3.75	2	4	100	-589	-0.09%	-0.56	0.001
BEVERLY	DANVERS	5.51	1	20	10	-2115	-0.13%	-0.50	0.000
LEXINGTON	WALTHAM	4.18	1	20	11	-1375	-0.09%	0.00	0.000
WHITMAN	BROCKTON	4.46	2	4	19	-3152	-0.24%	18.84	-0.006
BILLERICA	BURLINGTON	5.81	1	0	9	-6107	-0.30%	42.55	-0.007
BROCKTON	EASTON	5.95	1	0	13	-6297	-0.28%	44.06	-0.007
BURLINGTON	WOBURN	3.61	1	4	13	-3230	-0.29%	26.93	-0.008
WALTHAM	LEXINGTON	4.18	1	0	12	-4014	-0.33%	34.48	-0.009
FRAMINGHAM	BOSTON CBD	20.46	2	4	119	-14572	-0.25%	134.77	-0.009
WALPOLE	NORWOOD	5.16	2	0	27	-4559	-0.31%	42.44	-0.009
NATICK	BOSTON CBD	16.37	2	0	79	-14264	-0.38%	177.17	-0.012
ACTON	CONCORD	4.33	1	0	11	-4112	-0.22%	66.62	-0.016
MILFORD	BOSTON CBD	31.16	1	0	12	-8665	-0.26%	150.86	-0.017
RANDOLPH	BOSTON CBD	12.63	2	0	101	-10490	-0.31%	202.86	-0.019
MALDEN	MEDFORD	2.94	2	4	57	-521	-0.07%	10.84	-0.021
ARLINGTON	WALTHAM	6.44	2	0	42	-7154	-0.49%	149.65	-0.021
BILLERICA	LOWELL	6.58	1	0	22	-2486	-0.14%	56.51	-0.023
BROCKTON	W. BRIDGEW.	4.77	1	0	9	-1512	-0.13%	39.17	-0.026

Table 6.17: Case 4B ($F \in [6, 20], c_v = 0$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
FRAMINGHAM	BOSTON CBD	20.46	2	6	115	-9366	-0.16%	96.17	-0.010
BROCKTON	EASTON	5.95	1	6	12	-4241	-0.19%	31.16	-0.007
BILLERICA	BURLINGTON	5.81	1	6	8	-3664	-0.18%	34.09	-0.009
BURLINGTON	WOBURN	3.61	1	6	13	-2711	-0.24%	22.81	-0.008
ARLINGTON	WALTHAM	6.44	2	6	38	-2655	-0.18%	108.91	-0.041
WALTHAM	LEXINGTON	4.18	1	6	11	-2428	-0.20%	22.74	-0.009
ACTON	CONCORD	4.33	1	6	9	-2333	-0.13%	56.46	-0.024
BEVERLY	DANVERS	5.51	1	20	10	-2115	-0.13%	-0.50	0.000
WHITMAN	BROCKTON	4.46	2	6	18	-2110	-0.16%	13.09	-0.006
DANVERS	BEVERLY	5.51	2	20	21	-1904	-0.12%	-21.90	0.012
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	-20.39	0.011
NATICK	BOSTON CBD	16.37	2	6	72	-1852	-0.05%	100.24	-0.054
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-275.83	0.170
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-395.95	0.245
LEXINGTON	WALTHAM	4.18	1	20	11	-1375	-0.09%	0.00	0.000
WALPOLE	NORWOOD	5.16	2	6	24	-1164	-0.08%	16.30	-0.014
PEABODY	DANVERS	4.85	2	20	38	-1081	-0.08%	-87.12	0.081
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-47.95	0.053
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-128.87	0.143
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-143.47	0.168
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	-21.06	0.027
MILFORD	BOSTON CBD	31.16	1	6	10	-762	-0.02%	139.72	-0.183
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-71.84	0.103
CHELMSFORD	LOWELL	4.63	4	12	40	-691	-0.03%	-56.60	0.082
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-25.01	0.042
BILLERICA	LOWELL	6.58	1	6	20	-576	-0.03%	34.83	-0.060
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-34.01	0.074
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-261.58	0.572
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-184.87	0.497
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	-4.78	0.014
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-48.92	0.152
LYNN	PEABODY	5.29	2	16	103	-237	-0.02%	-210.62	0.890
METHUEN	LAWRENCE	3.14	6	16	61	-190	-0.01%	-144.22	0.758
WALTHAM	NEWTON	5.21	3	20	82	-181	-0.01%	-155.71	0.860
WEYMOUTH	HINGHAM	4.65	1	18	16	-178	-0.01%	-26.98	0.152
BROCKTON	W. BRIDGEW.	4.77	1	6	8	-176	-0.02%	31.04	-0.176
WOBURN	BURLINGTON	3.61	1	20	13	-124	-0.01%	-16.57	0.134
DANVERS	PEABODY	4.85	2	12	23	-115	-0.01%	-6.93	0.060
N. ANDOVER	LAWRENCE	4.46	1	6	12	-115	-0.01%	-6.08	0.053
MEDFORD	SOMERVILLE	2.45	2	10	87	-98	-0.01%	-115.76	1.176
WALTHAM	WATERTOWN	4.46	2	12	61	-94	-0.01%	-62.12	0.663
ATTLEBORO	N. ATTLEBOR.	6.19	2	14	18	-88	0.00%	-26.34	0.299
HUDSON	MARLBORO.	4.02	2	16	13	-68	-0.01%	-26.00	0.382
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	-40.72	0.738
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-35.44	1.483
NORWOOD	WESTWOOD	2.22	1	6	25	-23	0.00%	-14.76	0.644
NEWTON	WATERTOWN	3.80	2	14	33	-5	0.00%	-22.20	4.833

Table 6.18: Case 4B ($F \in [6, 20], c_v = 0$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
NEWTON	WATERTOWN	3.80	2	14	33	-5	0.00%	-22.20	4.833
PEABODY	SALEM	5.22	1	8	52	-24	0.00%	-35.44	1.483
MEDFORD	SOMERVILLE	2.45	2	10	87	-98	-0.01%	-115.76	1.176
LYNN	PEABODY	5.29	2	16	103	-237	-0.02%	-210.62	0.890
WALTHAM	NEWTON	5.21	3	20	82	-181	-0.01%	-155.71	0.860
METHUEN	LAWRENCE	3.14	6	16	61	-190	-0.01%	-144.22	0.758
BELMONT	WALTHAM	3.91	2	8	72	-55	-0.01%	-40.72	0.738
WALTHAM	WATERTOWN	4.46	2	12	61	-94	-0.01%	-62.12	0.663
NORWOOD	WESTWOOD	2.22	1	6	25	-23	0.00%	-14.76	0.644
NEWTON	CAMBRIDGE	6.98	3	16	147	-457	-0.01%	-261.58	0.572
WEYMOUTH	QUINCY	6.14	2	16	88	-372	-0.01%	-184.87	0.497
HUDSON	MARLBORO.	4.02	2	16	13	-68	-0.01%	-26.00	0.382
ATTLEBORO	N. ATTLEBOR.	6.19	2	14	18	-88	0.00%	-26.34	0.299
WINTHROP	BOSTON CBD	5.93	3	18	155	-1619	-0.08%	-395.95	0.245
WEYMOUTH	BOSTON CBD	14.56	4	18	226	-1624	-0.03%	-275.83	0.170
WOBURN	BOSTON CBD	11.50	2	14	102	-852	-0.03%	-143.47	0.168
N. ATTLEBOR.	ATTLEBORO	6.19	2	18	21	-322	-0.02%	-48.92	0.152
WEYMOUTH	HINGHAM	4.65	1	18	16	-178	-0.01%	-26.98	0.152
LAWRENCE	METHUEN	3.14	4	20	41	-903	-0.06%	-128.87	0.143
WOBURN	BURLINGTON	3.61	1	20	13	-124	-0.01%	-16.57	0.134
SALEM	PEABODY	5.22	1	20	29	-700	-0.06%	-71.84	0.103
CHELMSFORD	LOWELL	4.63	4	12	40	-691	-0.03%	-56.60	0.082
PEABODY	DANVERS	4.85	2	20	38	-1081	-0.08%	-87.12	0.081
BELMONT	WATERTOWN	3.23	2	10	36	-461	-0.09%	-34.01	0.074
DANVERS	PEABODY	4.85	2	12	23	-115	-0.01%	-6.93	0.060
CAMBRIDGE	WATERTOWN	3.43	2	6	105	-904	-0.10%	-47.95	0.053
N. ANDOVER	LAWRENCE	4.46	1	6	12	-115	-0.01%	-6.08	0.053
LAWRENCE	N. ANDOVER	4.46	2	10	22	-593	-0.04%	-25.01	0.042
NEEDHAM	NEWTON	4.49	2	8	66	-794	-0.05%	-21.06	0.027
NEEDHAM	WELLESLEY	3.48	2	8	23	-340	-0.04%	-4.78	0.014
DANVERS	BEVERLY	5.51	2	20	21	-1904	-0.12%	-21.90	0.012
WEYMOUTH	BRAINTREE	3.82	1	20	14	-1861	-0.08%	-20.39	0.011
BEVERLY	DANVERS	5.51	1	20	10	-2115	-0.13%	-0.50	0.000
LEXINGTON	WALTHAM	4.18	1	20	11	-1375	-0.09%	0.00	0.000
WHITMAN	BROCKTON	4.46	2	6	18	-2110	-0.16%	13.09	-0.006
BROCKTON	EASTON	5.95	1	6	12	-4241	-0.19%	31.16	-0.007
BURLINGTON	WOBURN	3.61	1	6	13	-2711	-0.24%	22.81	-0.008
BILLERICA	BURLINGTON	5.81	1	6	8	-3664	-0.18%	34.09	-0.009
WALTHAM	LEXINGTON	4.18	1	6	11	-2428	-0.20%	22.74	-0.009
FRAMINGHAM	BOSTON CBD	20.46	2	6	115	-9366	-0.16%	96.17	-0.010
WALPOLE	NORWOOD	5.16	2	6	24	-1164	-0.08%	16.30	-0.014
ACTON	CONCORD	4.33	1	6	9	-2333	-0.13%	56.46	-0.024
ARLINGTON	WALTHAM	6.44	2	6	38	-2655	-0.18%	108.91	-0.041
NATICK	BOSTON CBD	16.37	2	6	72	-1852	-0.05%	100.24	-0.054
BILLERICA	LOWELL	6.58	1	6	20	-576	-0.03%	34.83	-0.060
BROCKTON	W. BRIDGEW.	4.77	1	6	8	-176	-0.02%	31.04	-0.176
MILFORD	BOSTON CBD	31.16	1	6	10	-762	-0.02%	139.72	-0.183

Table 6.19: Case 5B ($\Delta F = 0, c_v = 0$): OD pairs ranked by GHG reduction (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
WINTHROP	BOSTON CBD	5.93	4	0.41	217	-18323	-0.96%	52.07	-0.003
METHUEN	LAWRENCE	3.14	1	0.00	35	-16443	-0.80%	4.90	0.000
WOBURN	BOSTON CBD	11.50	2	1.25	115	-10999	-0.36%	-30.23	0.003
CHELMSFORD	LOWELL	4.63	1	0.00	21	-10248	-0.51%	7.22	-0.001
LAWRENCE	METHUEN	3.14	1	0.00	26	-9964	-0.63%	4.90	0.000
WEYMOUTH	QUINCY	6.14	2	0.87	98	-8763	-0.35%	-16.89	0.002
ATTLEBORO	N. ATTLEBOR.	6.19	2	0.00	25	-8596	-0.37%	19.31	-0.002
WEYMOUTH	BRAINTREE	3.82	1	0.80	19	-7484	-0.34%	15.50	-0.002
BEVERLY	DANVERS	5.51	1	0.89	14	-6762	-0.41%	22.55	-0.003
WALTHAM	WATERTOWN	4.46	2	0.18	75	-6619	-0.52%	56.33	-0.009
LYNN	PEABODY	5.29	2	0.76	112	-6610	-0.44%	1.04	0.000
DANVERS	BEVERLY	5.51	1	0.57	16	-6462	-0.41%	17.54	-0.003
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	17	-6318	-0.30%	9.65	-0.002
LEXINGTON	WALTHAM	4.18	1	0.67	15	-5966	-0.39%	29.41	-0.005
PEABODY	DANVERS	4.85	1	0.30	34	-5616	-0.43%	14.05	-0.003
LAWRENCE	N. ANDOVER	4.46	2	0.00	27	-5261	-0.40%	13.91	-0.003
NEWTON	WATERTOWN	3.80	2	0.60	40	-5232	-0.45%	35.74	-0.007
WALTHAM	NEWTON	5.21	1	1.03	52	-4679	-0.17%	-7.70	0.002
SALEM	PEABODY	5.22	1	0.92	34	-4605	-0.37%	0.86	0.000
NEEDHAM	NEWTON	4.49	2	0.27	72	-4513	-0.28%	54.26	-0.012
HUDSON	MARLBORO.	4.02	1	0.00	10	-4225	-0.38%	6.27	-0.001
WHITMAN	BROCKTON	4.46	2	0.39	19	-4146	-0.31%	24.65	-0.006
WOBURN	BURLINGTON	3.61	1	0.64	17	-4132	-0.34%	17.23	-0.004
BILLERICA	BURLINGTON	5.81	1	0.87	8	-4106	-0.20%	35.52	-0.009
WALPOLE	NORWOOD	5.16	2	0.16	27	-4032	-0.27%	38.20	-0.009
BROCKTON	EASTON	5.95	1	1.28	12	-3884	-0.17%	29.06	-0.007
WEYMOUTH	HINGHAM	4.65	1	0.72	19	-3639	-0.22%	11.16	-0.003
MEDFORD	SOMERVILLE	2.45	2	0.21	102	-3324	-0.44%	18.48	-0.006
NEWTON	CAMBRIDGE	6.98	4	1.44	182	-3264	-0.09%	-49.55	0.015
BURLINGTON	WOBURN	3.61	1	0.71	13	-3243	-0.29%	27.04	-0.008
WALTHAM	LEXINGTON	4.18	1	0.63	11	-3066	-0.26%	27.29	-0.009
BELMONT	WATERTOWN	3.23	2	0.33	41	-3057	-0.61%	16.64	-0.005
DANVERS	PEABODY	4.85	1	0.37	17	-2817	-0.26%	14.87	-0.005
NEEDHAM	WELLESLEY	3.48	2	0.31	26	-2572	-0.31%	19.72	-0.008
ACTON	CONCORD	4.33	1	1.24	9	-2076	-0.11%	55.09	-0.027
ARLINGTON	WALTHAM	6.44	2	1.38	37	-1567	-0.11%	98.41	-0.063
N. ANDOVER	LAWRENCE	4.46	1	0.00	14	-1360	-0.13%	6.95	-0.005
PEABODY	SALEM	5.22	1	0.55	56	-1309	-0.11%	8.63	-0.007
CAMBRIDGE	WATERTOWN	3.43	2	0.93	107	-1281	-0.14%	-34.49	0.027
NORWOOD	WESTWOOD	2.22	1	0.20	26	-785	-0.12%	6.85	-0.009
WEYMOUTH	BOSTON CBD	14.56	4	3.32	227	-769	-0.01%	-300.44	0.391
MALDEN	MEDFORD	2.94	2	0.66	58	-640	-0.08%	13.74	-0.021
BEVERLY	PEABODY	8.34	1	0.54	10	-456	-0.03%	34.25	-0.075
MARBLEHEAD	SALEM	3.75	2	0.88	99	-268	-0.04%	-15.71	0.059
FRAMINGHAM	BOSTON CBD	20.46	2	1.75	108	-266	0.00%	29.75	-0.112
GLOUCESTER	BEVERLY	10.14	2	0.00	57	-247	-0.01%	31.63	-0.128
BELMONT	WALTHAM	3.91	1	0.57	52	-236	-0.03%	1.67	-0.007
BILLERICA	LOWELL	6.58	1	1.29	20	-228	-0.01%	30.93	-0.136
LAWRENCE	ANDOVER	4.80	2	0.00	29	-95	-0.01%	14.97	-0.157

Table 6.20: Case 5B ($\Delta F = 0, c_v = 0$): OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
WEYMOUTH	BOSTON CBD	14.56	4	3.32	227	-769	-0.01%	-300.44	0.391
MARBLEHEAD	SALEM	3.75	2	0.88	99	-268	-0.04%	-15.71	0.059
CAMBRIDGE	WATERTOWN	3.43	2	0.93	107	-1281	-0.14%	-34.49	0.027
NEWTON	CAMBRIDGE	6.98	4	1.44	182	-3264	-0.09%	-49.55	0.015
WOBURN	BOSTON CBD	11.50	2	1.25	115	-10999	-0.36%	-30.23	0.003
WEYMOUTH	QUINCY	6.14	2	0.87	98	-8763	-0.35%	-16.89	0.002
WALTHAM	NEWTON	5.21	1	1.03	52	-4679	-0.17%	-7.70	0.002
LYNN	PEABODY	5.29	2	0.76	112	-6610	-0.44%	1.04	0.000
SALEM	PEABODY	5.22	1	0.92	34	-4605	-0.37%	0.86	0.000
METHUEN	LAWRENCE	3.14	1	0.00	35	-16443	-0.80%	4.90	0.000
LAWRENCE	METHUEN	3.14	1	0.00	26	-9964	-0.63%	4.90	0.000
CHELMSFORD	LOWELL	4.63	1	0.00	21	-10248	-0.51%	7.22	-0.001
HUDSON	MARLBORO.	4.02	1	0.00	10	-4225	-0.38%	6.27	-0.001
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	17	-6318	-0.30%	9.65	-0.002
WEYMOUTH	BRAINTREE	3.82	1	0.80	19	-7484	-0.34%	15.50	-0.002
ATTLEBORO	N. ATTLEBOR.	6.19	2	0.00	25	-8596	-0.37%	19.31	-0.002
PEABODY	DANVERS	4.85	1	0.30	34	-5616	-0.43%	14.05	-0.003
LAWRENCE	N. ANDOVER	4.46	2	0.00	27	-5261	-0.40%	13.91	-0.003
DANVERS	BEVERLY	5.51	1	0.57	16	-6462	-0.41%	17.54	-0.003
WINTHROP	BOSTON CBD	5.93	4	0.41	217	-18323	-0.96%	52.07	-0.003
WEYMOUTH	HINGHAM	4.65	1	0.72	19	-3639	-0.22%	11.16	-0.003
BEVERLY	DANVERS	5.51	1	0.89	14	-6762	-0.41%	22.55	-0.003
WOBURN	BURLINGTON	3.61	1	0.64	17	-4132	-0.34%	17.23	-0.004
LEXINGTON	WALTHAM	4.18	1	0.67	15	-5966	-0.39%	29.41	-0.005
N. ANDOVER	LAWRENCE	4.46	1	0.00	14	-1360	-0.13%	6.95	-0.005
DANVERS	PEABODY	4.85	1	0.37	17	-2817	-0.26%	14.87	-0.005
BELMONT	WATERTOWN	3.23	2	0.33	41	-3057	-0.61%	16.64	-0.005
MEDFORD	SOMERVILLE	2.45	2	0.21	102	-3324	-0.44%	18.48	-0.006
WHITMAN	BROCKTON	4.46	2	0.39	19	-4146	-0.31%	24.65	-0.006
PEABODY	SALEM	5.22	1	0.55	56	-1309	-0.11%	8.63	-0.007
NEWTON	WATERTOWN	3.80	2	0.60	40	-5232	-0.45%	35.74	-0.007
BELMONT	WALTHAM	3.91	1	0.57	52	-236	-0.03%	1.67	-0.007
BROCKTON	EASTON	5.95	1	1.28	12	-3884	-0.17%	29.06	-0.007
NEEDHAM	WELLESLEY	3.48	2	0.31	26	-2572	-0.31%	19.72	-0.008
BURLINGTON	WOBURN	3.61	1	0.71	13	-3243	-0.29%	27.04	-0.008
WALTHAM	WATERTOWN	4.46	2	0.18	75	-6619	-0.52%	56.33	-0.009
BILLERICA	BURLINGTON	5.81	1	0.87	8	-4106	-0.20%	35.52	-0.009
NORWOOD	WESTWOOD	2.22	1	0.20	26	-785	-0.12%	6.85	-0.009
WALTHAM	LEXINGTON	4.18	1	0.63	11	-3066	-0.26%	27.29	-0.009
WALPOLE	NORWOOD	5.16	2	0.16	27	-4032	-0.27%	38.20	-0.009
NEEDHAM	NEWTON	4.49	2	0.27	72	-4513	-0.28%	54.26	-0.012
MALDEN	MEDFORD	2.94	2	0.66	58	-640	-0.08%	13.74	-0.021
ACTON	CONCORD	4.33	1	1.24	9	-2076	-0.11%	55.09	-0.027
ARLINGTON	WALTHAM	6.44	2	1.38	37	-1567	-0.11%	98.41	-0.063
BEVERLY	PEABODY	8.34	1	0.54	10	-456	-0.03%	34.25	-0.075
FRAMINGHAM	BOSTON CBD	20.46	2	1.75	108	-266	0.00%	29.75	-0.112
GLOUCESTER	BEVERLY	10.14	2	0.00	57	-247	-0.01%	31.63	-0.128
BILLERICA	LOWELL	6.58	1	1.29	20	-228	-0.01%	30.93	-0.136
LAWRENCE	ANDOVER	4.80	2	0.00	29	-95	-0.01%	14.97	-0.157

6.2 Appendix B: Detailed Results for OD Pairs in the PM Peak

Table 6.21: Case 1A ($F = 0, c_v = 71$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WALTHAM	NEWTON	5.21	3	0	179	-116025	-1.52%	220.27	-0.002
BOSTON CBD	WEYMOUTH	14.56	4	0	206	-92352	-1.16%	809.43	-0.009
CAMBRIDGE	NEWTON	6.98	3	0	177	-68959	-1.27%	272.77	-0.004
FRAMINGHAM	NATICK	6.94	2	0	69	-60276	-0.96%	49.60	-0.001
BOSTON CBD	WINTHROP	5.93	5	0	281	-56389	-2.18%	330.74	-0.006
NEWTON	WALTHAM	5.21	2	0	114	-56114	-0.85%	140.23	-0.002
BOSTON CBD	BRAINTREE	11.92	5	0	260	-55245	-0.86%	930.60	-0.017
DEDHAM	BOSTON	7.55	3	0	171	-52643	-0.65%	288.14	-0.005
WOBURN	BURLINGTON	3.61	2	0	67	-52622	-1.62%	98.96	-0.002
BRAINTREE	WEYMOUTH	3.82	2	0	50	-50887	-1.08%	154.86	-0.003
WALTHAM	WATERTOWN	4.46	5	0	245	-49950	-1.46%	293.02	-0.006
QUINCY	BRAINTREE	4.05	3	0	171	-47908	-0.99%	178.03	-0.004
BOSTON CBD	NORWOOD	14.70	4	0	215	-46318	-0.76%	596.39	-0.013
BOSTON CBD	RANDOLPH	12.63	2	0	97	-44945	-0.93%	320.32	-0.007
NEWTON	WATERTOWN	3.80	2	0	100	-42126	-1.42%	98.16	-0.002
SALEM	PEABODY	5.22	2	0	108	-41532	-1.50%	112.10	-0.003
QUINCY	WEYMOUTH	6.14	2	0	118	-39171	-0.68%	144.23	-0.004
BOSTON CBD	FRAMINGHAM	20.46	2	0	103	-39011	-0.66%	319.89	-0.008
BOSTON CBD	WOBURN	11.50	2	0	116	-38092	-1.12%	173.55	-0.005
WALTHAM	ARLINGTON	6.44	2	0	55	-37754	-1.41%	242.32	-0.006
WATERTOWN	CAMBRIDGE	3.43	3	0	174	-37330	-1.44%	153.83	-0.004
BOSTON	MILTON	5.58	3	0	165	-35070	-0.38%	269.37	-0.008
NORWOOD	WALPOLE	5.16	2	0	52	-35037	-1.15%	80.45	-0.002
LAWRENCE	METHUEN	3.14	1	0	49	-34888	-0.84%	17.19	0.000
BOSTON	DEDHAM	7.55	2	0	97	-34033	-0.29%	197.63	-0.006
BEVERLY	DANVERS	5.51	1	0	32	-32213	-0.86%	58.28	-0.002
CHELMSFORD	LOWELL	4.63	1	0	37	-32169	-0.73%	19.06	-0.001
SOMERVILLE	MEDFORD	2.45	5	0	287	-31887	-1.52%	197.28	-0.006
PEABODY	SALEM	5.22	2	0	68	-31557	-1.16%	113.52	-0.004
CAMBRIDGE	WATERTOWN	3.43	7	0	410	-31501	-1.05%	384.96	-0.012
BRAINTREE	QUINCY	4.05	3	0	170	-30261	-0.90%	162.86	-0.005
DANVERS	BEVERLY	5.51	1	0	30	-29304	-0.75%	61.87	-0.002
LEXINGTON	WALTHAM	4.18	1	0	27	-29159	-0.80%	64.99	-0.002
BURLINGTON	WOBURN	3.61	1	0	42	-28810	-0.84%	46.72	-0.002
PEABODY	LYNN	5.29	3	0	136	-28272	-1.01%	209.66	-0.007
WALTHAM	LEXINGTON	4.18	1	0	28	-27850	-0.80%	65.37	-0.002
WELLESLEY	NEWTON	4.88	2	0	71	-27829	-1.01%	118.64	-0.004
WELLESLEY	NEEDHAM	3.48	2	0	46	-27718	-1.38%	61.58	-0.002
NEEDHAM	WELLESLEY	3.48	2	0	41	-26835	-1.34%	59.51	-0.002
BRAINTREE	RANDOLPH	4.08	2	0	33	-26801	-1.09%	149.86	-0.006
LYNN	PEABODY	5.29	2	0	91	-26596	-1.00%	140.04	-0.005
BROOKLINE	NEWTON	4.21	4	0	226	-26512	-0.89%	250.64	-0.009
ANDOVER	LAWRENCE	4.80	2	0	59	-26478	-0.89%	43.42	-0.002
WATERTOWN	WALTHAM	4.46	2	0	102	-26198	-0.84%	116.62	-0.004
WALTHAM	CAMBRIDGE	6.85	4	0	231	-25983	-0.85%	398.60	-0.015
WATERTOWN	NEWTON	3.80	2	0	54	-25975	-0.86%	105.82	-0.004
WALTHAM	BELMONT	3.91	2	0	93	-25465	-1.27%	109.66	-0.004
WELLESLEY	NATICK	3.77	2	0	42	-24940	-0.87%	112.51	-0.005
NEWTON	CAMBRIDGE	6.98	2	0	120	-24874	-0.79%	170.32	-0.007
LOWELL	CHELMSFORD	4.63	1	0	30	-24740	-0.63%	19.06	-0.001

Table 6.22: Case 1A ($F = 0, c_v = 71$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
LAWRENCE	METHUEN	3.14	1	0	49	-34888	-0.84%	17.19	0.000
CHELMSFORD	LOWELL	4.63	1	0	37	-32169	-0.73%	19.06	-0.001
LOWELL	CHELMSFORD	4.63	1	0	30	-24740	-0.63%	19.06	-0.001
FRAMINGHAM	NATICK	6.94	2	0	69	-60276	-0.96%	49.60	-0.001
N. ATTLEBOR.	ATTLEBORO	6.19	1	0	26	-23534	-0.57%	21.49	-0.001
HUDSON	MARLBORO.	4.02	1	0	21	-16856	-0.74%	18.10	-0.001
ATTLEBORO	N. ATTLEBOR.	6.19	1	0	22	-17267	-0.43%	21.49	-0.001
LAWRENCE	N. ANDOVER	4.46	1	0	21	-13472	-0.61%	18.85	-0.001
FRAMINGHAM	MARLBORO.	9.72	1	0	13	-19111	-0.41%	26.99	-0.001
BURLINGTON	WOBURN	3.61	1	0	42	-28810	-0.84%	46.72	-0.002
ANDOVER	LAWRENCE	4.80	2	0	59	-26478	-0.89%	43.42	-0.002
BEVERLY	DANVERS	5.51	1	0	32	-32213	-0.86%	58.28	-0.002
WOBURN	BURLINGTON	3.61	2	0	67	-52622	-1.62%	98.96	-0.002
FRAMINGHAM	ASHLAND	9.19	1	0	16	-13885	-0.41%	26.17	-0.002
WALTHAM	NEWTON	5.21	3	0	179	-116025	-1.52%	220.27	-0.002
ASHLAND	FRAMINGHAM	9.19	1	0	16	-13048	-0.43%	26.17	-0.002
DANVERS	PEABODY	4.85	1	0	55	-20667	-0.75%	43.26	-0.002
DANVERS	BEVERLY	5.51	1	0	30	-29304	-0.75%	61.87	-0.002
PEABODY	DANVERS	4.85	1	0	45	-19886	-0.70%	42.56	-0.002
LOWELL	TEWKSBURY	5.57	2	0	29	-21452	-0.73%	46.66	-0.002
NEEDHAM	WELLESLEY	3.48	2	0	41	-26835	-1.34%	59.51	-0.002
WELLESLEY	NEEDHAM	3.48	2	0	46	-27718	-1.38%	61.58	-0.002
LEXINGTON	WALTHAM	4.18	1	0	27	-29159	-0.80%	64.99	-0.002
WEYMOUTH	HINGHAM	4.65	1	0	32	-22771	-0.59%	51.64	-0.002
NORWOOD	WALPOLE	5.16	2	0	52	-35037	-1.15%	80.45	-0.002
NEWTON	WATERTOWN	3.80	2	0	100	-42126	-1.42%	98.16	-0.002
FOXBOROUGH	MANSFIELD	4.03	1	0	13	-7771	-0.45%	18.12	-0.002
WALTHAM	LEXINGTON	4.18	1	0	28	-27850	-0.80%	65.37	-0.002
NEWTON	WALTHAM	5.21	2	0	114	-56114	-0.85%	140.23	-0.002
ROCKPORT	GLOUCESTER	5.59	2	0	61	-16406	-0.80%	41.10	-0.003
NORWOOD	WESTWOOD	2.22	1	0	26	-10607	-0.75%	28.14	-0.003
SALEM	PEABODY	5.22	2	0	108	-41532	-1.50%	112.10	-0.003
BELMONT	WATERTOWN	3.23	2	0	79	-23628	-1.94%	64.61	-0.003
NEWBURYP.	AMESBURY	5.14	1	0	11	-6959	-0.57%	19.86	-0.003
MANSFIELD	FOXBOROUGH	4.03	1	0	12	-6034	-0.40%	18.12	-0.003
BEDFORD	BILLERICA	5.24	1	0	18	-16727	-0.57%	50.43	-0.003
BRAINTREE	WEYMOUTH	3.82	2	0	50	-50887	-1.08%	154.86	-0.003
WOBURN	READING	4.99	1	0	16	-11572	-0.68%	35.57	-0.003
BROCKTON	EASTON	5.95	1	0	22	-23486	-0.53%	72.83	-0.003
WESTBORO.	NORTHBORO.	4.56	1	0	10	-5717	-0.37%	18.95	-0.003
BURLINGTON	BILLERICA	5.81	1	0	14	-15656	-0.53%	52.81	-0.003
WATERTOWN	BELMONT	3.23	2	0	69	-18626	-1.46%	64.14	-0.003
HINGHAM	WEYMOUTH	4.65	1	0	32	-19564	-0.51%	68.11	-0.003
WEYMOUTH	BRAINTREE	3.82	1	0	32	-16354	-0.61%	57.54	-0.004
PEABODY	SALEM	5.22	2	0	68	-31557	-1.16%	113.52	-0.004
QUINCY	WEYMOUTH	6.14	2	0	118	-39171	-0.68%	144.23	-0.004
QUINCY	BRAINTREE	4.05	3	0	171	-47908	-0.99%	178.03	-0.004
TAUNTON	RAYNHAM	3.79	1	0	10	-4731	-0.20%	17.75	-0.004
BILLERICA	LOWELL	6.58	1	0	46	-24157	-0.55%	90.83	-0.004
SOUTHBORO.	MARLBORO.	3.66	1	0	9	-4639	-0.35%	17.55	-0.004

Table 6.23: Case 2A ($F = 8, c_v = 71$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WALTHAM	NEWTON	5.21	3	8	156	-88961	-1.16%	-3.84	0.000
BOSTON CBD	WEYMOUTH	14.56	3	8	176	-66755	-0.84%	354.75	-0.005
CAMBRIDGE	NEWTON	6.98	3	8	155	-46520	-0.86%	50.46	-0.001
BOSTON CBD	BRAINTREE	11.92	4	8	234	-45595	-0.71%	408.83	-0.009
WALTHAM	WATERTOWN	4.46	4	8	218	-41132	-1.20%	-77.98	0.002
NEWTON	WALTHAM	5.21	2	8	95	-39325	-0.59%	4.65	0.000
BRAINTREE	WEYMOUTH	3.82	2	8	42	-37666	-0.80%	94.44	-0.003
BOSTON CBD	WINTHROP	5.93	5	8	264	-35518	-1.37%	-47.07	0.001
DEDHAM	BOSTON	7.55	3	8	150	-32914	-0.41%	73.06	-0.002
SALEM	PEABODY	5.22	2	8	98	-31729	-1.14%	-28.13	0.001
LAWRENCE	METHUEN	3.14	1	8	41	-27757	-0.67%	-41.58	0.001
WALTHAM	ARLINGTON	6.44	2	8	48	-26774	-1.00%	173.57	-0.006
CHELMSFORD	LOWELL	4.63	1	8	32	-25877	-0.59%	-26.36	0.001
BEVERLY	DANVERS	5.51	1	8	27	-25551	-0.68%	19.84	-0.001
BOSTON CBD	RANDOLPH	12.63	2	8	84	-23439	-0.49%	200.46	-0.009
LEXINGTON	WALTHAM	4.18	1	8	23	-22971	-0.63%	31.95	-0.001
DANVERS	BEVERLY	5.51	1	8	25	-22625	-0.58%	26.03	-0.001
BOSTON CBD	WOBURN	11.50	2	8	105	-22513	-0.66%	23.42	-0.001
BURLINGTON	WOBURN	3.61	1	8	35	-22338	-0.65%	-4.00	0.000
WALTHAM	LEXINGTON	4.18	1	8	24	-21800	-0.62%	31.13	-0.001
WOBURN	BURLINGTON	3.61	1	8	30	-20115	-0.62%	6.18	0.000
FRAMINGHAM	NATICK	6.94	1	8	31	-19913	-0.32%	-20.31	0.001
BRAINTREE	QUINCY	4.05	3	8	149	-19341	-0.58%	-50.82	0.003
LOWELL	CHELMSFORD	4.63	1	8	25	-19110	-0.48%	-17.39	0.001
BRAINTREE	RANDOLPH	4.08	2	8	28	-18471	-0.75%	110.07	-0.006
N. ATTLEBOR.	ATTLEBORO	6.19	1	8	23	-18316	-0.44%	-10.87	0.001
BROCKTON	EASTON	5.95	1	8	19	-18161	-0.41%	45.60	-0.003
BILLERICA	LOWELL	6.58	1	8	42	-18027	-0.41%	30.05	-0.002
BOSTON	DEDHAM	7.55	2	8	77	-17516	-0.15%	86.67	-0.005
PEABODY	LYNN	5.29	2	8	111	-17445	-0.62%	-19.96	0.001
WEYMOUTH	HINGHAM	4.65	1	8	29	-17427	-0.45%	10.74	-0.001
BOSTON CBD	FRAMINGHAM	20.46	2	8	92	-16552	-0.28%	188.16	-0.011
WATERTOWN	NEWTON	3.80	2	8	43	-16415	-0.54%	44.21	-0.003
WELLESLEY	NATICK	3.77	2	8	36	-16233	-0.57%	61.37	-0.004
WATERTOWN	WALTHAM	4.46	2	8	83	-15997	-0.51%	-2.32	0.000
DANVERS	PEABODY	4.85	1	8	50	-15930	-0.58%	-27.73	0.002
SALEM	MARBLEHEAD	3.75	2	8	101	-15920	-1.24%	-26.97	0.002
PEABODY	DANVERS	4.85	1	8	40	-15072	-0.53%	-14.53	0.001
BOSTON	MILTON	5.58	2	8	104	-14943	-0.16%	30.91	-0.002
ARLINGTON	CAMBRIDGE	4.14	3	8	179	-14685	-0.63%	-83.72	0.006
BROCKTON	WHITMAN	4.46	2	8	22	-14412	-0.62%	76.96	-0.005
HINGHAM	WEYMOUTH	4.65	1	8	28	-14368	-0.37%	28.28	-0.002
MEDFORD	MALDEN	2.94	2	8	79	-13819	-0.77%	-11.75	0.001
BELMONT	CAMBRIDGE	3.56	3	8	148	-13768	-0.80%	-53.59	0.004
BROOKLINE	NEWTON	4.21	4	8	201	-13695	-0.46%	-38.07	0.003
LOWELL	TEWKSBURY	5.57	2	8	24	-13676	-0.47%	12.25	-0.001
LEXINGTON	BURLINGTON	5.47	2	8	23	-13571	-0.59%	134.70	-0.010
FRAMINGHAM	MARLBORO.	9.72	1	8	11	-13237	-0.28%	10.73	-0.001
HUDSON	MARLBORO.	4.02	1	8	18	-13199	-0.58%	-7.51	0.001
SAUGUS	LYNN	3.42	2	8	42	-12646	-0.64%	65.66	-0.005

Table 6.24: Case 2A ($F = 8, c_v = 71$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-30.85	0.268
MALDEN	EVERETT	2.09	5	8	133	-128	-0.02%	-26.23	0.204
MELROSE	MALDEN	2.46	4	8	162	-577	-0.07%	-66.39	0.115
LYNN	SWAMPSCOTT	4.13	3	8	128	-658	-0.06%	-66.87	0.102
SWAMPSCOTT	LYNN	4.13	3	8	128	-739	-0.07%	-69.92	0.095
MEDFORD	SOMERVILLE	2.45	8	8	313	-1626	-0.08%	-140.46	0.086
NEWTON	BROOKLINE	4.21	5	8	280	-1714	-0.06%	-92.54	0.054
LYNN	SALEM	5.61	4	8	177	-950	-0.04%	-29.79	0.031
CAMBRIDGE	MEDFORD	4.01	6	8	329	-5264	-0.19%	-154.67	0.029
ROCKPORT	GLOUCESTER	5.59	4	8	65	-446	-0.02%	-11.03	0.025
LYNN	REVERE	5.52	3	8	152	-2914	-0.18%	-64.17	0.022
EVERETT	MALDEN	2.09	1	8	45	-1559	-0.17%	-30.98	0.020
CAMBRIDGE	EVERETT	4.41	3	8	152	-1188	-0.09%	-22.85	0.019
WEYMOUTH	QUINCY	6.14	2	8	116	-2553	-0.14%	-47.29	0.019
MALDEN	MELROSE	2.46	2	8	90	-1976	-0.21%	-31.62	0.016
GLOUCESTER	ROCKPORT	5.59	3	8	62	-1822	-0.08%	-27.16	0.015
CAMBRIDGE	WATERTOWN	3.43	8	8	360	-5971	-0.20%	-76.59	0.013
MALDEN	SOMERVILLE	4.89	1	8	51	-542	-0.04%	-6.89	0.013
EVERETT	CHELSEA	1.81	1	8	29	-867	-0.17%	-10.77	0.012
SOMERVILLE	MEDFORD	2.45	8	8	252	-3849	-0.18%	-45.39	0.012
CAMBRIDGE	BELMONT	3.56	5	8	233	-4193	-0.19%	-48.55	0.012
CHELSEA	EVERETT	1.81	1	8	38	-2173	-0.36%	-21.19	0.010
ARLINGTON	SOMERVILLE	3.92	1	8	50	-1936	-0.13%	-17.62	0.009
MEDFORD	CAMBRIDGE	4.01	3	8	168	-10949	-0.57%	-80.00	0.007
ARLINGTON	CAMBRIDGE	4.14	3	8	179	-14685	-0.63%	-83.72	0.006
BELMONT	CAMBRIDGE	3.56	3	8	148	-13768	-0.80%	-53.59	0.004
WATERTOWN	CAMBRIDGE	3.43	1	8	48	-4635	-0.18%	-16.86	0.004
SOMERVILLE	ARLINGTON	3.92	1	8	45	-2818	-0.17%	-9.37	0.003
QUINCY	BRAINTREE	4.05	1	8	59	-7574	-0.16%	-24.69	0.003
BROOKLINE	NEWTON	4.21	4	8	201	-13695	-0.46%	-38.07	0.003
ANDOVER	LAWRENCE	4.80	1	8	31	-8061	-0.27%	-22.32	0.003
BRAINTREE	QUINCY	4.05	3	8	149	-19341	-0.58%	-50.82	0.003
BELMONT	WATERTOWN	3.23	1	8	35	-6953	-0.57%	-18.22	0.003
WALTHAM	BELMONT	3.91	1	8	50	-6356	-0.32%	-16.24	0.003
CHELSEA	REVERE	2.75	1	8	35	-2156	-0.21%	-4.62	0.002
WALTHAM	WATERTOWN	4.46	4	8	218	-41132	-1.20%	-77.98	0.002
DANVERS	PEABODY	4.85	1	8	50	-15930	-0.58%	-27.73	0.002
SALEM	MARBLEHEAD	3.75	2	8	101	-15920	-1.24%	-26.97	0.002
LAWRENCE	METHUEN	3.14	1	8	41	-27757	-0.67%	-41.58	0.001
NEWTON	WATERTOWN	3.80	1	8	47	-12151	-0.41%	-17.64	0.001
WATERTOWN	BELMONT	3.23	2	8	57	-12467	-0.98%	-17.58	0.001
BOSTON CBD	WINTHROP	5.93	5	8	264	-35518	-1.37%	-47.07	0.001
LYNN	PEABODY	5.29	1	8	55	-7320	-0.27%	-8.87	0.001
LYNN	MARBLEHEAD	7.38	1	8	45	-1656	-0.11%	-1.90	0.001
PEABODY	LYNN	5.29	2	8	111	-17445	-0.62%	-19.96	0.001
FRAMINGHAM	NATICK	6.94	1	8	31	-19913	-0.32%	-20.31	0.001
CHELMSFORD	LOWELL	4.63	1	8	32	-25877	-0.59%	-26.36	0.001
PEABODY	DANVERS	4.85	1	8	40	-15072	-0.53%	-14.53	0.001
MEDFORD	ARLINGTON	3.64	1	8	37	-5531	-0.36%	-5.18	0.001
LOWELL	CHELMSFORD	4.63	1	8	25	-19110	-0.48%	-17.39	0.001

Table 6.25: Case 3A ($F \leq 20, c_v = 71$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
BOSTON CBD	RANDOLPH	12.63	2	0	97	-44945	-0.93%	320.32	-0.007
BOSTON CBD	FRAMINGHAM	20.46	2	0	103	-39011	-0.66%	319.89	-0.008
WALTHAM	ARLINGTON	6.44	2	4	51	-32044	-1.20%	205.61	-0.006
BOSTON CBD	BRAINTREE	11.92	4	12	221	-30145	-0.47%	269.18	-0.009
BRAINTREE	RANDOLPH	4.08	2	0	33	-26801	-1.09%	149.86	-0.006
BROCKTON	WHITMAN	4.46	2	0	27	-21920	-0.94%	108.93	-0.005
BRAINTREE	WEYMOUTH	3.82	2	20	32	-21665	-0.46%	38.80	-0.002
LEXINGTON	BURLINGTON	5.47	2	0	28	-20965	-0.91%	167.97	-0.008
PEABODY	BEVERLY	8.34	2	0	29	-18726	-0.70%	155.69	-0.008
BEVERLY	DANVERS	5.51	1	20	21	-17343	-0.46%	-15.93	0.001
WALTHAM	NEWTON	5.21	1	20	54	-16333	-0.21%	-120.32	0.007
LAWRENCE	METHUEN	3.14	8	20	83	-15519	-0.37%	-158.40	0.010
LEXINGTON	WALTHAM	4.18	1	20	18	-15363	-0.42%	0.72	0.000
RANDOLPH	BRAINTREE	4.08	2	0	29	-14547	-0.89%	125.42	-0.009
BURLINGTON	WOBURN	3.61	1	20	28	-14456	-0.42%	-51.98	0.004
DANVERS	BEVERLY	5.51	1	20	19	-14447	-0.37%	-5.68	0.000
WALTHAM	LEXINGTON	4.18	1	20	19	-14363	-0.41%	-1.67	0.000
BOSTON CBD	MILTON	8.55	2	0	92	-13933	-0.48%	227.74	-0.016
CONCORD	ACTON	4.33	1	0	16	-13753	-0.43%	100.01	-0.007
WOBURN	LEXINGTON	5.67	1	0	14	-13209	-0.63%	80.13	-0.006
WOBURN	BURLINGTON	3.61	1	20	23	-12653	-0.39%	-33.13	0.003
BEVERLY	GLOUCESTER	10.14	2	0	65	-12635	-0.31%	261.35	-0.021
WATERTOWN	ARLINGTON	5.75	2	0	26	-12328	-0.83%	175.65	-0.014
ACTON	CONCORD	4.33	1	0	16	-12164	-0.43%	112.28	-0.009
LEXINGTON	ARLINGTON	4.27	2	0	43	-12153	-0.67%	125.03	-0.010
BILLERICA	BURLINGTON	5.81	1	0	13	-11875	-0.49%	56.94	-0.005
BROCKTON	EASTON	5.95	1	20	15	-11605	-0.26%	19.01	-0.002
BOSTON CBD	MILFORD	31.16	1	0	8	-11562	-0.36%	215.30	-0.019
BROCKTON	ABINGTON	5.29	2	0	21	-11182	-0.48%	96.51	-0.009
BURLINGTON	BILLERICA	5.81	1	8	12	-11149	-0.38%	36.17	-0.003
WEYMOUTH	HINGHAM	4.65	1	20	24	-10868	-0.28%	-32.73	0.003
ARLINGTON	LEXINGTON	4.27	2	0	45	-10702	-0.75%	122.60	-0.011
BOSTON	DEDHAM	7.55	2	12	69	-10683	-0.09%	50.05	-0.005
BURLINGTON	WALTHAM	9.64	1	0	11	-10563	-0.42%	158.36	-0.015
CANTON	STOUGHTON	4.94	1	0	19	-10501	-0.45%	166.69	-0.016
BILLERICA	LOWELL	6.58	1	20	38	-10490	-0.24%	-45.80	0.004
DANVERS	PEABODY	4.85	1	20	43	-10102	-0.36%	-110.75	0.011
BEVERLY	PEABODY	8.34	1	10	18	-10045	-0.35%	47.75	-0.005
BOSTON	WINTHROP	9.36	2	4	108	-9999	-0.27%	144.50	-0.014
LEXINGTON	WOBURN	5.67	1	0	12	-9933	-0.49%	95.09	-0.010
ARLINGTON	WALTHAM	6.44	2	0	25	-9881	-0.54%	232.97	-0.024
NEWTON	WELLESLEY	4.88	2	8	43	-9751	-0.31%	61.61	-0.006
ARLINGTON	WATERTOWN	5.75	2	0	24	-9504	-0.84%	164.33	-0.017
CAMBRIDGE	WOBURN	9.18	2	0	73	-9468	-0.45%	196.10	-0.021
NEWTON	BELMONT	7.01	2	0	32	-9242	-0.59%	154.92	-0.017
PEABODY	DANVERS	4.85	1	20	33	-9172	-0.32%	-76.20	0.008
NEEDHAM	DEDHAM	4.49	2	0	20	-9053	-0.59%	181.84	-0.020
SALEM	PEABODY	5.22	1	20	58	-9019	-0.33%	-151.41	0.017
WOBURN	WAKEFIELD	5.89	1	0	13	-8989	-0.57%	76.60	-0.009
BOSTON CBD	ROCKLAND	20.40	1	0	10	-8974	-0.33%	247.22	-0.028

Table 6.26: Case 3A ($F \leq 20, c_v = 71$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
MEDFORD	CAMBRIDGE	4.01	3	20	135	-26	0.00%	-321.35	12.602
ARLINGTON	SOMERVILLE	3.92	3	20	97	-28	0.00%	-184.13	6.518
WINCHESTER	ARLINGTON	3.32	2	20	32	-9	0.00%	-37.87	4.400
MEDFORD	SOMERVILLE	2.45	7	14	282	-113	-0.01%	-437.49	3.870
ARLINGTON	CAMBRIDGE	4.14	4	16	161	-77	0.00%	-231.57	3.003
MALDEN	MEDFORD	2.94	1	20	24	-26	0.00%	-40.73	1.574
GLOUCESTER	ROCKPORT	5.59	3	10	60	-32	0.00%	-45.74	1.416
MALDEN	EVERETT	2.09	4	16	116	-146	-0.02%	-199.88	1.369
EVERETT	CHELSEA	1.81	1	14	25	-29	-0.01%	-31.45	1.098
EVERETT	REVERE	3.89	1	18	25	-34	0.00%	-33.23	0.967
SOMERVILLE	ARLINGTON	3.92	1	16	36	-50	0.00%	-47.83	0.961
CAMBRIDGE	BELMONT	3.56	4	18	190	-461	-0.02%	-384.72	0.834
NEWTON	CAMBRIDGE	6.98	1	14	50	-51	0.00%	-39.84	0.788
EVERETT	MALDEN	2.09	1	16	36	-95	-0.01%	-68.52	0.719
CAMBRIDGE	WATERTOWN	3.43	6	20	289	-1093	-0.04%	-705.18	0.645
BRAINTREE	QUINCY	4.05	1	20	44	-173	-0.01%	-104.52	0.606
MELROSE	MALDEN	2.46	2	18	108	-456	-0.05%	-264.25	0.580
WEYMOUTH	QUINCY	6.14	2	12	113	-242	-0.01%	-123.19	0.509
SOMERVILLE	MEDFORD	2.45	6	20	202	-1004	-0.05%	-488.85	0.487
BROOKLINE	NEWTON	4.21	4	18	171	-624	-0.02%	-300.70	0.482
LYNN	SWAMPSCOTT	4.13	2	12	99	-319	-0.03%	-133.99	0.420
BELMONT	CAMBRIDGE	3.56	1	16	48	-204	-0.01%	-85.26	0.418
TAUNTON	RAYNHAM	3.79	2	18	13	-14	0.00%	-5.17	0.362
CHELSEA	EVERETT	1.81	4	16	73	-227	-0.04%	-79.49	0.351
SWAMPSCOTT	LYNN	4.13	2	12	100	-482	-0.05%	-138.42	0.287
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-30.85	0.268
CAMBRIDGE	MEDFORD	4.01	5	16	287	-2094	-0.08%	-560.00	0.267
WATERTOWN	CAMBRIDGE	3.43	1	20	32	-233	-0.01%	-62.21	0.267
LYNN	MARBLEHEAD	7.38	1	12	42	-109	-0.01%	-27.74	0.255
NEWTON	WATERTOWN	3.80	6	20	88	-92	0.00%	-20.92	0.228
MALDEN	MELROSE	2.46	3	10	108	-208	-0.02%	-47.17	0.227
N. ATTLEBOR.	ATTLEBORO	6.19	5	20	41	-177	0.00%	-39.86	0.225
CAMBRIDGE	WALTHAM	6.85	3	18	176	-1167	-0.03%	-261.64	0.224
WALTHAM	WATERTOWN	4.46	6	20	180	-1337	-0.04%	-292.59	0.219
LYNN	REVERE	5.52	2	14	119	-905	-0.06%	-195.29	0.216
LYNN	SALEM	5.61	3	14	148	-949	-0.04%	-203.55	0.214
ANDOVER	LAWRENCE	4.80	4	20	53	-545	-0.02%	-102.67	0.188
MEDFORD	MALDEN	2.94	1	20	26	-238	-0.01%	-41.38	0.174
MEDFORD	ARLINGTON	3.64	4	20	65	-261	-0.02%	-40.93	0.157
ROCKPORT	GLOUCESTER	5.59	1	20	32	-643	-0.03%	-95.48	0.148
WALTHAM	CAMBRIDGE	6.85	3	20	180	-2531	-0.08%	-344.56	0.136
PEABODY	LYNN	5.29	1	20	59	-1150	-0.04%	-141.21	0.123
MALDEN	SOMERVILLE	4.89	2	16	81	-849	-0.07%	-100.26	0.118
CHELSEA	REVERE	2.75	1	16	28	-305	-0.03%	-34.07	0.112
SOMERVILLE	MALDEN	4.89	2	16	58	-198	-0.01%	-22.01	0.111
BOSTON CBD	WINTHROP	5.93	6	16	247	-3420	-0.13%	-309.76	0.091
BELMONT	WATERTOWN	3.23	5	20	69	-973	-0.08%	-85.00	0.087
QUINCY	BRAINTREE	4.05	5	18	131	-1430	-0.03%	-124.74	0.087
BOSTON	MILTON	5.58	2	20	72	-1053	-0.01%	-80.10	0.076
READING	WAKEFIELD	3.41	2	14	36	-126	-0.01%	-9.22	0.073

Table 6.27: Case 4A ($F \in [6, 20], c_v = 71$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
BOSTON CBD	BRAINTREE	11.92	4	12	221	-30145	-0.47%	269.18	-0.009
WALTHAM	ARLINGTON	6.44	2	6	50	-29356	-1.10%	189.03	-0.006
BOSTON CBD	RANDOLPH	12.63	2	6	87	-28433	-0.59%	226.92	-0.008
BOSTON CBD	FRAMINGHAM	20.46	2	6	95	-21800	-0.37%	218.19	-0.010
BRAINTREE	WEYMOUTH	3.82	2	20	32	-21665	-0.46%	38.80	-0.002
BRAINTREE	RANDOLPH	4.08	2	6	29	-20428	-0.83%	118.73	-0.006
BEVERLY	DANVERS	5.51	1	20	21	-17343	-0.46%	-15.93	0.001
WALTHAM	NEWTON	5.21	1	20	54	-16333	-0.21%	-120.32	0.007
BROCKTON	WHITMAN	4.46	2	6	23	-16175	-0.69%	83.73	-0.005
LAWRENCE	METHUEN	3.14	8	20	83	-15519	-0.37%	-158.40	0.010
LEXINGTON	WALTHAM	4.18	1	20	18	-15363	-0.42%	0.72	0.000
LEXINGTON	BURLINGTON	5.47	2	6	24	-15309	-0.66%	141.79	-0.009
BURLINGTON	WOBURN	3.61	1	20	28	-14456	-0.42%	-51.98	0.004
DANVERS	BEVERLY	5.51	1	20	19	-14447	-0.37%	-5.68	0.000
WALTHAM	LEXINGTON	4.18	1	20	19	-14363	-0.41%	-1.67	0.000
PEABODY	BEVERLY	8.34	2	6	26	-12700	-0.47%	128.22	-0.010
WOBURN	BURLINGTON	3.61	1	20	23	-12653	-0.39%	-33.13	0.003
BROCKTON	EASTON	5.95	1	20	15	-11605	-0.26%	19.01	-0.002
BURLINGTON	BILLERICA	5.81	1	8	12	-11149	-0.38%	36.17	-0.003
WEYMOUTH	HINGHAM	4.65	1	20	24	-10868	-0.28%	-32.73	0.003
CONCORD	ACTON	4.33	1	6	14	-10687	-0.33%	84.90	-0.008
BOSTON	DEDHAM	7.55	2	12	69	-10683	-0.09%	50.05	-0.005
BILLERICA	LOWELL	6.58	1	20	38	-10490	-0.24%	-45.80	0.004
WOBURN	LEXINGTON	5.67	1	6	12	-10309	-0.49%	66.91	-0.006
RANDOLPH	BRAINTREE	4.08	2	6	26	-10280	-0.63%	97.55	-0.009
DANVERS	PEABODY	4.85	1	20	43	-10102	-0.36%	-110.75	0.011
BEVERLY	PEABODY	8.34	1	10	18	-10045	-0.35%	47.75	-0.005
NEWTON	WELLESLEY	4.88	2	8	43	-9751	-0.31%	61.61	-0.006
ACTON	CONCORD	4.33	1	6	14	-9460	-0.34%	97.41	-0.010
PEABODY	DANVERS	4.85	1	20	33	-9172	-0.32%	-76.20	0.008
BILLERICA	BURLINGTON	5.81	1	6	12	-9050	-0.38%	44.11	-0.005
SALEM	PEABODY	5.22	1	20	58	-9019	-0.33%	-151.41	0.017
HINGHAM	WEYMOUTH	4.65	1	20	22	-8059	-0.21%	-11.65	0.001
CANTON	STOUGHTON	4.94	1	6	17	-7846	-0.34%	148.00	-0.019
BOSTON	WINTHROP	9.36	2	6	106	-7490	-0.20%	108.30	-0.014
LEXINGTON	ARLINGTON	4.27	2	6	37	-7390	-0.41%	84.77	-0.011
LEXINGTON	WOBURN	5.67	1	6	11	-7156	-0.35%	83.50	-0.012
BEDFORD	BILLERICA	5.24	1	20	12	-7155	-0.24%	7.68	-0.001
WEYMOUTH	BRAINTREE	3.82	1	20	22	-6908	-0.26%	-23.00	0.003
WATERTOWN	ARLINGTON	5.75	2	6	22	-6864	-0.46%	152.09	-0.022
BURLINGTON	WALTHAM	9.64	1	6	10	-6760	-0.27%	147.74	-0.022
ARLINGTON	LEXINGTON	4.27	2	6	40	-6589	-0.46%	79.43	-0.012
WOBURN	WAKEFIELD	5.89	1	6	12	-6408	-0.41%	64.23	-0.010
BROCKTON	E. BRIDGEW.	6.51	1	6	10	-6278	-0.27%	58.89	-0.009
BROCKTON	ABINGTON	5.29	2	6	18	-6147	-0.26%	77.12	-0.013
CANTON	NORWOOD	5.86	1	6	10	-6089	-0.33%	72.09	-0.012
FRAMINGHAM	MARLBORO.	9.72	1	20	9	-6005	-0.13%	-4.61	0.001
WELLESLEY	NATICK	3.77	2	20	27	-5887	-0.21%	15.66	-0.003
BROCKTON	W. BRIDGEW.	4.77	1	6	12	-5883	-0.30%	52.75	-0.009
ABINGTON	BROCKTON	5.29	1	6	12	-5809	-0.31%	38.93	-0.007

Table 6.28: Case 4A ($F \in [6, 20], c_v = 71$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
MEDFORD	CAMBRIDGE	4.01	3	20	135	-26	0.00%	-321.35	12.602
ARLINGTON	SOMERVILLE	3.92	3	20	97	-28	0.00%	-184.13	6.518
WINCHESTER	ARLINGTON	3.32	2	20	32	-9	0.00%	-37.87	4.400
MEDFORD	SOMERVILLE	2.45	7	14	282	-113	-0.01%	-437.49	3.870
ARLINGTON	CAMBRIDGE	4.14	4	16	161	-77	0.00%	-231.57	3.003
MALDEN	MEDFORD	2.94	1	20	24	-26	0.00%	-40.73	1.574
GLOUCESTER	ROCKPORT	5.59	3	10	60	-32	0.00%	-45.74	1.416
MALDEN	EVERETT	2.09	4	16	116	-146	-0.02%	-199.88	1.369
EVERETT	CHELSEA	1.81	1	14	25	-29	-0.01%	-31.45	1.098
EVERETT	REVERE	3.89	1	18	25	-34	0.00%	-33.23	0.967
SOMERVILLE	ARLINGTON	3.92	1	16	36	-50	0.00%	-47.83	0.961
CAMBRIDGE	BELMONT	3.56	4	18	190	-461	-0.02%	-384.72	0.834
NEWTON	CAMBRIDGE	6.98	1	14	50	-51	0.00%	-39.84	0.788
EVERETT	MALDEN	2.09	1	16	36	-95	-0.01%	-68.52	0.719
CAMBRIDGE	WATERTOWN	3.43	6	20	289	-1093	-0.04%	-705.18	0.645
BRAINTREE	QUINCY	4.05	1	20	44	-173	-0.01%	-104.52	0.606
MELROSE	MALDEN	2.46	2	18	108	-456	-0.05%	-264.25	0.580
WEYMOUTH	QUINCY	6.14	2	12	113	-242	-0.01%	-123.19	0.509
SOMERVILLE	MEDFORD	2.45	6	20	202	-1004	-0.05%	-488.85	0.487
BROOKLINE	NEWTON	4.21	4	18	171	-624	-0.02%	-300.70	0.482
LYNN	SWAMPSCOTT	4.13	2	12	99	-319	-0.03%	-133.99	0.420
BELMONT	CAMBRIDGE	3.56	1	16	48	-204	-0.01%	-85.26	0.418
TAUNTON	RAYNHAM	3.79	2	18	13	-14	0.00%	-5.17	0.362
CHELSEA	EVERETT	1.81	4	16	73	-227	-0.04%	-79.49	0.351
SWAMPSCOTT	LYNN	4.13	2	12	100	-482	-0.05%	-138.42	0.287
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-30.85	0.268
CAMBRIDGE	MEDFORD	4.01	5	16	287	-2094	-0.08%	-560.00	0.267
WATERTOWN	CAMBRIDGE	3.43	1	20	32	-233	-0.01%	-62.21	0.267
LYNN	MARBLEHEAD	7.38	1	12	42	-109	-0.01%	-27.74	0.255
NEWTON	WATERTOWN	3.80	6	20	88	-92	0.00%	-20.92	0.228
MALDEN	MELROSE	2.46	3	10	108	-208	-0.02%	-47.17	0.227
N. ATTLEBOR.	ATTLEBORO	6.19	5	20	41	-177	0.00%	-39.86	0.225
CAMBRIDGE	WALTHAM	6.85	3	18	176	-1167	-0.03%	-261.64	0.224
WALTHAM	WATERTOWN	4.46	6	20	180	-1337	-0.04%	-292.59	0.219
LYNN	REVERE	5.52	2	14	119	-905	-0.06%	-195.29	0.216
LYNN	SALEM	5.61	3	14	148	-949	-0.04%	-203.55	0.214
ANDOVER	LAWRENCE	4.80	4	20	53	-545	-0.02%	-102.67	0.188
MEDFORD	MALDEN	2.94	1	20	26	-238	-0.01%	-41.38	0.174
MEDFORD	ARLINGTON	3.64	4	20	65	-261	-0.02%	-40.93	0.157
ROCKPORT	GLOUCESTER	5.59	1	20	32	-643	-0.03%	-95.48	0.148
WALTHAM	CAMBRIDGE	6.85	3	20	180	-2531	-0.08%	-344.56	0.136
PEABODY	LYNN	5.29	1	20	59	-1150	-0.04%	-141.21	0.123
MALDEN	SOMERVILLE	4.89	2	16	81	-849	-0.07%	-100.26	0.118
CHELSEA	REVERE	2.75	1	16	28	-305	-0.03%	-34.07	0.112
SOMERVILLE	MALDEN	4.89	2	16	58	-198	-0.01%	-22.01	0.111
BOSTON CBD	WINTHROP	5.93	6	16	247	-3420	-0.13%	-309.76	0.091
BELMONT	WATERTOWN	3.23	5	20	69	-973	-0.08%	-85.00	0.087
QUINCY	BRAINTREE	4.05	5	18	131	-1430	-0.03%	-124.74	0.087
BOSTON	MILTON	5.58	2	20	72	-1053	-0.01%	-80.10	0.076
READING	WAKEFIELD	3.41	2	14	36	-126	-0.01%	-9.22	0.073

Table 6.29: Case 5A ($\Delta F = 0, c_v = 71$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
WALTHAM	NEWTON	5.21	3	5.58	164	-97880	-1.28%	56.43	-0.001
FRAMINGHAM	NATICK	6.94	2	0.00	70	-60656	-0.97%	49.60	-0.001
WALTHAM	WATERTOWN	4.46	5	0.99	242	-47862	-1.40%	249.94	-0.005
BOSTON CBD	WINTHROP	5.93	5	3.72	273	-46552	-1.80%	149.01	-0.003
NEWTON	WALTHAM	5.21	2	4.77	103	-46348	-0.70%	51.93	-0.001
CAMBRIDGE	NEWTON	6.98	3	8.71	154	-46158	-0.85%	32.55	-0.001
BRAINTREE	WEYMOUTH	3.82	2	6.87	43	-39866	-0.84%	101.41	-0.003
NEWTON	WATERTOWN	3.80	2	3.02	94	-37943	-1.28%	47.11	-0.001
QUINCY	BRAINTREE	4.05	3	5.53	156	-37323	-0.77%	23.46	-0.001
SALEM	PEABODY	5.22	2	5.14	102	-35448	-1.28%	18.46	-0.001
LAWRENCE	METHUEN	3.14	1	0.00	50	-35197	-0.85%	17.19	0.000
WATERTOWN	CAMBRIDGE	3.43	3	1.85	168	-34398	-1.33%	98.24	-0.003
DEDHAM	BOSTON	7.55	3	8.32	151	-34309	-0.43%	62.29	-0.002
NORWOOD	WALPOLE	5.16	2	1.38	52	-33804	-1.11%	67.71	-0.002
CHELMSFORD	LOWELL	4.63	1	0.00	37	-32258	-0.74%	19.06	-0.001
BOSTON CBD	NORWOOD	14.70	3	8.38	179	-30980	-0.51%	178.01	-0.006
BEVERLY	DANVERS	5.51	1	3.43	30	-29429	-0.78%	40.00	-0.001
SOMERVILLE	MEDFORD	2.45	5	1.88	280	-29291	-1.40%	102.88	-0.004
QUINCY	WEYMOUTH	6.14	2	5.86	107	-28915	-0.50%	31.76	-0.001
PEABODY	SALEM	5.22	2	2.90	65	-28259	-1.04%	79.98	-0.003
ANDOVER	LAWRENCE	4.80	2	0.00	59	-26602	-0.89%	43.42	-0.002
BURLINGTON	WOBURN	3.61	1	2.92	40	-26536	-0.78%	26.05	-0.001
LEXINGTON	WALTHAM	4.18	1	3.52	25	-26480	-0.73%	48.94	-0.002
PEABODY	LYNN	5.29	3	1.46	134	-26474	-0.94%	174.51	-0.007
WELLESLEY	NEEDHAM	3.48	2	2.11	45	-25954	-1.29%	44.66	-0.002
BOSTON CBD	WOBURN	11.50	2	6.47	107	-25871	-0.76%	49.09	-0.002
BRAINTREE	QUINCY	4.05	3	3.39	162	-25797	-0.77%	64.74	-0.003
NEEDHAM	WELLESLEY	3.48	2	1.75	40	-25385	-1.27%	46.94	-0.002
DANVERS	BEVERLY	5.51	1	4.81	27	-25287	-0.65%	38.53	-0.002
WALTHAM	LEXINGTON	4.18	1	3.77	26	-25117	-0.72%	47.68	-0.002
LOWELL	CHELMSFORD	4.63	1	0.00	31	-24856	-0.63%	19.06	-0.001
WALTHAM	ARLINGTON	6.44	2	10.07	46	-24407	-0.91%	158.52	-0.006
WATERTOWN	WALTHAM	4.46	2	1.86	98	-24086	-0.77%	83.94	-0.003
WELLESLEY	NEWTON	4.88	2	3.76	68	-23926	-0.87%	73.08	-0.003
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	27	-23826	-0.57%	21.49	-0.001
WALTHAM	BELMONT	3.91	2	1.86	91	-23616	-1.18%	79.33	-0.003
WOBURN	BURLINGTON	3.61	1	3.61	33	-23578	-0.73%	27.85	-0.001
BRAINTREE	RANDOLPH	4.08	2	3.86	30	-22826	-0.93%	128.85	-0.006
NEEDHAM	NEWTON	4.49	2	1.43	69	-22400	-0.83%	105.92	-0.005
WATERTOWN	NEWTON	3.80	2	3.30	50	-22308	-0.74%	76.52	-0.003
BELMONT	WATERTOWN	3.23	2	1.99	76	-22053	-1.81%	37.65	-0.002
MEDFORD	SOMERVILLE	2.45	6	0.89	352	-21732	-1.12%	174.87	-0.008
LOWELL	TEWKSBURY	5.57	2	0.00	29	-21664	-0.74%	46.66	-0.002
WALTHAM	CAMBRIDGE	6.85	4	2.62	226	-21016	-0.69%	292.66	-0.014
BELMONT	CAMBRIDGE	3.56	3	2.54	162	-20199	-1.17%	84.20	-0.004
CAMBRIDGE	WATERTOWN	3.43	7	5.18	378	-20087	-0.67%	33.94	-0.002
WEYMOUTH	HINGHAM	4.65	1	4.61	30	-19808	-0.51%	26.59	-0.001
FRAMINGHAM	MARLBORO.	9.72	1	0.00	13	-19376	-0.41%	26.99	-0.001
PEABODY	DANVERS	4.85	1	1.10	44	-19331	-0.68%	33.77	-0.002
DANVERS	PEABODY	4.85	1	2.78	53	-19115	-0.69%	16.91	-0.001

Table 6.30: Case 5A ($\Delta F = 0, c_v = 71$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
NEWTON	BROOKLINE	4.21	5	6.37	286	-4138	-0.15%	-18.77	0.005
BOSTON CBD	WEYMOUTH	14.56	2	23.10	112	-15873	-0.20%	-60.75	0.004
MILTON	BOSTON	5.58	2	11.12	92	-7580	-0.12%	-9.86	0.001
LAWRENCE	METHUEN	3.14	1	0.00	50	-35197	-0.85%	17.19	0.000
SALEM	PEABODY	5.22	2	5.14	102	-35448	-1.28%	18.46	-0.001
WALTHAM	NEWTON	5.21	3	5.58	164	-97880	-1.28%	56.43	-0.001
CHELMSFORD	LOWELL	4.63	1	0.00	37	-32258	-0.74%	19.06	-0.001
QUINCY	BRAINTREE	4.05	3	5.53	156	-37323	-0.77%	23.46	-0.001
CAMBRIDGE	NEWTON	6.98	3	8.71	154	-46158	-0.85%	32.55	-0.001
LOWELL	CHELMSFORD	4.63	1	0.00	31	-24856	-0.63%	19.06	-0.001
FRAMINGHAM	NATICK	6.94	2	0.00	70	-60656	-0.97%	49.60	-0.001
DANVERS	PEABODY	4.85	1	2.78	53	-19115	-0.69%	16.91	-0.001
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	27	-23826	-0.57%	21.49	-0.001
BOSTON	MILTON	5.58	2	9.20	101	-13850	-0.15%	13.47	-0.001
BURLINGTON	WOBURN	3.61	1	2.92	40	-26536	-0.78%	26.05	-0.001
HUDSON	MARLBORO.	4.02	1	0.00	21	-17031	-0.75%	18.10	-0.001
QUINCY	WEYMOUTH	6.14	2	5.86	107	-28915	-0.50%	31.76	-0.001
NEWTON	WALTHAM	5.21	2	4.77	103	-46348	-0.70%	51.93	-0.001
WOBURN	BURLINGTON	3.61	1	3.61	33	-23578	-0.73%	27.85	-0.001
NEWTON	CAMBRIDGE	6.98	1	7.75	58	-3354	-0.11%	4.04	-0.001
ATTLEBORO	N. ATTLEBOR.	6.19	1	0.00	22	-17528	-0.44%	21.49	-0.001
NEWTON	WATERTOWN	3.80	2	3.02	94	-37943	-1.28%	47.11	-0.001
WEYMOUTH	HINGHAM	4.65	1	4.61	30	-19808	-0.51%	26.59	-0.001
BEVERLY	DANVERS	5.51	1	3.43	30	-29429	-0.78%	40.00	-0.001
LAWRENCE	N. ANDOVER	4.46	1	0.00	22	-13672	-0.61%	18.85	-0.001
FRAMINGHAM	MARLBORO.	9.72	1	0.00	13	-19376	-0.41%	26.99	-0.001
WEYMOUTH	QUINCY	6.14	2	5.29	119	-4390	-0.23%	6.64	-0.002
DANVERS	BEVERLY	5.51	1	4.81	27	-25287	-0.65%	38.53	-0.002
ANDOVER	LAWRENCE	4.80	2	0.00	59	-26602	-0.89%	43.42	-0.002
CAMBRIDGE	WATERTOWN	3.43	7	5.18	378	-20087	-0.67%	33.94	-0.002
BELMONT	WATERTOWN	3.23	2	1.99	76	-22053	-1.81%	37.65	-0.002
SALEM	MARBLEHEAD	3.75	2	4.58	105	-18563	-1.45%	31.87	-0.002
WELLESLEY	NEEDHAM	3.48	2	2.11	45	-25954	-1.29%	44.66	-0.002
PEABODY	DANVERS	4.85	1	1.10	44	-19331	-0.68%	33.77	-0.002
DEDHAM	BOSTON	7.55	3	8.32	151	-34309	-0.43%	62.29	-0.002
LEXINGTON	WALTHAM	4.18	1	3.52	25	-26480	-0.73%	48.94	-0.002
NEEDHAM	WELLESLEY	3.48	2	1.75	40	-25385	-1.27%	46.94	-0.002
FRAMINGHAM	ASHLAND	9.19	1	0.00	16	-13998	-0.42%	26.17	-0.002
BOSTON CBD	WOBURN	11.50	2	6.47	107	-25871	-0.76%	49.09	-0.002
WALTHAM	LEXINGTON	4.18	1	3.77	26	-25117	-0.72%	47.68	-0.002
ASHLAND	FRAMINGHAM	9.19	1	0.00	16	-13213	-0.44%	26.17	-0.002
BILLERICA	LOWELL	6.58	1	6.94	43	-18874	-0.43%	37.50	-0.002
NORWOOD	WALPOLE	5.16	2	1.38	52	-33804	-1.11%	67.71	-0.002
LOWELL	TEWKSBURY	5.57	2	0.00	29	-21664	-0.74%	46.66	-0.002
LYNN	SWAMPSCOTT	4.13	2	3.23	117	-4665	-0.44%	10.15	-0.002
MEDFORD	MALDEN	2.94	2	4.00	86	-17321	-0.97%	39.33	-0.002
FOXBOROUGH	MANSFIELD	4.03	1	0.00	13	-7896	-0.45%	18.12	-0.002
NORWOOD	WESTWOOD	2.22	1	0.83	26	-10392	-0.74%	24.25	-0.002
SOMERVILLE	ARLINGTON	3.92	2	4.14	99	-15958	-0.99%	37.95	-0.002
WATERTOWN	BELMONT	3.23	2	1.92	66	-17157	-1.35%	41.38	-0.002

Table 6.31: Case 1B ($F = 0, c_v = 0$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
WALTHAM	NEWTON	5.21	3	0	179	-116025	-1.52%	136.48	-0.001
BOSTON CBD	WEYMOUTH	14.56	4	0	206	-92352	-1.16%	568.77	-0.006
CAMBRIDGE	NEWTON	6.98	3	0	177	-68959	-1.27%	176.38	-0.003
FRAMINGHAM	NATICK	6.94	2	0	69	-60276	-0.96%	21.67	0.000
BOSTON CBD	WINTHROP	5.93	5	0	281	-56389	-2.18%	206.34	-0.004
NEWTON	WALTHAM	5.21	2	0	114	-56114	-0.85%	84.37	-0.002
BOSTON CBD	BRAINTREE	11.92	5	0	260	-55245	-0.86%	630.17	-0.011
DEDHAM	BOSTON	7.55	3	0	171	-52643	-0.65%	183.83	-0.003
WOBURN	BURLINGTON	3.61	2	0	67	-52622	-1.62%	56.26	-0.001
BRAINTREE	WEYMOUTH	3.82	2	0	50	-50887	-1.08%	100.31	-0.002
WALTHAM	WATERTOWN	4.46	5	0	245	-49950	-1.46%	172.24	-0.003
QUINCY	BRAINTREE	4.05	3	0	171	-47908	-0.99%	106.49	-0.002
BOSTON CBD	NORWOOD	14.70	4	0	215	-46318	-0.76%	407.14	-0.009
BOSTON CBD	RANDOLPH	12.63	2	0	97	-44945	-0.93%	218.80	-0.005
NEWTON	WATERTOWN	3.80	2	0	100	-42126	-1.42%	53.84	-0.001
SALEM	PEABODY	5.22	2	0	108	-41532	-1.50%	65.79	-0.002
QUINCY	WEYMOUTH	6.14	2	0	118	-39171	-0.68%	92.97	-0.002
BOSTON CBD	FRAMINGHAM	20.46	2	0	103	-39011	-0.66%	224.19	-0.006
BOSTON CBD	WOBURN	11.50	2	0	116	-38092	-1.12%	112.16	-0.003
WALTHAM	ARLINGTON	6.44	2	0	55	-37754	-1.41%	158.41	-0.004
WATERTOWN	CAMBRIDGE	3.43	3	0	174	-37330	-1.44%	84.81	-0.002
BOSTON	MILTON	5.58	3	0	165	-35070	-0.38%	170.63	-0.005
NORWOOD	WALPOLE	5.16	2	0	52	-35037	-1.15%	44.58	-0.001
LAWRENCE	METHUEN	3.14	1	0	49	-34888	-0.84%	4.90	0.000
BOSTON	DEDHAM	7.55	2	0	97	-34033	-0.29%	128.09	-0.004
BEVERLY	DANVERS	5.51	1	0	32	-32213	-0.86%	34.13	-0.001
CHELMSFORD	LOWELL	4.63	1	0	37	-32169	-0.73%	7.22	0.000
SOMERVILLE	MEDFORD	2.45	5	0	287	-31887	-1.52%	101.85	-0.003
PEABODY	SALEM	5.22	2	0	68	-31557	-1.16%	67.21	-0.002
CAMBRIDGE	WATERTOWN	3.43	7	0	410	-31501	-1.05%	223.92	-0.007
BRAINTREE	QUINCY	4.05	3	0	170	-30261	-0.90%	91.32	-0.003
DANVERS	BEVERLY	5.51	1	0	30	-29304	-0.75%	37.72	-0.001
LEXINGTON	WALTHAM	4.18	1	0	27	-29159	-0.80%	38.60	-0.001
BURLINGTON	WOBURN	3.61	1	0	42	-28810	-0.84%	25.37	-0.001
PEABODY	LYNN	5.29	3	0	136	-28272	-1.01%	127.67	-0.005
WALTHAM	LEXINGTON	4.18	1	0	28	-27850	-0.80%	38.99	-0.001
WELLESLEY	NEWTON	4.88	2	0	71	-27829	-1.01%	69.59	-0.003
WELLESLEY	NEEDHAM	3.48	2	0	46	-27718	-1.38%	29.83	-0.001
NEEDHAM	WELLESLEY	3.48	2	0	41	-26835	-1.34%	27.75	-0.001
BRAINTREE	RANDOLPH	4.08	2	0	33	-26801	-1.09%	94.73	-0.004
LYNN	PEABODY	5.29	2	0	91	-26596	-1.00%	85.38	-0.003
BROOKLINE	NEWTON	4.21	4	0	226	-26512	-0.89%	148.95	-0.006
ANDOVER	LAWRENCE	4.80	2	0	59	-26478	-0.89%	14.97	-0.001
WATERTOWN	WALTHAM	4.46	2	0	102	-26198	-0.84%	68.31	-0.003
WALTHAM	CAMBRIDGE	6.85	4	0	231	-25983	-0.85%	254.26	-0.010
WATERTOWN	NEWTON	3.80	2	0	54	-25975	-0.86%	61.50	-0.002
WALTHAM	BELMONT	3.91	2	0	93	-25465	-1.27%	61.87	-0.002
WELLESLEY	NATICK	3.77	2	0	42	-24940	-0.87%	70.40	-0.003
NEWTON	CAMBRIDGE	6.98	2	0	120	-24874	-0.79%	106.06	-0.004
LOWELL	CHELMSFORD	4.63	1	0	30	-24740	-0.63%	7.22	0.000

Table 6.32: Case 1B ($F = 0, c_v = 0$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
LAWRENCE	METHUEN	3.14	1	0	49	-34888	-0.84%	4.90	0.000
CHELMSFORD	LOWELL	4.63	1	0	37	-32169	-0.73%	7.22	0.000
LOWELL	CHELMSFORD	4.63	1	0	30	-24740	-0.63%	7.22	0.000
FRAMINGHAM	NATICK	6.94	2	0	69	-60276	-0.96%	21.67	0.000
HUDSON	MARLBORO.	4.02	1	0	21	-16856	-0.74%	6.27	0.000
N. ATTLEBOR.	ATTLEBORO	6.19	1	0	26	-23534	-0.57%	9.65	0.000
LAWRENCE	N. ANDOVER	4.46	1	0	21	-13472	-0.61%	6.95	-0.001
ATTLEBORO	N. ATTLEBOR.	6.19	1	0	22	-17267	-0.43%	9.65	-0.001
ANDOVER	LAWRENCE	4.80	2	0	59	-26478	-0.89%	14.97	-0.001
FRAMINGHAM	MARLBORO.	9.72	1	0	13	-19111	-0.41%	15.16	-0.001
LOWELL	TEWKSBURY	5.57	2	0	29	-21452	-0.73%	17.37	-0.001
FOXBOROUGH	MANSFIELD	4.03	1	0	13	-7771	-0.45%	6.29	-0.001
BURLINGTON	WOBURN	3.61	1	0	42	-28810	-0.84%	25.37	-0.001
MILFORD	HOPEDALE	2.62	1	0	11	-4155	-0.62%	4.08	-0.001
FRAMINGHAM	ASHLAND	9.19	1	0	16	-13885	-0.41%	14.34	-0.001
NEEDHAM	WELLESLEY	3.48	2	0	41	-26835	-1.34%	27.75	-0.001
MANSFIELD	FOXBOROUGH	4.03	1	0	12	-6034	-0.40%	6.29	-0.001
BEVERLY	DANVERS	5.51	1	0	32	-32213	-0.86%	34.13	-0.001
ROCKPORT	GLOUCESTER	5.59	2	0	61	-16406	-0.80%	17.43	-0.001
WOBURN	BURLINGTON	3.61	2	0	67	-52622	-1.62%	56.26	-0.001
WELLESLEY	NEEDHAM	3.48	2	0	46	-27718	-1.38%	29.83	-0.001
ASHLAND	FRAMINGHAM	9.19	1	0	16	-13048	-0.43%	14.34	-0.001
NEWBURYP.	AMESBURY	5.14	1	0	11	-6959	-0.57%	8.02	-0.001
DANVERS	PEABODY	4.85	1	0	55	-20667	-0.75%	24.12	-0.001
NORWOOD	WESTWOOD	2.22	1	0	26	-10607	-0.75%	12.39	-0.001
WALTHAM	NEWTON	5.21	3	0	179	-116025	-1.52%	136.48	-0.001
PEABODY	DANVERS	4.85	1	0	45	-19886	-0.70%	23.42	-0.001
WEYMOUTH	HINGHAM	4.65	1	0	32	-22771	-0.59%	27.13	-0.001
SOUTHBORO.	MARLBORO.	3.66	1	0	9	-4639	-0.35%	5.71	-0.001
WESTBORO.	NORTHBORO.	4.56	1	0	10	-5717	-0.37%	7.11	-0.001
TAUNTON	RAYNHAM	3.79	1	0	10	-4731	-0.20%	5.91	-0.001
NORWOOD	WALPOLE	5.16	2	0	52	-35037	-1.15%	44.58	-0.001
NEWTON	WATERTOWN	3.80	2	0	100	-42126	-1.42%	53.84	-0.001
DANVERS	BEVERLY	5.51	1	0	30	-29304	-0.75%	37.72	-0.001
LEXINGTON	WALTHAM	4.18	1	0	27	-29159	-0.80%	38.60	-0.001
BELMONT	WATERTOWN	3.23	2	0	79	-23628	-1.94%	31.42	-0.001
MARLBORO.	HUDSON	4.02	2	0	21	-9187	-0.36%	12.53	-0.001
WALTHAM	LEXINGTON	4.18	1	0	28	-27850	-0.80%	38.99	-0.001
PLAINVILLE	N. ATTLEBOR.	3.25	1	0	10	-3556	-0.36%	5.07	-0.001
NEWTON	WALTHAM	5.21	2	0	114	-56114	-0.85%	84.37	-0.002
SALEM	PEABODY	5.22	2	0	108	-41532	-1.50%	65.79	-0.002
FRANKLIN	BELLINGHAM	4.09	1	0	9	-3973	-0.25%	6.38	-0.002
GLOUCESTER	ROCKPORT	5.59	2	0	60	-10755	-0.46%	17.43	-0.002
WATERTOWN	BELMONT	3.23	2	0	69	-18626	-1.46%	30.96	-0.002
WOBURN	READING	4.99	1	0	16	-11572	-0.68%	19.46	-0.002
BEDFORD	BILLERICA	5.24	1	0	18	-16727	-0.57%	29.20	-0.002
WEYMOUTH	BRAINTREE	3.82	1	0	32	-16354	-0.61%	30.27	-0.002
LOWELL	TYNGSBORO.	7.38	1	0	11	-6010	-0.31%	11.51	-0.002
CHELMSFORD	WESTFORD	4.51	1	0	9	-3633	-0.20%	7.04	-0.002
BURLINGTON	BILLERICA	5.81	1	0	14	-15656	-0.53%	30.42	-0.002

Table 6.33: Case 2B ($F = 8, c_v = 0$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare (\$)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost (\$)	Efficiency (\$/gCO$_2$e)
WALTHAM	NEWTON	5.21	3	8	156	-88961	-1.16%	-87.63	0.001
BOSTON CBD	WEYMOUTH	14.56	3	8	176	-66755	-0.84%	174.25	-0.003
CAMBRIDGE	NEWTON	6.98	3	8	155	-46520	-0.86%	-45.93	0.001
BOSTON CBD	BRAINTREE	11.92	4	8	234	-45595	-0.71%	168.48	-0.004
BRAINTREE	WEYMOUTH	3.82	2	8	42	-37666	-0.80%	39.89	-0.001
LAWRENCE	METHUEN	3.14	8	8	107	-36167	-0.87%	-113.87	0.003
DEDHAM	BOSTON	7.55	3	8	150	-32914	-0.41%	-31.25	0.001
SALEM	PEABODY	5.22	2	8	98	-31729	-1.14%	-74.44	0.002
BEVERLY	DANVERS	5.51	1	8	27	-25551	-0.68%	-4.31	0.000
BOSTON CBD	RANDOLPH	12.63	2	8	84	-23439	-0.49%	98.95	-0.004
LEXINGTON	WALTHAM	4.18	1	8	23	-22971	-0.63%	5.57	0.000
DANVERS	BEVERLY	5.51	1	8	25	-22625	-0.58%	1.88	0.000
BOSTON CBD	WOBURN	11.50	2	8	105	-22513	-0.66%	-37.98	0.002
BURLINGTON	WOBURN	3.61	1	8	35	-22338	-0.65%	-25.35	0.001
WALTHAM	LEXINGTON	4.18	1	8	24	-21800	-0.62%	4.75	0.000
WOBURN	BURLINGTON	3.61	1	8	30	-20115	-0.62%	-15.17	0.001
BRAINTREE	RANDOLPH	4.08	2	8	28	-18471	-0.75%	54.95	-0.003
BROCKTON	EASTON	5.95	1	8	19	-18161	-0.41%	22.62	-0.001
BILLERICA	LOWELL	6.58	1	8	42	-18027	-0.41%	2.49	0.000
BOSTON	DEDHAM	7.55	2	8	77	-17516	-0.15%	17.13	-0.001
PEABODY	LYNN	5.29	2	8	111	-17445	-0.62%	-74.62	0.004
WEYMOUTH	HINGHAM	4.65	1	8	29	-17427	-0.45%	-13.77	0.001
BOSTON CBD	FRAMINGHAM	20.46	2	8	92	-16552	-0.28%	92.46	-0.006
WATERTOWN	NEWTON	3.80	2	8	43	-16415	-0.54%	-0.11	0.000
WELLESLEY	NATICK	3.77	2	8	36	-16233	-0.57%	19.26	-0.001
DANVERS	PEABODY	4.85	1	8	50	-15930	-0.58%	-46.86	0.003
SALEM	MARBLEHEAD	3.75	2	8	101	-15920	-1.24%	-80.30	0.005
PEABODY	DANVERS	4.85	1	8	40	-15072	-0.53%	-33.67	0.002
BOSTON	MILTON	5.58	2	8	104	-14943	-0.16%	-34.92	0.002
BROCKTON	WHITMAN	4.46	2	8	22	-14412	-0.62%	35.51	-0.002
HINGHAM	WEYMOUTH	4.65	1	8	28	-14368	-0.37%	3.78	0.000
LEXINGTON	BURLINGTON	5.47	2	8	23	-13571	-0.59%	71.64	-0.005
FRAMINGHAM	MARLBORO.	9.72	1	8	11	-13237	-0.28%	-1.11	0.000
SAUGUS	LYNN	3.42	2	8	42	-12646	-0.64%	14.48	-0.001
BEDFORD	BILLERICA	5.24	1	8	15	-12439	-0.42%	7.40	-0.001
NEWTON	WATERTOWN	3.80	1	8	47	-12151	-0.41%	-39.80	0.003
WEYMOUTH	BRAINTREE	3.82	1	8	28	-12100	-0.45%	-9.29	0.001
NEWTON	WALTHAM	5.21	1	8	42	-11951	-0.18%	-17.52	0.001
NORWOOD	WALPOLE	5.16	1	8	26	-11778	-0.39%	-14.38	0.001
WALTHAM	ARLINGTON	6.44	1	8	29	-11454	-0.43%	38.20	-0.003
BEVERLY	PEABODY	8.34	1	8	18	-11155	-0.38%	24.63	-0.002
BURLINGTON	BILLERICA	5.81	1	8	12	-11149	-0.38%	13.78	-0.001
PEABODY	BEVERLY	8.34	2	8	25	-10847	-0.40%	63.54	-0.006
CHELMSFORD	LOWELL	4.63	8	8	74	-10767	-0.25%	-47.77	0.004
WALTHAM	CAMBRIDGE	6.85	4	8	214	-10711	-0.35%	-51.90	0.005
WELLESLEY	NEEDHAM	3.48	1	8	21	-9774	-0.49%	-14.86	0.002
NEWTON	WELLESLEY	4.88	2	8	43	-9751	-0.31%	12.56	-0.001
CONCORD	ACTON	4.33	1	8	13	-9745	-0.30%	41.64	-0.004
BOSTON CBD	NORWOOD	14.70	4	8	190	-9726	-0.16%	134.23	-0.014
CAMBRIDGE	WALTHAM	6.85	4	8	229	-9714	-0.24%	-66.69	0.007

Table 6.34: Case 2B ($F = 8, c_v = 0$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
MALDEN	EVERETT	2.09	5	8	133	-128	-0.02%	-113.63	0.885
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-69.12	0.601
MELROSE	MALDEN	2.46	4	8	162	-577	-0.07%	-150.39	0.261
READING	WAKEFIELD	3.41	1	8	23	-41	0.00%	-10.63	0.260
LYNN	SWAMPSCOTT	4.13	3	8	128	-658	-0.06%	-121.11	0.184
MEDFORD	SOMERVILLE	2.45	8	8	313	-1626	-0.08%	-293.16	0.180
SWAMPSCOTT	LYNN	4.13	3	8	128	-739	-0.07%	-124.17	0.168
EVERETT	MALDEN	2.09	5	8	122	-627	-0.07%	-93.49	0.149
NEWBURYP.	NEWBURY	4.05	2	8	15	-56	-0.01%	-8.24	0.148
ROCKPORT	GLOUCESTER	5.59	4	8	65	-446	-0.02%	-58.36	0.131
NEWTON	BROOKLINE	4.21	5	8	280	-1714	-0.06%	-219.66	0.128
LYNN	SALEM	5.61	4	8	177	-950	-0.04%	-121.42	0.128
WINCHESTER	MEDFORD	3.62	1	8	34	-171	-0.02%	-20.29	0.119
WATERTOWN	BELMONT	3.23	6	8	78	-178	-0.01%	-19.08	0.107
ARLINGTON	CAMBRIDGE	4.14	5	8	192	-1285	-0.05%	-110.40	0.086
CAMBRIDGE	EVERETT	4.41	3	8	152	-1188	-0.09%	-101.04	0.085
EVERETT	CHELSEA	1.81	4	8	71	-682	-0.13%	-47.93	0.070
MALDEN	SOMERVILLE	4.89	1	8	51	-542	-0.04%	-34.08	0.063
MALDEN	MELROSE	2.46	3	8	113	-1255	-0.13%	-78.21	0.062
LOWELL	CHELMSFORD	4.63	8	8	65	-585	-0.01%	-35.65	0.061
CAMBRIDGE	MEDFORD	4.01	6	8	329	-5264	-0.19%	-291.00	0.055
SOMERVILLE	MEDFORD	2.45	8	8	252	-3849	-0.18%	-198.09	0.051
BELMONT	CAMBRIDGE	3.56	5	8	156	-1529	-0.09%	-77.90	0.051
LYNN	REVERE	5.52	3	8	152	-2914	-0.18%	-127.34	0.044
CAMBRIDGE	WATERTOWN	3.43	8	8	360	-5971	-0.20%	-260.64	0.044
TAUNTON	RAYNHAM	3.79	3	8	19	-225	-0.01%	-9.59	0.043
CAMBRIDGE	BELMONT	3.56	5	8	233	-4193	-0.19%	-166.00	0.040
WEYMOUTH	QUINCY	6.14	2	8	116	-2553	-0.14%	-98.55	0.039
GLOUCESTER	ROCKPORT	5.59	3	8	62	-1822	-0.08%	-62.66	0.034
BROOKLINE	NEWTON	4.21	5	8	201	-3930	-0.13%	-102.52	0.026
MARBLEHEAD	LYNN	7.38	2	8	69	-916	-0.07%	-22.35	0.024
BEDFORD	LEXINGTON	4.47	1	8	32	-792	-0.06%	-18.00	0.023
MEDFORD	CAMBRIDGE	4.01	4	8	177	-6014	-0.31%	-131.03	0.022
ARLINGTON	SOMERVILLE	3.92	1	8	50	-1936	-0.13%	-41.01	0.021
REVERE	LYNN	5.52	3	8	84	-1844	-0.10%	-36.61	0.020
CHELSEA	EVERETT	1.81	1	8	38	-2173	-0.36%	-38.27	0.018
MILFORD	HOPEDALE	2.62	3	8	21	-1051	-0.16%	-17.43	0.017
LYNN	MARBLEHEAD	7.38	1	8	45	-1656	-0.11%	-25.88	0.016
ANDOVER	LAWRENCE	4.80	5	8	65	-3594	-0.12%	-55.39	0.015
HUDSON	MARLBORO.	4.02	6	8	42	-1463	-0.06%	-22.33	0.015
FRAMINGHAM	NATICK	6.94	8	8	77	-1725	-0.03%	-23.80	0.014
CHELSEA	REVERE	2.75	5	8	92	-674	-0.07%	-9.25	0.014
BOSTON CBD	WINTHROP	5.93	7	8	264	-7255	-0.28%	-88.93	0.012
SOMERVILLE	ARLINGTON	3.92	1	8	45	-2818	-0.17%	-32.76	0.012
BRAINTREE	QUINCY	4.05	5	8	158	-7185	-0.21%	-73.70	0.010
SALEM	DANVERS	5.97	1	8	36	-1437	-0.12%	-14.23	0.010
N. ATTLEBOR.	PLAINVILLE	3.25	2	8	15	-1081	-0.12%	-10.68	0.010
REVERE	CHELSEA	2.75	3	8	65	-2292	-0.28%	-22.16	0.010
NEWTON	CAMBRIDGE	6.98	1	8	58	-3101	-0.10%	-29.92	0.010
WATERTOWN	CAMBRIDGE	3.43	6	8	157	-5918	-0.23%	-55.97	0.009

Table 6.35: Case 3B ($F \leq 20, c_v = 0$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO$_2$e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/gCO$_2$e)
MALDEN	EVERETT	2.09	5	8	133	-128	-0.02%	-113.63	0.885
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-69.12	0.601
MELROSE	MALDEN	2.46	4	8	162	-577	-0.07%	-150.39	0.261
READING	WAKEFIELD	3.41	1	8	23	-41	0.00%	-10.63	0.260
LYNN	SWAMPSCOTT	4.13	3	8	128	-658	-0.06%	-121.11	0.184
MEDFORD	SOMERVILLE	2.45	8	8	313	-1626	-0.08%	-293.16	0.180
SWAMPSCOTT	LYNN	4.13	3	8	128	-739	-0.07%	-124.17	0.168
EVERETT	MALDEN	2.09	5	8	122	-627	-0.07%	-93.49	0.149
NEWBURYP.	NEWBURY	4.05	2	8	15	-56	-0.01%	-8.24	0.148
ROCKPORT	GLOUCESTER	5.59	4	8	65	-446	-0.02%	-58.36	0.131
NEWTON	BROOKLINE	4.21	5	8	280	-1714	-0.06%	-219.66	0.128
LYNN	SALEM	5.61	4	8	177	-950	-0.04%	-121.42	0.128
WINCHESTER	MEDFORD	3.62	1	8	34	-171	-0.02%	-20.29	0.119
WATERTOWN	BELMONT	3.23	6	8	78	-178	-0.01%	-19.08	0.107
ARLINGTON	CAMBRIDGE	4.14	5	8	192	-1285	-0.05%	-110.40	0.086
CAMBRIDGE	EVERETT	4.41	3	8	152	-1188	-0.09%	-101.04	0.085
EVERETT	CHELSEA	1.81	4	8	71	-682	-0.13%	-47.93	0.070
MALDEN	SOMERVILLE	4.89	1	8	51	-542	-0.04%	-34.08	0.063
MALDEN	MELROSE	2.46	3	8	113	-1255	-0.13%	-78.21	0.062
LOWELL	CHELMSFORD	4.63	8	8	65	-585	-0.01%	-35.65	0.061
CAMBRIDGE	MEDFORD	4.01	6	8	329	-5264	-0.19%	-291.00	0.055
SOMERVILLE	MEDFORD	2.45	8	8	252	-3849	-0.18%	-198.09	0.051
BELMONT	CAMBRIDGE	3.56	5	8	156	-1529	-0.09%	-77.90	0.051
LYNN	REVERE	5.52	3	8	152	-2914	-0.18%	-127.34	0.044
CAMBRIDGE	WATERTOWN	3.43	8	8	360	-5971	-0.20%	-260.64	0.044
TAUNTON	RAYNHAM	3.79	3	8	19	-225	-0.01%	-9.59	0.043
CAMBRIDGE	BELMONT	3.56	5	8	233	-4193	-0.19%	-166.00	0.040
WEYMOUTH	QUINCY	6.14	2	8	116	-2553	-0.14%	-98.55	0.039
GLOUCESTER	ROCKPORT	5.59	3	8	62	-1822	-0.08%	-62.66	0.034
BROOKLINE	NEWTON	4.21	5	8	201	-3930	-0.13%	-102.52	0.026
MARBLEHEAD	LYNN	7.38	2	8	69	-916	-0.07%	-22.35	0.024
BEDFORD	LEXINGTON	4.47	1	8	32	-792	-0.06%	-18.00	0.023
MEDFORD	CAMBRIDGE	4.01	4	8	177	-6014	-0.31%	-131.03	0.022
ARLINGTON	SOMERVILLE	3.92	1	8	50	-1936	-0.13%	-41.01	0.021
REVERE	LYNN	5.52	3	8	84	-1844	-0.10%	-36.61	0.020
CHELSEA	EVERETT	1.81	1	8	38	-2173	-0.36%	-38.27	0.018
MILFORD	HOPEDALE	2.62	3	8	21	-1051	-0.16%	-17.43	0.017
LYNN	MARBLEHEAD	7.38	1	8	45	-1656	-0.11%	-25.88	0.016
ANDOVER	LAWRENCE	4.80	5	8	65	-3594	-0.12%	-55.39	0.015
HUDSON	MARLBORO.	4.02	6	8	42	-1463	-0.06%	-22.33	0.015
FRAMINGHAM	NATICK	6.94	8	8	77	-1725	-0.03%	-23.80	0.014
CHELSEA	REVERE	2.75	5	8	92	-674	-0.07%	-9.25	0.014
BOSTON CBD	WINTHROP	5.93	7	8	264	-7255	-0.28%	-88.93	0.012
SOMERVILLE	ARLINGTON	3.92	1	8	45	-2818	-0.17%	-32.76	0.012
BRAINTREE	QUINCY	4.05	5	8	158	-7185	-0.21%	-73.70	0.010
SALEM	DANVERS	5.97	1	8	36	-1437	-0.12%	-14.23	0.010
N. ATTLEBOR.	PLAINVILLE	3.25	2	8	15	-1081	-0.12%	-10.68	0.010
REVERE	CHELSEA	2.75	3	8	65	-2292	-0.28%	-22.16	0.010
NEWTON	CAMBRIDGE	6.98	1	8	58	-3101	-0.10%	-29.92	0.010
WATERTOWN	CAMBRIDGE	3.43	6	8	157	-5918	-0.23%	-55.97	0.009

Table 6.36: Case 3B ($F \leq 20, c_v = 0$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
MEDFORD	CAMBRIDGE	4.01	3	20	135	-26	0.00%	-389.52	15.275
ARLINGTON	SOMERVILLE	3.92	3	20	97	-28	0.00%	-254.30	9.002
WINCHESTER	ARLINGTON	3.32	2	20	32	-9	0.00%	-75.34	8.754
MEDFORD	SOMERVILLE	2.45	7	14	282	-113	-0.01%	-571.10	5.052
ARLINGTON	CAMBRIDGE	4.14	4	16	161	-77	0.00%	-330.12	4.281
BELMONT	WATERTOWN	3.23	6	14	77	-24	0.00%	-100.05	4.203
GLOUCESTER	ROCKPORT	5.59	3	10	60	-32	0.00%	-81.24	2.516
MALDEN	MEDFORD	2.94	1	20	24	-26	0.00%	-62.54	2.417
TAUNTON	RAYNHAM	3.79	2	18	13	-14	0.00%	-28.84	2.018
MALDEN	EVERETT	2.09	4	16	116	-146	-0.02%	-269.80	1.848
EVERETT	CHELSEA	1.81	1	14	25	-29	-0.01%	-48.53	1.695
NEWTON	WATERTOWN	3.80	6	20	88	-92	0.00%	-153.88	1.676
EVERETT	REVERE	3.89	1	18	25	-34	0.00%	-54.64	1.590
SOMERVILLE	ARLINGTON	3.92	1	16	36	-50	0.00%	-71.22	1.430
NEWTON	CAMBRIDGE	6.98	1	14	50	-51	0.00%	-71.97	1.423
WATERTOWN	WALTHAM	4.46	5	12	105	-52	0.00%	-55.84	1.079
CAMBRIDGE	BELMONT	3.56	4	18	190	-461	-0.02%	-478.68	1.038
EVERETT	MALDEN	2.09	1	16	36	-95	-0.01%	-86.00	0.902
CAMBRIDGE	WATERTOWN	3.43	6	20	289	-1093	-0.04%	-843.22	0.771
BRAINTREE	QUINCY	4.05	1	20	44	-173	-0.01%	-128.37	0.744
WEYMOUTH	QUINCY	6.14	2	12	113	-242	-0.01%	-174.44	0.721
MELROSE	MALDEN	2.46	2	18	108	-456	-0.05%	-306.25	0.672
CHELSEA	EVERETT	1.81	4	16	73	-227	-0.04%	-147.84	0.652
BROOKLINE	NEWTON	4.21	4	18	171	-624	-0.02%	-402.40	0.645
SOMERVILLE	MEDFORD	2.45	6	20	202	-1004	-0.05%	-603.37	0.601
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-69.12	0.601
N. ATTLEBOR.	ATTLEBORO	6.19	5	20	41	-177	0.00%	-99.03	0.559
LYNN	SWAMPSCOTT	4.13	2	12	99	-319	-0.03%	-170.15	0.534
BELMONT	CAMBRIDGE	3.56	1	16	48	-204	-0.01%	-108.75	0.533
MALDEN	MELROSE	2.46	3	10	108	-208	-0.02%	-110.17	0.530
NEEDHAM	WELLESLEY	3.48	5	18	37	-97	0.00%	-51.14	0.525
MEDFORD	ARLINGTON	3.64	4	20	65	-261	-0.02%	-124.78	0.478
LYNN	MARBLEHEAD	7.38	1	12	42	-109	-0.01%	-51.72	0.476
ATTLEBORO	N. ATTLEBOR.	6.19	5	14	41	-133	0.00%	-54.54	0.410
MANSFIELD	FOXBOROUGH	4.03	3	12	21	-64	0.00%	-25.59	0.400
SOMERVILLE	MALDEN	4.89	2	16	58	-198	-0.01%	-76.39	0.386
READING	WAKEFIELD	3.41	2	14	36	-126	-0.01%	-47.69	0.380
WELLESLEY	NEEDHAM	3.48	5	20	40	-191	-0.01%	-70.39	0.369
WATERTOWN	CAMBRIDGE	3.43	1	20	32	-233	-0.01%	-85.22	0.366
SWAMPSCOTT	LYNN	4.13	2	12	100	-482	-0.05%	-174.59	0.362
WALTHAM	WATERTOWN	4.46	6	20	180	-1337	-0.04%	-437.54	0.327
CAMBRIDGE	MEDFORD	4.01	5	16	287	-2094	-0.08%	-673.61	0.322
CAMBRIDGE	WALTHAM	6.85	3	18	176	-1167	-0.03%	-369.89	0.317
WALTHAM	CAMBRIDGE	6.85	4	14	200	-795	-0.03%	-248.32	0.312
BEDFORD	LEXINGTON	4.47	2	12	42	-113	-0.01%	-34.53	0.306
ANDOVER	LAWRENCE	4.80	4	20	53	-545	-0.02%	-159.57	0.293
BURLINGTON	WOBURN	3.61	8	20	66	-113	0.00%	-33.01	0.292
LYNN	SAUGUS	3.42	1	18	19	-96	-0.01%	-27.69	0.290
LYNN	SALEM	5.61	3	14	148	-949	-0.04%	-272.27	0.287
WOBURN	WINCHESTER	3.39	3	16	36	-177	-0.02%	-49.51	0.280

Table 6.37: Case 4B ($F \in [6, 20], c_v = 0$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
BEVERLY	DANVERS	5.51	1	20	21	-17343	-0.46%	-40.09	0.002
LAWRENCE	METHUEN	3.14	8	20	83	-15519	-0.37%	-256.73	0.017
LEXINGTON	WALTHAM	4.18	1	20	18	-15363	-0.42%	-25.67	0.002
LEXINGTON	BURLINGTON	5.47	2	6	24	-15309	-0.66%	78.72	-0.005
DANVERS	BEVERLY	5.51	1	20	19	-14447	-0.37%	-29.84	0.002
WALTHAM	LEXINGTON	4.18	1	20	19	-14363	-0.41%	-28.05	0.002
PEABODY	BEVERLY	8.34	2	6	26	-12700	-0.47%	71.20	-0.006
WOBURN	BURLINGTON	3.61	1	20	23	-12653	-0.39%	-54.48	0.004
BROCKTON	EASTON	5.95	1	20	15	-11605	-0.26%	-3.96	0.000
BOSTON CBD	FRAMINGHAM	20.46	2	10	89	-11536	-0.20%	64.36	-0.006
BILLERICA	LOWELL	6.58	1	20	38	-10490	-0.24%	-73.35	0.007
CONCORD	ACTON	4.33	1	8	13	-9745	-0.30%	41.64	-0.004
ACTON	CONCORD	4.33	1	6	14	-9460	-0.34%	58.37	-0.006
WALTHAM	NEWTON	5.21	8	20	134	-9377	-0.12%	-117.37	0.013
BRAINTREE	RANDOLPH	4.08	2	20	21	-8297	-0.34%	18.05	-0.002
HINGHAM	WEYMOUTH	4.65	1	20	22	-8059	-0.21%	-36.15	0.004
CANTON	STOUGHTON	4.94	1	6	17	-7846	-0.34%	101.79	-0.013
BRAINTREE	WEYMOUTH	3.82	1	20	16	-7164	-0.15%	-5.58	0.001
LEXINGTON	WOBURN	5.67	1	6	11	-7156	-0.35%	50.87	-0.007
BEDFORD	BILLERICA	5.24	1	20	12	-7155	-0.24%	-13.55	0.002
WATERTOWN	ARLINGTON	5.75	2	6	22	-6864	-0.46%	88.54	-0.013
BURLINGTON	WALTHAM	9.64	1	6	10	-6760	-0.27%	90.57	-0.013
WOBURN	WAKEFIELD	5.89	1	6	12	-6408	-0.41%	38.32	-0.006
BROCKTON	E. BRIDGEW.	6.51	1	6	10	-6278	-0.27%	37.59	-0.006
BROCKTON	ABINGTON	5.29	2	6	18	-6147	-0.26%	34.97	-0.006
CANTON	NORWOOD	5.86	1	6	10	-6089	-0.33%	42.20	-0.007
BROCKTON	W. BRIDGEW.	4.77	1	6	12	-5883	-0.30%	31.57	-0.005
BOSTON CBD	MILTON	8.55	2	6	81	-5639	-0.20%	61.44	-0.011
BURLINGTON	BILLERICA	5.81	1	20	9	-5602	-0.19%	-1.67	0.000
WOBURN	LEXINGTON	5.67	1	18	10	-5443	-0.26%	16.63	-0.003
BROCKTON	WHITMAN	4.46	2	20	16	-5260	-0.22%	8.68	-0.002
BEVERLY	PEABODY	8.34	1	20	15	-5116	-0.18%	-2.16	0.000
BEVERLY	GLOUCESTER	10.14	2	6	60	-5114	-0.13%	111.53	-0.022
ARLINGTON	WATERTOWN	5.75	2	6	21	-5014	-0.44%	78.48	-0.016
NEEDHAM	DEDHAM	4.49	2	6	17	-4957	-0.32%	98.87	-0.020
WEYMOUTH	HINGHAM	4.65	5	20	48	-4892	-0.13%	-35.35	0.007
DEDHAM	NEEDHAM	4.49	1	6	11	-4867	-0.34%	34.92	-0.007
WALTHAM	WELLESLEY	7.15	1	6	11	-4793	-0.24%	39.79	-0.008
NEWTON	BELMONT	7.01	2	6	29	-4645	-0.30%	63.34	-0.014
LYNNFIELD	PEABODY	4.98	1	8	10	-4512	-0.34%	23.39	-0.005
WALTHAM	ARLINGTON	6.44	1	20	23	-4454	-0.17%	-1.93	0.000
ARLINGTON	WALTHAM	6.44	2	6	21	-4449	-0.24%	126.04	-0.028
CANTON	RANDOLPH	4.92	1	6	8	-4220	-0.26%	43.53	-0.010
WAKEFIELD	PEABODY	6.00	1	6	8	-4175	-0.30%	71.96	-0.017
BOSTON CBD	MILFORD	31.16	1	6	7	-3703	-0.12%	148.22	-0.040
BILLERICA	BURLINGTON	5.81	1	20	9	-3627	-0.15%	2.46	-0.001
PEABODY	WAKEFIELD	6.00	1	6	8	-3444	-0.26%	49.08	-0.014
BOSTON CBD	WINTHROP	5.93	6	16	247	-3420	-0.13%	-459.04	0.134
WOBURN	ARLINGTON	6.71	2	6	27	-3408	-0.23%	46.04	-0.014
WALTHAM	BOSTON	10.82	3	8	177	-3292	-0.04%	-1.30	0.000

Table 6.38: Case 4B ($F \in [6, 20], c_v = 0$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
MEDFORD	CAMBRIDGE	4.01	3	20	135	-26	0.00%	-389.52	15.275
ARLINGTON	SOMERVILLE	3.92	3	20	97	-28	0.00%	-254.30	9.002
WINCHESTER	ARLINGTON	3.32	2	20	32	-9	0.00%	-75.34	8.754
MEDFORD	SOMERVILLE	2.45	7	14	282	-113	-0.01%	-571.10	5.052
ARLINGTON	CAMBRIDGE	4.14	4	16	161	-77	0.00%	-330.12	4.281
BELMONT	WATERTOWN	3.23	6	14	77	-24	0.00%	-100.05	4.203
GLOUCESTER	ROCKPORT	5.59	3	10	60	-32	0.00%	-81.24	2.516
MALDEN	MEDFORD	2.94	1	20	24	-26	0.00%	-62.54	2.417
TAUNTON	RAYNHAM	3.79	2	18	13	-14	0.00%	-28.84	2.018
MALDEN	EVERETT	2.09	4	16	116	-146	-0.02%	-269.80	1.848
EVERETT	CHELSEA	1.81	1	14	25	-29	-0.01%	-48.53	1.695
NEWTON	WATERTOWN	3.80	6	20	88	-92	0.00%	-153.88	1.676
EVERETT	REVERE	3.89	1	18	25	-34	0.00%	-54.64	1.590
SOMERVILLE	ARLINGTON	3.92	1	16	36	-50	0.00%	-71.22	1.430
NEWTON	CAMBRIDGE	6.98	1	14	50	-51	0.00%	-71.97	1.423
WATERTOWN	WALTHAM	4.46	5	12	105	-52	0.00%	-55.84	1.079
CAMBRIDGE	BELMONT	3.56	4	18	190	-461	-0.02%	-478.68	1.038
EVERETT	MALDEN	2.09	1	16	36	-95	-0.01%	-86.00	0.902
CAMBRIDGE	WATERTOWN	3.43	6	20	289	-1093	-0.04%	-843.22	0.771
BRAINTREE	QUINCY	4.05	1	20	44	-173	-0.01%	-128.37	0.744
WEYMOUTH	QUINCY	6.14	2	12	113	-242	-0.01%	-174.44	0.721
MELROSE	MALDEN	2.46	2	18	108	-456	-0.05%	-306.25	0.672
CHELSEA	EVERETT	1.81	4	16	73	-227	-0.04%	-147.84	0.652
BROOKLINE	NEWTON	4.21	4	18	171	-624	-0.02%	-402.40	0.645
SOMERVILLE	MEDFORD	2.45	6	20	202	-1004	-0.05%	-603.37	0.601
LAWRENCE	HAVERHILL	8.50	3	8	76	-115	0.00%	-69.12	0.601
N. ATTLEBOR.	ATTLEBORO	6.19	5	20	41	-177	0.00%	-99.03	0.559
LYNN	SWAMPSCOTT	4.13	2	12	99	-319	-0.03%	-170.15	0.534
BELMONT	CAMBRIDGE	3.56	1	16	48	-204	-0.01%	-108.75	0.533
MALDEN	MELROSE	2.46	3	10	108	-208	-0.02%	-110.17	0.530
NEEDHAM	WELLESLEY	3.48	5	18	37	-97	0.00%	-51.14	0.525
MEDFORD	ARLINGTON	3.64	4	20	65	-261	-0.02%	-124.78	0.478
LYNN	MARBLEHEAD	7.38	1	12	42	-109	-0.01%	-51.72	0.476
ATTLEBORO	N. ATTLEBOR.	6.19	5	14	41	-133	0.00%	-54.54	0.410
MANSFIELD	FOXBOROUGH	4.03	3	12	21	-64	0.00%	-25.59	0.400
SOMERVILLE	MALDEN	4.89	2	16	58	-198	-0.01%	-76.39	0.386
READING	WAKEFIELD	3.41	2	14	36	-126	-0.01%	-47.69	0.380
WELLESLEY	NEEDHAM	3.48	5	20	40	-191	-0.01%	-70.39	0.369
WATERTOWN	CAMBRIDGE	3.43	1	20	32	-233	-0.01%	-85.22	0.366
SWAMPSCOTT	LYNN	4.13	2	12	100	-482	-0.05%	-174.59	0.362
WALTHAM	WATERTOWN	4.46	6	20	180	-1337	-0.04%	-437.54	0.327
CAMBRIDGE	MEDFORD	4.01	5	16	287	-2094	-0.08%	-673.61	0.322
CAMBRIDGE	WALTHAM	6.85	3	18	176	-1167	-0.03%	-369.89	0.317
WALTHAM	CAMBRIDGE	6.85	4	14	200	-795	-0.03%	-248.32	0.312
BEDFORD	LEXINGTON	4.47	2	12	42	-113	-0.01%	-34.53	0.306
ANDOVER	LAWRENCE	4.80	4	20	53	-545	-0.02%	-159.57	0.293
BURLINGTON	WOBURN	3.61	8	20	66	-113	0.00%	-33.01	0.292
LYNN	SAUGUS	3.42	1	18	19	-96	-0.01%	-27.69	0.290
LYNN	SALEM	5.61	3	14	148	-949	-0.04%	-272.27	0.287
WOBURN	WINCHESTER	3.39	3	16	36	-177	-0.02%	-49.51	0.280

Table 6.39: Case 5B ($\Delta F = 0, c_v = 0$): OD pairs ranked by GHG reduction (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
WALTHAM	NEWTON	5.21	3	5.58	164	-97880	-1.28%	-27.36	0.000
FRAMINGHAM	NATICK	6.94	2	0.00	70	-60656	-0.97%	21.67	0.000
WALTHAM	WATERTOWN	4.46	5	0.99	242	-47862	-1.40%	129.15	-0.003
BOSTON CBD	WINTHROP	5.93	5	3.72	273	-46552	-1.80%	24.61	-0.001
NEWTON	WALTHAM	5.21	2	4.77	103	-46348	-0.70%	-3.92	0.000
CAMBRIDGE	NEWTON	6.98	3	8.71	154	-46158	-0.85%	-63.84	0.001
BRAINTREE	WEYMOUTH	3.82	2	6.87	43	-39866	-0.84%	46.87	-0.001
QUINCY	BRAINTREE	4.05	3	5.53	156	-37323	-0.77%	-48.08	0.001
SALEM	PEABODY	5.22	2	5.14	102	-35448	-1.28%	-27.85	0.001
LAWRENCE	METHUEN	3.14	1	0.00	50	-35197	-0.85%	4.90	0.000
WATERTOWN	CAMBRIDGE	3.43	3	1.85	168	-34398	-1.33%	29.22	-0.001
DEDHAM	BOSTON	7.55	3	8.32	151	-34309	-0.43%	-42.02	0.001
CHELMSFORD	LOWELL	4.63	1	0.00	37	-32258	-0.74%	7.22	0.000
BOSTON CBD	NORWOOD	14.70	3	8.38	179	-30980	-0.51%	36.07	-0.001
BEVERLY	DANVERS	5.51	1	3.43	30	-29429	-0.78%	15.85	-0.001
SOMERVILLE	MEDFORD	2.45	5	1.88	280	-29291	-1.40%	7.45	0.000
PEABODY	SALEM	5.22	2	2.90	65	-28259	-1.04%	33.67	-0.001
ANDOVER	LAWRENCE	4.80	2	0.00	59	-26602	-0.89%	14.97	-0.001
BURLINGTON	WOBURN	3.61	1	2.92	40	-26536	-0.78%	4.70	0.000
LEXINGTON	WALTHAM	4.18	1	3.52	25	-26480	-0.73%	22.55	-0.001
PEABODY	LYNN	5.29	3	1.46	134	-26474	-0.94%	92.52	-0.003
BOSTON CBD	WOBURN	11.50	2	6.47	107	-25871	-0.76%	-12.30	0.000
BRAINTREE	QUINCY	4.05	3	3.39	162	-25797	-0.77%	-6.80	0.000
DANVERS	BEVERLY	5.51	1	4.81	27	-25287	-0.65%	14.37	-0.001
WALTHAM	LEXINGTON	4.18	1	3.77	26	-25117	-0.72%	21.29	-0.001
LOWELL	CHELMSFORD	4.63	1	0.00	31	-24856	-0.63%	7.22	0.000
WATERTOWN	WALTHAM	4.46	2	1.86	98	-24086	-0.77%	35.62	-0.001
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	27	-23826	-0.57%	9.65	0.000
WOBURN	BURLINGTON	3.61	1	3.61	33	-23578	-0.73%	6.50	0.000
BRAINTREE	RANDOLPH	4.08	2	3.86	30	-22826	-0.93%	73.72	-0.003
NEEDHAM	NEWTON	4.49	2	1.43	69	-22400	-0.83%	55.58	-0.002
WATERTOWN	NEWTON	3.80	2	3.30	50	-22308	-0.74%	32.20	-0.001
MEDFORD	SOMERVILLE	2.45	6	0.89	352	-21732	-1.12%	60.35	-0.003
LOWELL	TEWKSBURY	5.57	2	0.00	29	-21664	-0.74%	17.37	-0.001
WALTHAM	CAMBRIDGE	6.85	4	2.62	226	-21016	-0.69%	148.33	-0.007
BELMONT	CAMBRIDGE	3.56	3	2.54	162	-20199	-1.17%	13.73	-0.001
WEYMOUTH	HINGHAM	4.65	1	4.61	30	-19808	-0.51%	2.09	0.000
FRAMINGHAM	MARLBORO.	9.72	1	0.00	13	-19376	-0.41%	15.16	-0.001
PEABODY	DANVERS	4.85	1	1.10	44	-19331	-0.68%	14.64	-0.001
DANVERS	PEABODY	4.85	1	2.78	53	-19115	-0.69%	-2.23	0.000
BILLERICA	LOWELL	6.58	1	6.94	43	-18874	-0.43%	9.94	-0.001
BROCKTON	EASTON	5.95	1	7.37	19	-18829	-0.42%	24.18	-0.001
ARLINGTON	CAMBRIDGE	4.14	4	2.55	215	-18706	-0.80%	33.86	-0.002
BROOKLINE	NEWTON	4.21	4	5.17	211	-18580	-0.63%	-46.48	0.003
SALEM	MARBLEHEAD	3.75	2	4.58	105	-18563	-1.45%	-21.45	0.001
SAUGUS	LYNN	3.42	2	2.06	48	-17665	-0.90%	57.73	-0.003
ATTLEBORO	N. ATTLEBOR.	6.19	1	0.00	22	-17528	-0.44%	9.65	-0.001
MEDFORD	MALDEN	2.94	2	4.00	86	-17321	-0.97%	-4.29	0.000
LEXINGTON	BURLINGTON	5.47	2	4.06	26	-17300	-0.75%	86.22	-0.005
WATERTOWN	BELMONT	3.23	2	1.92	66	-17157	-1.35%	8.19	0.000

Table 6.40: Case 5B ($\Delta F = 0, c_v = 0$): OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of buses	Fare ($)	Daily Ridership	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
CAMBRIDGE	BELMONT	3.56	6	5.19	246	-49	0.00%	-27.18	0.554
BROOKLINE	CAMBRIDGE	4.81	3	4.43	177	-100	-0.01%	-38.06	0.379
BOSTON	WATERTOWN	7.34	4	7.36	208	-133	0.00%	-32.83	0.247
BOSTON CBD	BRAINTREE	11.92	4	21.36	191	-2582	-0.04%	-228.59	0.089
MILTON	BOSTON	5.58	4	11.12	128	-500	-0.01%	-38.46	0.077
CAMBRIDGE	ARLINGTON	4.14	8	5.40	477	-3969	-0.12%	-168.38	0.042
NEWTON	BROOKLINE	4.21	5	6.37	286	-4138	-0.15%	-145.89	0.035
CAMBRIDGE	MEDFORD	4.01	7	4.26	349	-3271	-0.12%	-56.09	0.017
BOSTON CBD	WEYMOUTH	14.56	3	23.10	137	-11932	-0.15%	-141.46	0.012
WEYMOUTH	QUINCY	6.14	2	5.29	119	-4390	-0.23%	-44.62	0.010
BOSTON	MILTON	5.58	1	9.20	39	-831	-0.01%	-7.05	0.008
NEWTON	CAMBRIDGE	6.98	1	7.75	58	-3354	-0.11%	-28.09	0.008
CAMBRIDGE	WATERTOWN	3.43	8	5.18	378	-12095	-0.40%	-95.11	0.008
LYNN	SWAMPSCOTT	4.13	2	3.23	117	-4665	-0.44%	-26.01	0.006
SWAMPSCOTT	LYNN	4.13	2	2.92	118	-4973	-0.50%	-22.36	0.004
BROOKLINE	NEWTON	4.21	4	5.17	211	-18580	-0.63%	-46.48	0.003
CAMBRIDGE	WALTHAM	6.85	4	6.82	234	-12996	-0.32%	-24.87	0.002
QUINCY	WEYMOUTH	6.14	1	5.86	56	-8107	-0.14%	-12.39	0.002
CAMBRIDGE	NEWTON	6.98	3	8.71	154	-46158	-0.85%	-63.84	0.001
QUINCY	BRAINTREE	4.05	3	5.53	156	-37323	-0.77%	-48.08	0.001
MALDEN	MELROSE	2.46	2	3.38	101	-4069	-0.44%	-5.22	0.001
DEDHAM	BOSTON	7.55	3	8.32	151	-34309	-0.43%	-42.02	0.001
SALEM	MARBLEHEAD	3.75	2	4.58	105	-18563	-1.45%	-21.45	0.001
SOMERVILLE	ARLINGTON	3.92	1	4.14	51	-4489	-0.28%	-5.10	0.001
SALEM	PEABODY	5.22	2	5.14	102	-35448	-1.28%	-27.85	0.001
MALDEN	EVERETT	2.09	2	1.73	118	-9536	-1.12%	-5.87	0.001
BOSTON CBD	WOBURN	11.50	2	6.47	107	-25871	-0.76%	-12.30	0.000
MEDFORD	ARLINGTON	3.64	1	4.09	41	-7234	-0.47%	-2.28	0.000
WALTHAM	NEWTON	5.21	3	5.58	164	-97880	-1.28%	-27.36	0.000
BRAINTREE	QUINCY	4.05	3	3.39	162	-25797	-0.77%	-6.80	0.000
MALDEN	MEDFORD	2.94	1	3.75	39	-4902	-0.32%	-1.24	0.000
MEDFORD	MALDEN	2.94	2	4.00	86	-17321	-0.97%	-4.29	0.000
DANVERS	PEABODY	4.85	1	2.78	53	-19115	-0.69%	-2.23	0.000
NEWTON	WALTHAM	5.21	2	4.77	103	-46348	-0.70%	-3.92	0.000
NEWTON	WATERTOWN	3.80	1	3.02	52	-15540	-0.52%	-1.28	0.000
WEYMOUTH	HINGHAM	4.65	1	4.61	30	-19808	-0.51%	2.09	0.000
BELMONT	WATERTOWN	3.23	1	1.99	41	-9429	-0.78%	1.27	0.000
LAWRENCE	METHUEN	3.14	1	0.00	50	-35197	-0.85%	4.90	0.000
EVERETT	MALDEN	2.09	2	1.60	107	-10081	-1.09%	1.63	0.000
SOMERVILLE	MALDEN	4.89	2	6.92	72	-6994	-0.46%	1.17	0.000
BURLINGTON	WOBURN	3.61	1	2.92	40	-26536	-0.78%	4.70	0.000
CHELMSFORD	LOWELL	4.63	1	0.00	37	-32258	-0.74%	7.22	0.000
MALDEN	SOMERVILLE	4.89	1	3.77	56	-2080	-0.17%	0.50	0.000
SOMERVILLE	MEDFORD	2.45	5	1.88	280	-29291	-1.40%	7.45	0.000
BOSTON	DEDHAM	7.55	2	9.12	76	-16541	-0.14%	4.54	0.000
WOBURN	BURLINGTON	3.61	1	3.61	33	-23578	-0.73%	6.50	0.000
LOWELL	CHELMSFORD	4.63	1	0.00	31	-24856	-0.63%	7.22	0.000
FRAMINGHAM	NATICK	6.94	2	0.00	70	-60656	-0.97%	21.67	0.000
HUDSON	MARLBORO.	4.02	1	0.00	21	-17031	-0.75%	6.27	0.000
N. ATTLEBOR.	ATTLEBORO	6.19	1	0.00	27	-23826	-0.57%	9.65	0.000