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Commuter Bus Demand, Incentives for Modal Shift, and Impact on Greenhouse Gas Emissions: Part II – Service Delivery Concepts

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16. Abstract
This report is a continuation of a project to model and evaluate the potential to reduce greenhouse gas (GHG) emissions by expanding express commuter bus services in Greater Boston. (1) Data for socioeconomic factors in the CTPS travel demand model were collected to improve model accuracy. (2) Additional data for each commuting corridor were used to explain remaining variations. (3) The revised model was used to evaluate the impact of running buses in dedicated lanes or on highway shoulders and the effect of commuter bus stop location on the attractiveness for access by walking or driving. (4) The impacts of shoulder running and bus stop location were evaluated for the corridors with the greatest potential to reduce GHG per dollar of cost, including Framingham-Boston and Woburn-Boston CBDs. Results show that bus-on-shoulder running on existing feasible shoulders can improve bus travel times by up to 4 minutes, leading to double the reduction in GHG emissions associated with new commuter bus services compared to mixed traffic operations. Bus stop placement within a town can affect ridership by a factor of three, primarily by affecting walk-accessibility, and make the difference between a route causing a net reduction in GHG emissions or not.

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Final Report

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Executive Summary

This study of commuter bus demand and GHG emissions is 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 build upon an earlier study of 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 (Commuter Bus Demand, Incentives for Modal Shift, and Impact on GHG). The previous study is referred to in this report as Part I. This study (Part II) addresses three main objectives:

1. Improve the detail and accuracy of the commuter bus demand estimates by utilizing demographic data about the commuters in each origin-destination (OD) market.
2. Analyze the potential impact of operating buses on highway shoulders (space permitting) to achieve faster bus travel times and attract more riders.
3. Conduct an analysis of the specific local characteristics of commuter bus stop locations that are likely to impact ridership. The goal is to make specific projections of ridership that are consistent with the access distance by walking or driving considering the distances that commuters are actually likely to walk to access a commuter bus service.

Methodology

This study builds on a simplified version of the travel demand model that was developed for the Greater Boston area by the Central Transportation Planning Staff (CTPS), which is the Boston Region Metropolitan Planning Organization. The OD data is aggregated to 164 towns and the Boston Central Business District (CBD) for 12 transportation modes (single-occupant vehicle; high-occupancy vehicle; walk; bike; drive-access to boat, commuter rail, rapid transit, and local bus; and walk-access to boat, commuter rail, rapid transit, and local bus). The demand model is structured as a nested logit choice model in which the mode choices for commuters in each OD corridor are estimated from the following data:

1. Out-of-Vehicle Travel Time (OVTT) – including access time and waiting,
2. In-Vehicle Travel Time (IVTT),
3. Cost – including monetary cost for parking, tolls, and fares,
4. Vehicles per Worker (VPW) – average for each origin zone,
5. Square Root of Employment Density (ED) – based on a weighted average of employment in each destination zone that reflects the average localized density of employment in the census tracts in which people actually work, and
6. Walk Access Fraction (WAF) – the average fraction of the origin and destination zones' areas that are within 1 mile of a transit stop.

Data inputs 1 through 3 are the impedance variables that reflect the experience of travel by a specific mode. These were the only inputs included in the choice model for the Part I study, and the resulting estimates required extensive calibration to reproduce reported mode shares from CTPS. The original CTPS travel demand model also includes parameters for socioeconomic variables, so data inputs 4 through 6 were estimated and included in this Part II study. Furthermore, the following data were estimated for each OD pair using census data and a statistical technique called iterative proportional fitting:

7. Average Household Income
8. Industry Sector of Employment (from North American Industry Classification System)

A regression analysis was used to identify relationships between these variables and the error between the simplified logit model and the reported OD flows. The mode choice model is used to estimate the number of riders, the net cost (or profit) for the operator, and the effect on total GHG emissions for new express commuter bus services introduced in an OD corridor (i.e., corridor defined by an OD pair).

The revised mode choice model was used to estimate the impact of a policy to allow buses to operate on highway shoulders to bypass traffic congestion. Potential corridors were identified in the MassDOT Bus on Shoulder study based on the flow of buses, width of highway shoulder, and severity of congestion. For each corridor, a geographic information system (GIS) analysis was used to identify which commuter bus routes would be affected and how much travel time savings would likely result from a bus-on-shoulder policy. Revised bus travel times in the model produce estimates of the effect of a bus-on-shoulder policy on transit ridership and GHG emissions reduction.

The specific location of a bus stop within a community also affects the commuter bus performance. The simplified mode choice model uses a single estimated OVTT for the walk access time across a whole town, but evidence from the literature suggests that most commuters are unwilling to walk more than 0.25 miles to a bus stop. An analysis to compare specific bus stop locations in Framingham and Woburn accounts for the constraint that walking is only a feasible access mode for commuters residing near the bus stop; the location within the town also affects the IVTT for the commuter bus route.

Results

Socioeconomic Variables in the Mode Choice Model

The revised mode choice model, which includes socioeconomic variables in addition to impedance variables, does not significantly change how well the model fits the reported mode choice data. The regression analysis using data on household income and industry sector of employment shows the extent to which these variables explain errors in the estimated numbers of commuters choosing each mode. The analysis supports the following observations:

- Mean household income is not a statistically significant determinant of mode choice.
- Commuters employed in utilities and construction; trade; and education, community, and social services are more likely to drive than use transit.
- Commuters employed in hospitality and entertainment are more likely to walk to transit than to drive.

Efficiency of a new commuter bus service was defined as the dollar cost per unit of GHG emissions reduced. The top ranked based on efficiency OD pairs for the evening and morning peaks are summarized in Table 1 and Table 2.

Table 1: OD pairs ranked by efficiency (AM peak)

Origin	Destination	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
		Drive Access	Walk Access	Total				
WEYMOUTH	BOSTON CBD	13	214	226	10%	-1624	-260.39	0.160
WOBURN	BOSTON CBD	5	97	102	12%	-852	-70.22	0.082
FRAMINGHAM	BOSTON CBD	8	111	119	12%	-14572	219.32	-0.015
NATICK	BOSTON CBD	5	75	79	18%	-14264	271.33	-0.019
RANDOLPH	BOSTON CBD	6	95	101	13%	-10490	223.69	-0.021
MILFORD	BOSTON CBD	1	11	12	61%	-8665	227.01	-0.026
BEVERLY	PEABODY	1	10	11	70%	-1408	56.02	-0.040
PEABODY	BOSTON CBD	3	58	61	21%	-4786	241.62	-0.050
MILTON	BOSTON CBD	9	149	159	12%	-3107	219.80	-0.071
BRAINTREE	BOSTON CBD	15	210	225	11%	-2125	227.21	-0.107
WALTHAM	BURLINGTON	1	7	8	83%	-469	72.06	-0.154
BILLERICA	BOSTON CBD	2	30	32	37%	-1318	308.29	-0.234
GLOUCESTER	BEVERLY	2	54	57	23%	-247	151.56	-0.613
NORWOOD	BOSTON CBD	12	219	231	10%	-183	367.20	-2.006

Table 2: OD pairs ranked by efficiency (PM peak)

Origin	Destination	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
		Drive Access	Walk Access	Total				
BOSTON CBD	WEYMOUTH	6	51	57	10%	-220	-72.12	0.327
BOSTON CBD	BRAINTREE	14	180	195	12%	-3168	-275.37	0.087
BOSTON	WINTHROP	5	94	99	12%	-581	-38.13	0.066
BOSTON CBD	WOBURN	6	82	88	15%	-3665	-130.78	0.036
BOSTON CBD	NORWOOD	11	145	156	11%	-2399	-15.97	0.007
LAWRENCE	HAVERHILL	4	57	60	23%	-613	-0.33	0.001
BEVERLY	PEABODY	1	14	15	64%	-5116	4.95	-0.001
FRAMINGHAM	ASHLAND	1	14	14	85%	-11371	45.27	-0.004
ASHLAND	FRAMINGHAM	0	12	12	83%	-6738	27.37	-0.004
FRAMINGHAM	MARLBOROUGH	1	13	13	94%	-19111	81.22	-0.004
BOSTON CBD	RANDOLPH	6	81	87	19%	-28433	153.02	-0.005
PEABODY	BEVERLY	1	28	29	80%	-18726	116.43	-0.006
BURLINGTON	WALTHAM	1	11	11	89%	-10563	77.85	-0.007
BOSTON CBD	FRAMINGHAM	9	94	103	19%	-39011	288.32	-0.007

Bus-on-Shoulder Running

The MassDOT Bus on Shoulder Workshop identified three corridors emanating from downtown Boston for potential implementation of shoulder running: I-90 out to SR-30 in Wayland; I-93 out to SR-125 in Wilmington; and US-1 out to Broadway in Saugus. Analysis of each of these corridors identified which segments already have a shoulder at least 10 feet wide, which would make shoulder running *feasible* without significant construction. The cases that were identified as feasible are compared with a hypothetical *ideal* case in which shoulder running is implemented in the full length of the corridor. The reduction of in-vehicle travel time for buses running on shoulders amounts to less than 3 minutes for feasible cases and less than 8 minutes for ideal cases.

Of the top 14 corridors that were identified for cost-efficient reduction of GHGs (presented in Table 1 and Table 2), six corridors have routes that overlap highway segments with potential for shoulder running. The effect on AM peak ridership and GHG emissions for these six corridors is shown in Figure 1. The few minutes of travel time savings result in a modest increase in expected ridership compared to operating buses in existing traffic conditions. The magnitude of GHG emissions reduction is relatively larger, because faster speeds are associated with lower bus emissions in addition to the savings from the passengers that switch to the commuter bus from driving. This ultimately results in improved efficiency for commuter bus operations in each of the corridors.

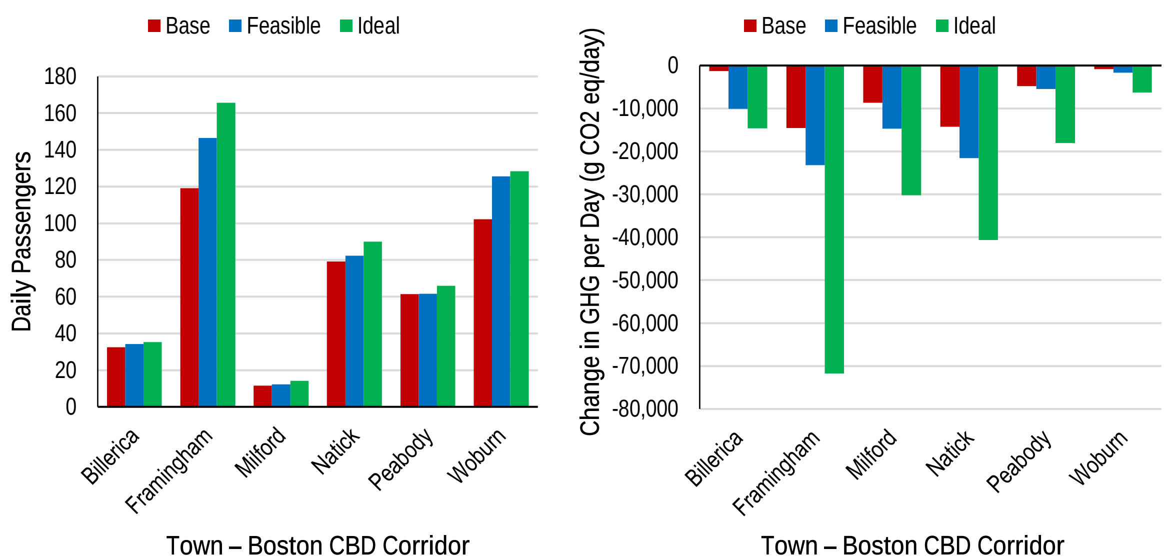

Figure 1: Comparison of ridership and GHG emissions for bus-on-shoulder cases

Bus Stop Location

The location of the commuter bus stop within a community is an important determinant of the route's performance. By accounting for the percentage of total Boston CBD-bound commuters that reside within 0.25 miles of a bus stop, the number of walk-access commuters can be more accurately estimated. Three potential bus stop locations were compared in Framingham and three in Woburn for an express commuter bus to the Boston CBD, one in the town center and two more suburban alternatives (see Table 3).

Table 3: Bus stop location characteristics

Stop Location	% of Boston CBD Commuters Residing in Catchment Area	AM Travel Time to Boston (min)	AM Travel Time from Boston (min)
FRAMINGHAM			
Center: 149 Concord Street	21.2%	46.9	31.2
Alternative 1: 541 Concord Street	7.8%	43.9	31.2
Alternative 2: 869 Concord Street	10.3%	43.9	27.2
WOBURN			
Center: 438 MA-38	26.0%	26.8	20.2
Alternative 1: 904 MA-38	11.2%	26.8	19.2
Alternative 2: 30 Atlantic Avenue	3.2%	27.8	18.2

The expected ridership and GHG emissions reduction associated with express commuter bus service is compared for each stop location in Framingham (Figure 2) and Woburn (Figure 3). The ridership estimates are much lower than in the previous implementations of the model, because significantly fewer commuters are expected to walk to the bus stop if we assume a 0.25 mile limit on walking distance. In both Framingham and Woburn, a bus stop location in the town center is likely to attract more than four times as many walk-access commuters as drive-access, and this results in significantly higher total ridership. difference change in ridership can easily make the difference between a commuter bus service reducing net GHG emissions or increasing net GHG emissions.

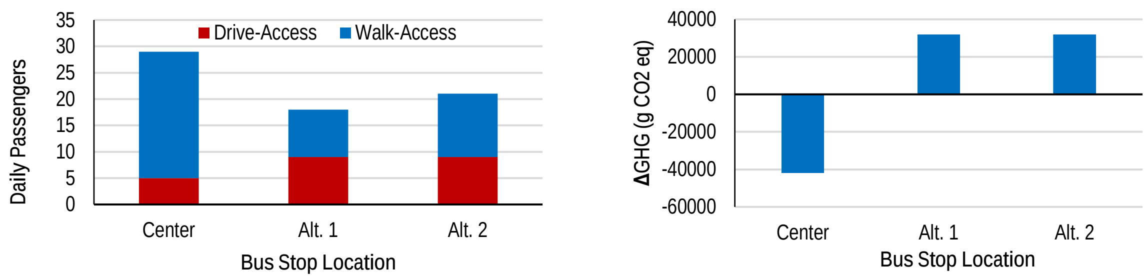

Figure 2: AM peak ridership and GHG reduction for bus stop locations in Framingham

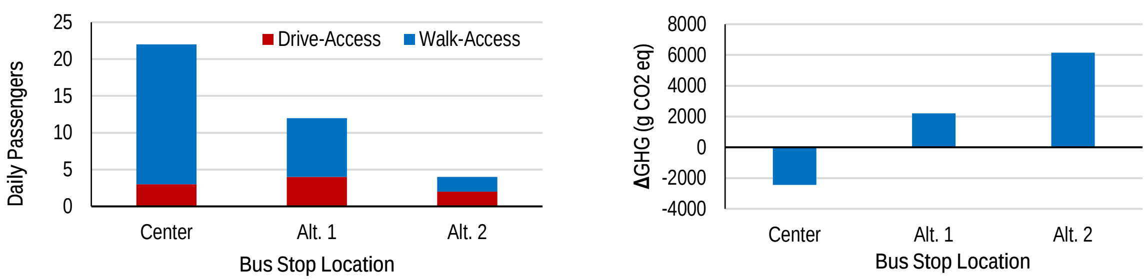

Figure 3: AM peak ridership and GHG reduction for bus stop locations in Woburn

Insights

- Adding socioeconomic parameters to the model leads to only a modest improvement in model fit. Calibration factors must still be calculated for each OD pair, because aggregation of 2,727 Travel Analysis Zones into 165 towns and the Boston CBD introduces some errors.

- A statistical analysis, controlling for the impedance and socioeconomic variables in the CTPS mode choice model, shows that employment in some industry sectors has significant impact on mode choice. Specifically, commuters employed in utilities and construction; trade; and education, community, and social services are more likely to drive than use transit, while commuters employed in hospitality and entertainment are more likely to walk to transit than to drive.
- Operating buses on highway shoulders leads to modest travel time savings on average between three and eight minutes. This leads to modest increases in expected commuter bus ridership. The reduction in GHG emissions associated with each route is greater than the relative increase in ridership for two reasons: 1) the shift of passengers from cars to commuter buses is small and results in a small reduction in GHG emissions; 2) increasing the speed of bus operations allows the commuter buses to operate at more efficient speeds at which emissions per mile are reduced. For example, buses emit 2,228 g CO2 eq/mile at 20 mph compared to 1,809 g CO2 eq/mile at 35 mph.
- The benefits of bus-on-shoulder running are identified in this study for isolated commuter bus routes. The corridors that are were identified in the MassDOT Bus on Shoulder study serve hundreds of buses per day. Therefore, bus-on-shoulder running would likely have large benefits for transit ridership and even larger benefits for GHG emissions reduction if implemented. This should justify minor investments in striping and signage that may be required to implement bus-on-shoulder running on existing feasible segments.
- The location of a commuter bus stop within a community affects its accessibility to potential passengers. Town-center locations are associated with greater expected ridership than more suburban bus stop locations, because the increased accessibility of a town center for walk-access commuters has a stronger effect in increasing ridership than that negative effect on ridership from a small increase of in-vehicle travel time for buses driving to and from town centers.
- Since commuters are more sensitive to the out-of-vehicle access time than in-vehicle riding time, it makes sense to consider making multiple stops in a community. Implementing a commuter bus route with multiple stops would add a couple of minutes of in-vehicle riding time to passengers, which has a very small impact on reducing ridership. Increasing the number of bus stops would, however, allow many more commuters to be able to walk to the commuter bus, making it a more competitive alternative to driving. This should make commuter bus services more effective at reducing GHG emissions and be able to do so more cost-efficiently.

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List of Acronyms	**Expansion**
ACS	American Community Survey
ASAI	Actual Stop Accessibility Index
BART	Bay Area Rapid Transit
CBD	Central Business District
CO_2	Carbon Dioxide
CTPS	Central Transportation Planning Staff
DAT+B	Drive-access transit: Boat
DAT+CR	Drive-access transit: Commuter rail
DAT+LB	Drive-access transit: Local bus
DAT+RT	Drive-access transit: Rapid transit
ED	Employment Density
EMFAC	Emission Factor (California Air Resources Board model from 2014)
GHG	Greenhouse Gas
GIS	Geographic Information System
HOV	High Occupancy Vehicle
IPCA	Impeded Pedestrian Catchment Area
IPF	Iterative Proportional Fitting
ISAI	Ideal Stop Accessibility Index
IVTT	In-Vehicle Travel Time
LEHD	Longitudinal Employer Household Dynamics (U.S. Census)
LODES	LEHD Origin-Destination Employment Statistics (U.S. Census)
LUE	Land Use Entropy
MassDOT	Massachusetts Department of Transportation
NAICS	North American Industry Classification System
OD	Origin-destination
OVTT	Out-of-Vehicle Travel Time
PCA	Pedestrian Catchment Area
PEV	Pedestrian Environment Variable
RAC	Residence Area Statistics
SCRI	Stop Coverage Ratio Index
SOV	Single Occupant Vehicle
TAZ	Transportation Analysis Zone
TOD	Transit-Oriented Development
VPW	Vehicles per Worker
WAC	Workplace Area Statistics
WAF	Walk-Access Fraction
WAT+B	Walk-access transit: Boat
WAT+CR	Walk-access transit: Commuter rail
WAT+LB	Walk-access transit: Local bus
WAT+RT	Walk-access transit: Rapid transit

List of Acronyms

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1 Introduction

This project is a continuation of an earlier project (Part I) to model and evaluate the opportunities to reduce greenhouse gas emissions by expanding express commuter bus services in the Greater Boston area *[1]*. This previous project developed a model to estimate the emissions associated with the current mode split of commuters traveling by car, carpool, walk, bike, or four transit modes (i.e., commuter rail, rapid transit, local bus, and ferry) by walk or drive access. The model was then used to estimate the effect of a new commuter bus service on operating costs, mode share, and greenhouse gas emissions. This study (Part II) expands on this previous work to improve the detail and accuracy of the commuter bus demand estimates by incorporating demographic data, analyze the potential impact of operating buses on highway shoulders, and conduct an analysis of the specific local characteristics of commuter bus stop locations that are likely to impact ridership.

In particular, the mode choice models are first revised and expanded to more closely match the data inputs required by the CTPS model and to include additional socioeconomic parameters that may explain the mode choice decisions that commuters make. Then, the improved models provide an opportunity to explore whether there are additional efficiencies that could be attained through service design adjustments (e.g., operating buses on shoulder lanes or optimizing placement of commuter bus stops within a town). The proposed project considers the most efficient Origin-Destination (OD) pairs from the previous study (including Framingham-Boston) and examine the implications of different service design concepts on commuter bus demand and greenhouse gas (GHG) emissions. Specifically, this study presents analyses on the potential impact of running buses in dedicated lanes or highway shoulders, and considers the specific details of commuter bus stop location that affect the attractiveness for access by walking or driving.

1.1 Background from the Part I Study

This project is a continuation of a project to model and evaluate the opportunities to reduce GHG emissions by expanding express commuter bus services in the Greater Boston area. The general structure of the model is illustrated in Figure 1.1, in which data inputs are used to calculate probabilities that commuters in each OD pair choose each of the 12 available modes:

1. (SOV) Single occupancy vehicle (drive alone)
2. (HOV) 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

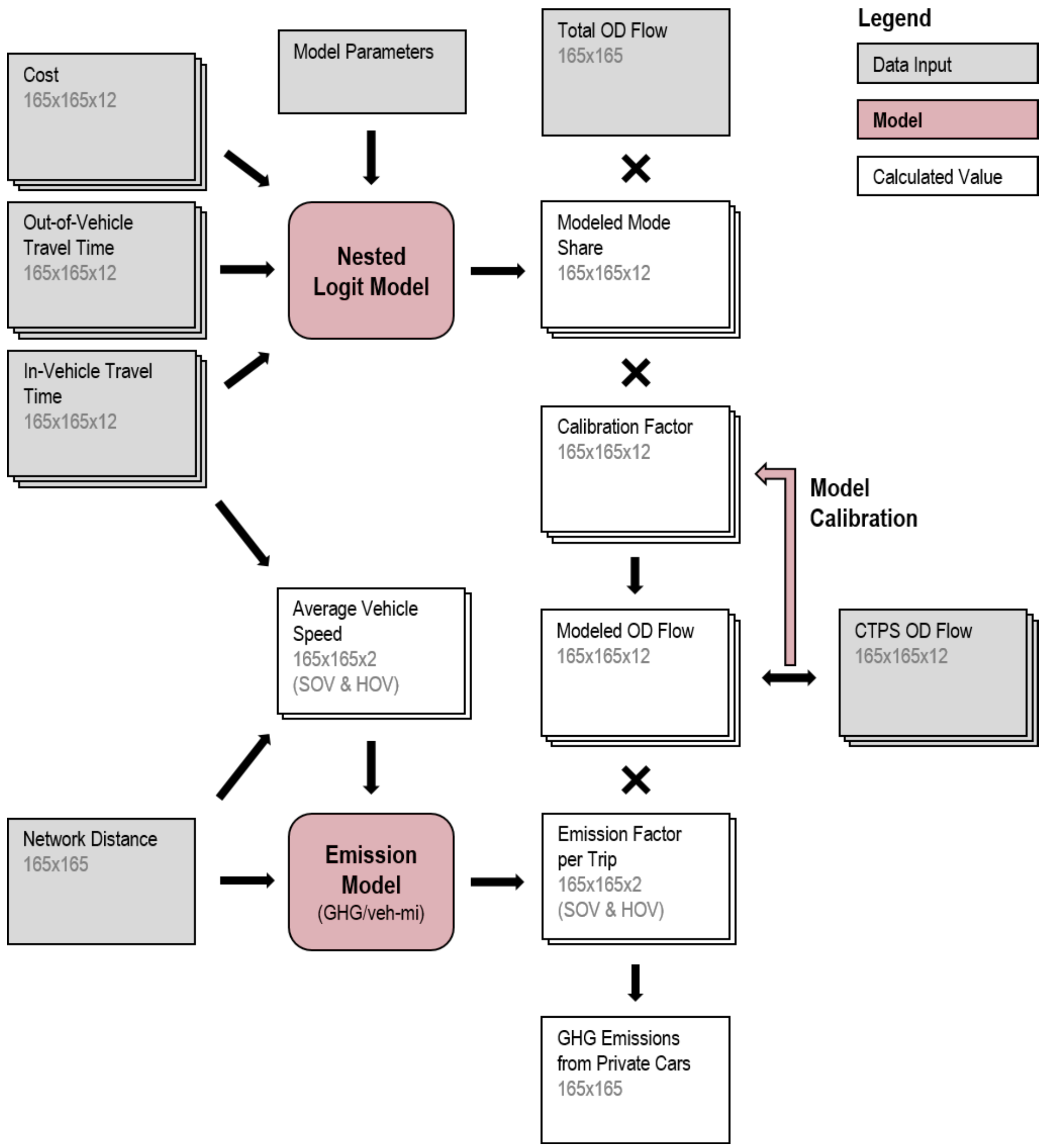


Figure 1.1: Overview of model structure

1.1.1 Mode Choice Model

The initial mode choice model for commuting trips from the Part I study was a simplified nested logit model based on the parameters of the regional travel demand model that is developed and maintained by the CTPS. Table 1.1 shows the parameter values from CTPS for each of the modes that are included in the original model. The Part I mode choice model only made use of the Impedance Variables on the left side of the table. These variables are the time and cost components associated with completing a home-based work trip between an OD pair by the specified mode:

1. Out-of-Vehicle Travel Time (OVTT)
2. In-Vehicle Travel Time (IVTT)
3. Cost

Table 1.1: CTPS mode choice model parameters [*1*]

	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]
SOV	1	-0.0199		-0.269	-0.111	1.25			
HOV	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).

Each of these components is estimated for each of the possible modes that can be used to travel between the 165 towns within the study area. The result is a 165x165 matrix of OD travel times and costs on which the multinomial logit choice model was developed. The simplified model that was developed for Part I approximately matched the reported mode splits from CTPS's existing model, but calibration factors were required to correct differences. Although the CTPS model includes parameters for Socioeconomic variables, these were omitted from the Part I modeling effort due to lack of available data.

The resulting Part I model (based only on Impedance Variables) fit the data in total, but there were large errors for specific origin-destination pairs and some modes. Figure 1.2 shows the comparison of the original modeled commuter flows by mode and the reported commuter flows by mode. Each point corresponds to an OD pair (town-to-town within the Greater Boston area) and one of the 12 modes listed in Table 1.1. A perfect model would have all points lying on the black diagonal line, which would indicate an exact match between modeled and reported mode flows.

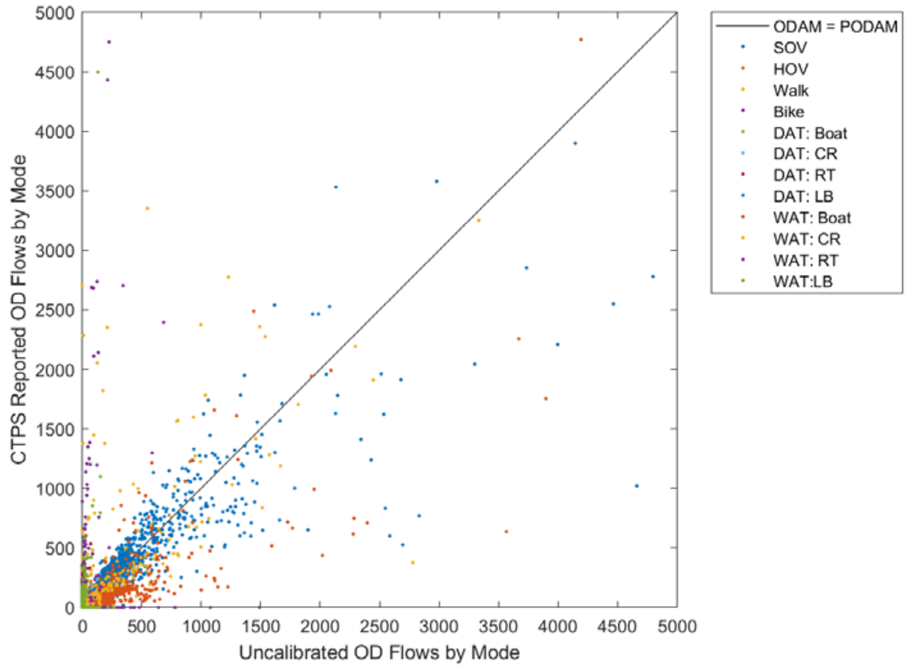


Figure 1.2: Comparison of uncalibrated AM mode flows and CTPS mode flows (Part I)

The errors were corrected with a mode- and OD-specific calibration parameter that is calculated as:

$$CODAM(i,j,m) = \frac{ODAM(i,j,m)}{PODAM(i,j,m)} \tag{1}$$

where $ODAM(i,j,m)$ is the reported morning OD flow from origin i to destination j by mode m; $PODAM(i,j,m)$ is the predicted OD mode flow from the model; and $CODAM(i,j,m)$ is the calibration factor that rescales a model estimate to reflect reality. The calibrated model estimates match the reported flows exactly, so the plot in Figure 1.2 would show all points lying along the black line when calibrated OD flows by mode are used.

1.1.2 Model for Emissions

The calibrated model was then used to estimate the effect of a new commuter bus service on operating costs, mode share, and greenhouse gas emissions. GHG emissions from cars were estimated using an emission factor model based on reported traffic speeds, distance traveled, and the estimated number of vehicles traveling. The emission factors were obtained from the Emission Factor (EMFAC2014) model, which was developed by the California Air Resources Board *[2]*. The average GHG emission rate for gasoline-powered cars and diesel buses is shown with relation to average speed in Figure 1.3. Generally, vehicles operate most efficiently near highway free-flow speeds of about 55 mph. Traffic congestion, which slows vehicles, corresponds to greater emissions per vehicle mile of operations. 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 produced from the new commuter bus services. Therefore, the emissions from cars are estimated before and after the introduction of commuter bus service, and the emissions associated with the new bus operations were also considered.

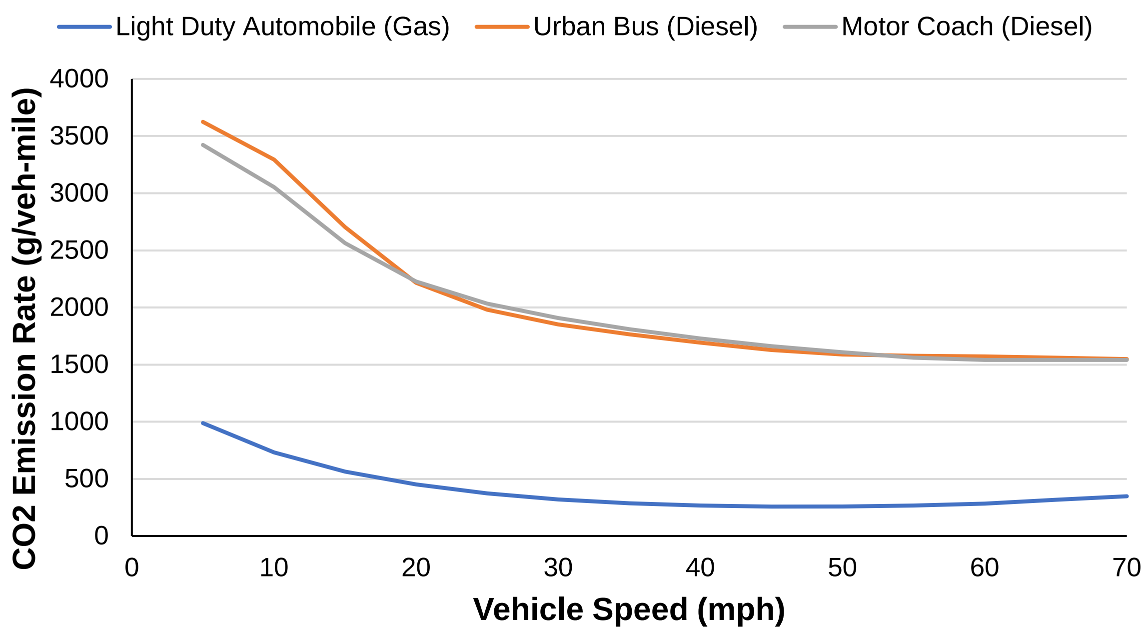


Figure 1.3: Emission factors for automobiles and buses from the EMFAC2014 model

1.1.3 Model of Commuter Bus Operations

New commuter bus services were 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 was 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. Each of these components of user cost contributes to the estimated utility associated with the new commuter bus service, which was used in the mode choice model to estimate the mode shift.

The decision variables also determined the agency cost of operating the bus service. This analysis considered the number of buses needed to operate the service, recognizing that a single bus can return to the origin to operate a second dispatch if the cycle time is short enough. The analysis of agency costs includes costs accrued per vehicle mile traveled (e.g., fuel, vehicle wear), costs accrued per vehicle hour traveled (e.g., driver wages), and the cost of vehicle procurement (amortized over a 12-year estimated service life). Furthermore, these decision variables, along with the distance traveled and the speed of traffic, were used to estimate GHG emissions from the buses.

Together, the estimated cost and GHG reduction were used to calculate an efficiency metric: cost per unit of GHG reduced. This is a metric that can be used to prioritize commuter bus corridors so that a limited budget can be expended to maximize the impact on GHG emissions reduction.

1.1.4 Results

Table 1.2 shows the corridors that ranked highest for cost-efficiency of GHG reduction for the AM peak hours. The efficiency metric represents the cost per gram of CO_2 equivalent reduced. A positive value implies that an express commuter bus would actually be profitable (bringing in more revenue than expected costs). A geographic representation of the top-ranked corridors for the AM and PM peak hours is shown in Figure 1.4.

Table 1.2: 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

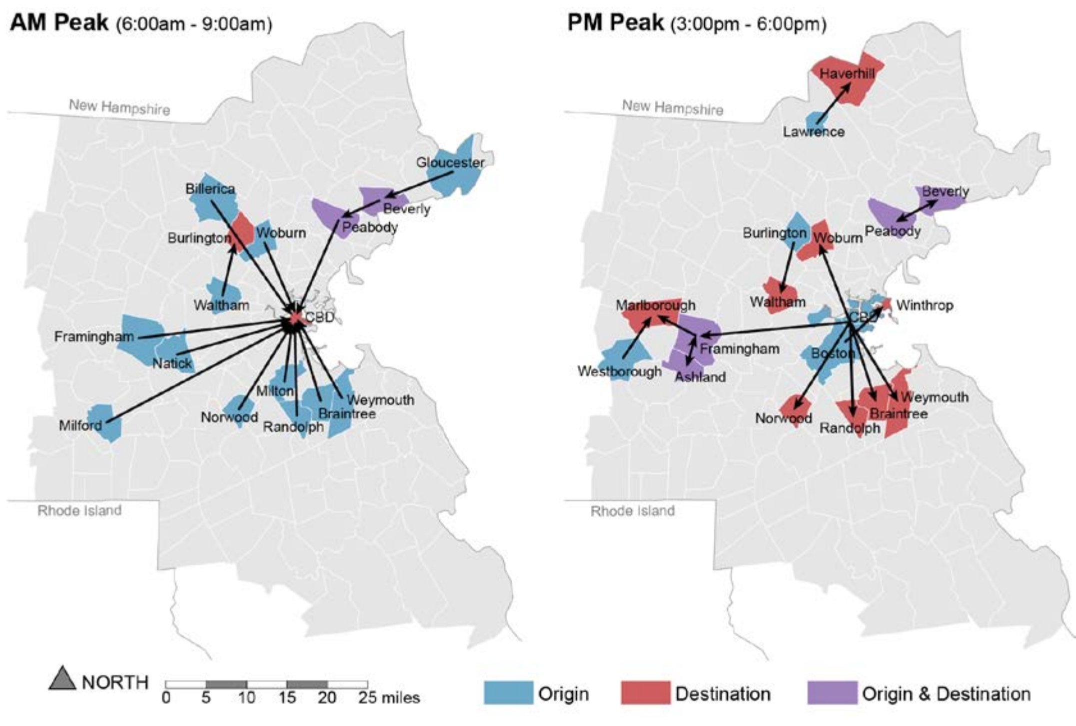


Figure 1.4: Top OD pairs for cost-efficient reduction of GHG emissions

1.2 Part II Study Objectives

Although the Part I study demonstrated the potential for GHG emissions reduction by introducing an express commuter bus service in a number of corridors, there were a number of shortcomings that warranted additional study and specific applications to be investigated. Specifically, this project is intended to address three main objectives:

1. Improve the detail and accuracy of the commuter bus demand estimates by utilizing demographic data about the commuters in each OD market.
2. Analyze the potential impact of operating buses on highway shoulders (space permitting) to achieve faster travel times and attract more riders.
3. Conduct an analysis of the specific local characteristics of commuter bus stop locations that are likely to impact ridership. The goal is to make specific projections of ridership that are consistent with the access distance by walking or driving and consider the distances that commuters are actually likely to walk to access a commuter bus service.

The first objective of this study is intended to address the shortcomings of the simplified mode choice model by including socioeconomic variables in the model. Ideally, the nested logit model should reproduce the reported mode choices for each OD pair when the same model inputs are used as the CTPS model. The simplified model from Part I aggregated the 2,727 Transportation Analysis Zones (TAZs) into 165 towns, and the mode choice estimate was based only on the impedance variables associated with the mode-specific trip characteristics (in-vehicle travel time, out-of-vehicle travel time, and cost). These estimates require large calibration parameters to match the reported OD flows from CTPS, as shown by the scatter of points in Figure 1.2. The CTPS model also includes socioeconomic parameters, so the goal is to improve the fit of the simplified model by adding the following parameters from the original CTPS model:

- Vehicles per Worker
- Square Root of Employment Density
- Walk Access Fraction

Additional data related to household income and industry sector of employment are also available, and these were used to further reduce model errors.

The second objective of this study is to quantify the impact on travel time, competitiveness, and GHG emission-reduction of running express commuter buses on freeway shoulders. Making use of results of a MassDOT feasibility study of running buses on shoulders *[3]*, we consider the impact of a shoulder-running policy on in-vehicle travel times for buses and re-evaluate the model to estimate the impact on commuter bus routes in corridors that overlap the potential shoulder running segments.

Finally, the third objective of this study is to provide analysis and guidance for locating express commuter bus stops within the communities of interest. While the Part I analysis utilized a centroid for each community as an estimated bus stop location, implementation of a new commuter bus service would require careful consideration of the specific location of bus stop. This must account for the catchment area serving those commuters who may walk or drive to the commuter bus stop, the need and availability of parking for commuters who drive, and other factors that can influence the attractiveness of transit.

2 Research Methodology

The research approach for this study consists of three main components described in Sections 2.1 through 2.3.

Section 2.1 presents the data sources and methods of calculating socioeconomic variables for inclusion in the nested logit model. It also includes a description of additional data sources and methods for extending the mode choice model using regression with household income and industry sector data in order to further reduce the need for calibration parameters.

Section 2.2 summarizes the relevant findings from the MassDOT feasibility study *[3]* for running buses on freeway shoulders. For the corridors that are identified to have the greatest potential for implementation of commuter bus service, the method for estimating the impact on ridership and GHG emissions from potential commuter bus routes spatial analysis with geographic information systems and the mode choice model is described.

Section 2.3 presents a concise review of the literature on the location-specific factors that affect the attractiveness of bus stops for riders. The most important quantitative finding is that commuters are typically willing to walk up to 0.25 miles to access a bus stop, and this is used to identify the catchment area for potential walk-access commuter bus passengers using geographic analysis.

2.1 Socioeconomic Data for Mode Choice Modeling

In the Part I study, the mode choice model that was used to estimate the number of home-based work trips between each OD pair was based on the impedance variables associated with completion of a trip by each mode:

1. Out-of-Vehicle Travel Time (OVTT)
2. In-Vehicle Travel Time (IVTT)
3. Cost

Each of these components was estimated for each of the possible modes that can be used to travel between the 165 towns within the study area (see Figure 2.1).

In this study, additional explanatory variables are added. Four socioeconomic variables are included in the original CTPS model, and therefore, utility model coefficients from the CTPS model have already been estimated and are available:

1. Vehicles per Worker
2. Pedestrian Environment Variable (PEV)
3. Square Root of Employment Density
4. Walk Access Fraction

Figure 2.1: Map of 165 zones (cities, towns, and Boston Central Business District)

Of the socioeconomic variables in the preceding list, 1, 3, and 4 are related to directly observable demographic features from the U.S. Census and other sources. The Pedestrian Environment Variable is a score that indicates walkability in a community based on walking features, vehicle volume and speeds, and the flow of heavy trucks, which have a negative effect on walkability.

Two additional explanatory variables area available in the data, but were not included in the CTPS model, so they can only be incorporated as an extension of the model using regression after logit model estimates have been calculated. Those are:

1. Median Household Income
2. Employment by Industry Sector

These additional socioeconomic measures are not available in relation to individual trip records from which new coefficients in the multinomial logit choice model can be estimated. However, they can be aggregated to the same 165 towns and can therefore be linked with the estimated mode splits associated with each origin or destination. As a result, these additional socioeconomic characteristics are used to adjust the mode split estimates from the logit model, thereby reducing the reliance on calibration factors.

The following subsections describe the data sources and processing performed to characterize each of the 165 towns within the study area. These data provide inputs for the revised nested multinomial logit mode choice modeling and re-estimation of calibration factors.

2.1.1 Socioeconomic Variables for Coefficients in the Existing Nested Logit Model

The coefficients from the multinomial logit model for the Greater Boston area provided by CTPS are presented in Table 2.1. The impedance variables are associated with the specific characteristics of a trip by the specified mode for an OD pair at the spatial resolution of 2,727 TAZs. These variables were the basis for the model developed in Part I of the study with data aggregated to the spatial resolution of 165 towns (see Figure 2.1). Data for the socioeconomic variables associated with households of commuters and the neighborhoods at the origin and destination ends of the trip have been acquired and aggregated at the same spatial resolution of towns to expand the choice model.

The PEV is not included, because the specific definition of how the variable was calculated from the contributing factors was not available. For the other measures, slight modifications in the definition are used due to the fact that data is sometimes only available in terms of households and the variables are used at an aggregated scale of cities, towns, and the Boston CBD rather than individual TAZs.

Vehicles per Worker, $\boldsymbol{VPW}(\boldsymbol{i})$

Using the American Fact Finder, data are extracted for the Greater Boston area from the 2010 U.S. Census *[4]* and the American Community Survey *[5]*. Specifically, data are collected for household-level vehicle ownership for each census tract within the CTPS region, and these data are then aggregated into towns and the Boston CBD. This value is an important determinant of the likelihood of commuting by driving or driving to transit, because a pre-requisite for using a car is to have access to one.

Table 2.1: CTPS mode choice model parameters *[6]*

	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]
SOV	1	-0.0199		-0.269	-0.111	1.25			
HOV	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 = pproduction 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 TAZ centroid (airline distance); 1: entire zone within 1 mile of stops.

Vehicle ownership per household is part of the ACS, so these data are from 2017, which is more recent than the CTPS skims that were estimated using 2012 survey data. A separate comparison of reported mode shares from ACS with those reported in the CTPS data reveals that total travel has increased over the years, but the relative use of each mode remains similar. Therefore, utilizing more recent ACS socioeconomic data should provide good explanatory power for the model.

The vehicles per worker for origin i, $VPW(i)$, is estimated by dividing the vehicles per household by the number of workers per household.

Employment Density, $ED(j)$

Population and employment densities are indicators of the built environment in a community where commuters live or work. More densely developed areas will include more commuters who are located within an easily reached "walkable" distance of a point, such as transit or commuter bus stops.

A TAZ is a small geographic area, averaging about 1 square mile in size. TAZs are smaller in more densely developed areas and larger in suburban and rural areas. For comparison, the average census tract in the Greater Boston area is 2.8 square miles. Commuters can walk across a TAZ, and the zone is small enough that very few trips start and end in the same TAZ. At this spatial scale, it is appropriate to treat the development within a TAZ as uniform, allowing density to be a simple calculation of the total population divided by the total area. When aggregated into towns, this simple calculation of population density can over-simplify the reality of where people actually live and work. For example, a suburban town may have a densely developed town center surrounded by parklands or forests. These undeveloped spaces reduce the aggregated employment density of the town, but this does not reflect the fact that most people live and work in a communities characterized by the density of the town center.

An alternative population or employment density metric is proposed to represent the population density of the TAZ or census tract in which the average resident lives. This measure is a weighted average of the population density of the census tracts within a town, with the weight defined as the census tract population. The resulting calculation is as follows:

$$ED(j) = \frac{\sum_{t \in j} P_t \frac{P_t}{A_t}}{\sum_{t \in j} P_t} \qquad (2)$$

where P_t is the employment in census tract t, A_t is the area of census tract t, and the numerator and denominator are summed for the set of census tracts in destination town j. The result is a population/employment density measure that is greater than the conventionally calculated density/employment for a town, but it provides a better indication of the density of the communities within which people live and work. This calculation is expected to maintain some of the explanatory power of this variable, which was used in the original CTPS model at the level of individual TAZs. For the mode choice model, the square root of employment density, $\sqrt{ED(j)}$, is used as an explanatory variable.

Walk Access Fraction, $WAF(i,j)$

The WAF is a measure of the proportion of a zone's area that is within 1 mile of a transit stop. To estimate this value at the level of towns, a spatial analysis using a geographic information system (GIS) is used. Specifically, this analysis makes use of census tract shapefiles available from the U.S. Census Bureau *[4]* and transit stop location data from MassGIS Data Layers *[7]*.

First, transit stops throughout the Greater Boston area are mapped, including data from nine agencies:

- Massachusetts Bay Transportation Authority
- Merrimack Valley Regional Transit Authority
- Montachusett Regional Transit Authority
- Metrowest Regional Transit Authority
- Worcester Regional Transit Authority
- Lowell Regional Transit Authority
- Greater Attleboro Tauton Regional Transit Authority
- Cape Anne Regional Transportation Authority
- Brockton Area Transit Authority

The transit stop data are used to determine how many of the census tracts in the Greater Boston area have a centroid within 1 mile of a transit stop. Then, the census tract level measures are aggregated to towns to present a measure of the proportion of commuters who are within 1 mile of a transit stop. In order to reduce computation time, the analysis is based on census tract centroids rather than explicitly calculating the percentage of area overlapping the 1 mile buffers around transit stops. In other words, the spatial analysis identifies the number of census tract centroids in each region that lie within 1 mile of a transit stop.

A difference between the WAF and the other metrics presented above is that this measure accounts for conditions at both the origin and destination ends of the trip, because a transit user will need to get to/from a transit stop at both ends of the trip. In order for an OD pair to be walkable, a commuter must be able to get to the transit stop from their home origin and also get to their place of work destination from the transit stop where they disembark the transit vehicle. For each OD pair, the WAF is expressed as the average of the values for the origin and destination communities. Therefore, $WAF(i,j)$ is a 165-by-165 matrix.

2.1.2 Socioeconomic Variables for Extending the Existing Nested Logit Model

In addition to the socioeconomic variables listed above, some additional demographic variables are identified that may also affect mode share but were not included in the original CTPS model (i.e., household income and industry sector of employment). The goal is to use these measures to reduce the magnitude of calibration factors estimated in Part I, finding methods to reduce the calibration factors in order to reveal more of the underlying causes for the mode choices that people make.

Mean Household Income

The U.S. Census reports income statistics. Income is potentially an influence on mode choice because it can affect how commuters value their time and how they perceive their time spent in different modes.

Employment by Industry Sector

A final socioeconomic variable considered is the industry sector in which commuters work. The U.S. Census Bureau reports Longitudinal Employer Household Dynamics (LEHD) data that includes the LEHD Origin-Destination Employment Statistics (LODES) *[8]*. LODES data reports the number of workers by industry residing in each census tract and the number of workers by industry employed in each census tract. The LODES data is aggregated to the spatial resolution of towns to match the other data.

The LODES data on industry sectors of employment is a categorical variable based on the North American Industry Classification System (NAICS). Industry sectors in the dataset are grouped into 11 aggregations of related occupations for this analysis as follows:

1. Manufacturing, Production, and Natural Resources – Agriculture, Forestry, Fishing and Hunting (NAICS 11); Mining, Quarrying, and Oil and Gas Extraction (NAICS 21); Manufacturing (NAICS 31-33)
2. Utilities and Construction – Utilities (NAICS 22); Construction (NAICS 23)
3. Trade – Wholesale Trade (NAICS 42); Retail Trade (NAICS 44-45)
4. Transportation and Warehousing (NAICS 48-49)
5. Hospitality and Entertainment – Arts, Entertainment, and Recreation (NAICS 71); Accommodation and Food Services (NAICS 72)
6. Information (NAICS 51)
7. Finance and Real estate – Finance and Insurance (NAICS 52); Real Estate and Rental and Leasing (NAICS 53)

8. Professional, Scientific, and Technical Services (NAICS 54)
9. Administration and Management – Management of Companies and Enterprises (NAICS 55); Administrative and Support and Waste Management and Remediation Services (NAICS 56)
10. Education, Community, and Social Services – Educational Services (NAICS 61); Health Care and Social Assistance (NAICS 62)
11. Public Administration and Other Services – Public Administration (NAICS 92); Other Services [except Public Administration] (NAICS 81)

By aggregating these industries into groupings of related occupations, the complexity of modeling the effect of employment sector on commute mode was reduced to make statistical analysis easier to interpret.

Estimating Income and Industry by OD Pair

The data on industry sector of employment in LODES is reported in two spatial datasets: the Residence Area Statistics (RAC) provides the number of workers by industry that reside in each census tract, and the Workplace Area Statistics (WAC) provides the number of workers by industry that work in those tracts. These are essentially the row totals and column totals of an OD matrix of commuters by industry sector. The LODES and census data itself does not include the specific OD flows by income or industry, but this is the data that would be needed to explain variations in mode choice for specific OD pairs.

To generate the necessary data for income and industry variables by OD pair, the census and LODES data are used to generate a synthetic population of commuters that match the aggregated characteristics presented in the data. A procedure referred to as Iterative Proportional Fitting (IPF) is used to populate the full OD matrix with synthetic commuters that are assigned specific socioeconomic characteristics at the household and individual person levels. This population is constructed using distributions from the census data. The IPF process then iteratively revises the synthetic population characteristics until the aggregated characteristics by origin and destination are consistent with the reported data. An overview of the process is illustrated in Figure 2.2, in which multiple data sources are used to fit OD industry characteristics, individual commuter characteristics, and household characteristics. A more detailed and technical description of the IPF process and application to the Boston metropolitan area is available in Fournier et al. *[9]*.

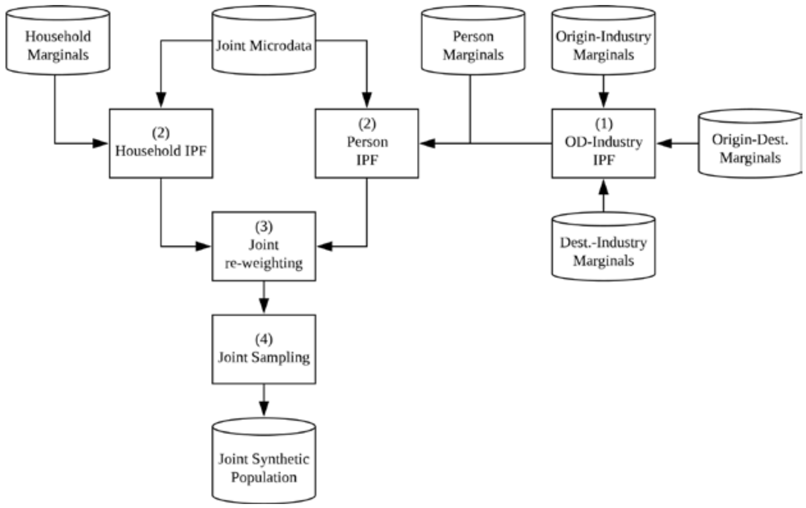


Figure 2.2: Overview of iterative proportional fitting (IPF) for constructing a joint synthetic population of commuters

2.1.3 Summary of Socioeconomic Variables

Table 2.2 shows the compiled and calculated socioeconomic variables for the top 10 towns that were identified for potential efficiency of new commuter bus service in the morning peak (listed in Table 1.2). These are the communities in which the original model from Part I of the study indicated they achieved the lowest cost per unit of GHG reduced when a commuter bus service was introduced.

Table 2.2: Socioeconomic variables for expanded mode choice model

Origin Town	Destination Town	Vehicles per Household	Population Density (pop/sq. mile)	Walk Access Fraction	Average Household Size	Median Household Income ($/year)
Woburn	Boston CBD	1.76	3,569	1.00	2.57	83,304
Weymouth	Boston CBD	1.71	3,427	1.00	2.41	75,892
Framingham	Boston CBD	1.64	3,844	1.00	2.44	73,182
Natick	Boston CBD	1.79	2,687	1.00	2.49	106,027
Milford	Boston CBD	1.79	3,631	0.91	2.57	72,807
Randolph	Boston CBD	1.71	3,317	1.00	2.74	69,969
Beverly	Peabody	1.70	5,060	0.88	2.33	77,893
Peabody	Boston CBD	1.71	5,223	0.88	2.42	65,085
Milton	Boston CBD	1.90	2,998	1.00	2.86	126,000
Gloucester	Beverly	1.65	4,000	1.00	2.29	65,348

2.1.4 Extension of Nested Logit Model to Include Socioeconomic Variables

The nested logit model used in Part I to estimate mode choice based on impedance variables has the same general structure as the extended model. The estimated utility from the Part I model was

$$V(i,j,m) = \beta_{ASC}(m) + \beta_{IVTT}IVTT(i,j,m) + \beta_{OVTT}OVTT(i,j,m) + \beta_{COST}COST(i,j,m) \quad (3)$$

where $IVTT(i,j,m)$ is the in-vehicle travel time from origin i to destination j by mode m, and the β values are the coefficients. Since CTPS has already estimated coefficients for the socioeconomic variables, the only change that is required for the model is to expand the calculation of the estimated utility associated with each mode to include the additional explanatory variables. Equation (3) is expanded in the new model to

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

where $VPW(i)$ is the vehicles per worker in origin i, $\sqrt{ED(j)}$ is the square root of employment density in destination j, and $WAF(i,j)$ is the average walk access fraction in origin i and destination j.

2.1.5 Regression Model to Include Additional Socioeconomic Variables

Even with the socioeconomic variables that are included in the expanded nested logit model, there remain errors in the model estimates. Without individual survey data, it is not possible to estimate additional socioeconomic factors within the nested logit model structure. However, the additional socioeconomic variables can be used in a regression model to investigate how much of the difference between the mode choice model estimates and the reported mode flows from CTPS can be explained. For each mode m, a linear regression model of the following form is estimated with observed data points for each OD pair, identified by i and j:

$$ODAM(i,j,m) = \beta_0 + \beta_P PODAM(i,j,m) + \beta_{Inc}Inc(i,j) + \sum_{k=1}^{11} \beta_k \, Ind(i,j,k) \quad (5)$$

where $Inc(i,j)$ is the average household income for commuters traveling from i to j, and $Ind(i,j,k)$ is the number of commuters in industry group k (based on the list in Section 2.1.2) traveling from i to j. Since there are 12 modes, 12 regression models are estimated in order to account for the different impacts that each of these explanatory variables can have on commuters' likelihood of using different modes for their commute trips.

Applying this regression model to the model outputs from nested logit model results in revised uncalibrated model estimates, $ODAM(i,j,m)$. The fit of the regression model will determine how much of the original calibration parameter value can be explained by the household income and industry sector variables. The errors that remain can again be corrected by calculating calibration parameters by the same Equation (1) as used in the Part I model. Mathematically, the worst case is that the regression model explains none of the calibration error and the calibration parameters remain unchanged. Ideally, the magnitude of the calibration parameters should be decreased.

A model with less reliance on calibration parameters is able to better capture the causes of the mode choices observed. The resulting model should provide more reliable estimates of future mode shares as conditions change for the modes or demographics associated with specific OD pairs.

2.2 Running Buses on Shoulders

One method used to speed up bus operations to make transit more competitive with driving is to operate buses on highway shoulders during congested periods. Concurrent with this study, a MassDOT study of the feasibility of running buses on shoulders culminated in a presentation identifying feasible corridors *[3]*. The use of highway shoulders to increase road capacity and allow buses to bypass congestion is common in some parts of the United States. The benefits of part-time shoulder use (also called shoulder running, hard shoulder running, and temporary shoulder running) are that capacity can be added to a roadway without the extensive construction and expenditures associated with widening the highway.

In Massachusetts, there is a precedent for allowing all traffic to use the shoulder break-down lane during rush hours (3pm – 7pm on weekdays) on over 45 miles of highway. Other states have specific programs permitting buses to utilize shoulders to bypass congestion. This practice is widespread in Minneapolis, Minnesota, but buses are also operated on highway shoulders in Kansas, Illinois, Ohio, Florida, North Carolina, Virginia, Maryland, and New Jersey. A difference between bus-on-shoulder operations and part-time shoulder use for all traffic is that a bus-on-shoulder policy reserves the shoulder space only for buses and trained bus drivers who make real-time decisions about whether or not to operate in the shoulder. The result is a method for speeding up bus operations with minimal required investment in striping, signage, or other infrastructure.

Most implementations of bus-on-shoulder running follow the model of Minneapolis. Guidelines from Minneapolis' experience for running buses on shoulders:

- Shoulder width is at least 10 feet;
- Buses operate no more than 15 mph faster than general traffic in adjacent lanes;
- Buses re-enter the mainline traffic lanes when the shoulder is obstructed, there is a complex interchange, or the road passes a pinch point.

The MassDOT "Bus on Shoulder" study *[3]* included analysis and evaluation of highway corridors throughout the Boston region based on three criteria, illustrated in Figure 2.3:

1. Shoulder width – A standard bus is approximately 8.5 feet wide with additional width added by mirrors. Guidelines are that shoulders should be at least 10 feet wide on straight sections and 11.5 feet wide on bridges, beside barriers, and along curbs *[10]*.
2. Flow of buses – only highways where buses are actually in operations does it make sense to implement bus-on-shoulder running. Even when a small investment in infrastructure is necessary, it is more efficient to implement bus-on-shoulder for segments that carry more bus traffic.
3. Congestion – Bus-on-shoulder only offers a travel time benefit for links that are congested (defined at speeds under 35 mph). The more hours per day a highway link is in congestion, the more buses will benefit from the implementation of a bus-on-shoulder policy.

Figure 2.3: Corridor characteristics for bus-on-shoulder *[3]*

As a result, the MassDOT "Bus on Shoulder" study *[3]* identifies three corridors for potential implementation and detailed evaluation as summarized in Table 2.3.

Table 2.3: Corridors identified for potential bus-on-shoulder running *[3]*

Corridor	**Start**	**End**	**Buses per Day**	**Total Length (mi)**	**% Congested by Length**
I-90	Downtown Boston	SR-30 in Wayland, MA	657	17.3	88%
I-93	Downtown Boston	SR-125 in Wilmington, MA	359	16.5	42%
US-1	Downtown Boston	Broadway in Saugus, MA	130	9.9	50%

2.2.1 Geographic Analysis of Feasible Corridors

In order to use information about the identified corridors for bus-on-shoulder running, information from the MassDOT "Bus on Shoulder" report *[3]* is used with a GIS representation of the regional road network. These corridors are shown in Figure 2.4. Each link that is included in the corridor is identified and classified in one of two categories:

1. Feasible links already have sufficient shoulder width to allow for bus-on-shoulder running without additional construction and infrastructure investment needed. Buses could be operated on shoulders on these links in the near term at low cost.
2. Ideal links do not currently have sufficient shoulder width to allow for bus-on-shoulder running but would complete the corridor if infrastructure were to be expanded for an ideal implementation. Currently, buses cannot operate on shoulders on these links without additional construction, so these are unlikely for actual implementation. Any links in the corridor that are not identified as "feasible" are by default considered "ideal."

The classification is based on the characterization from the MassDOT "Bus on Shoulder" workshop materials *[3]*. Links that are identified as being a "good choice" or having "minimal" operational issues are classified as feasible links for this analysis. This identification is closely linked to the segments that have sufficiently wide shoulders in the detailed maps accompanying the report. These maps (an example of which is shown for I-90 in Figure 2.5) show measurements of shoulder widths from Google Earth, actual field measurements, and locations of interchanges and bottlenecks. Once identified in GIS, the classified links are in a format that can be compared with the routes of express commuter buses in order to identify which bus routes would be able to operate on shoulders and in which locations.

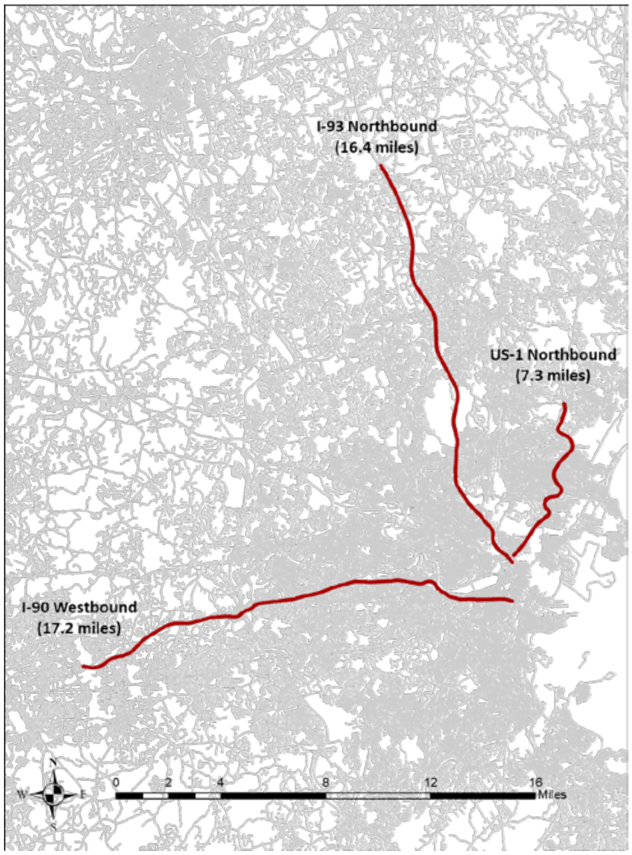


Figure 2.4: Corridors identified for bus-on-shoulder running

2.2.2 Geographic Analysis of Impacts on Bus Speeds

In order to estimate the effect of bus-on-shoulder running on potential express commuter bus operations, an estimate of the effect on in-vehicle travel time is needed. The procedure for estimating in-vehicle travel time with shoulder running involves first using GIS to identify the specific links that compose each commuter bus route. Then, the links on which the route overlaps the feasible or ideal bus-on-shoulder locations are identified in order to quantify the length of the route over which travel time savings can be accrued.

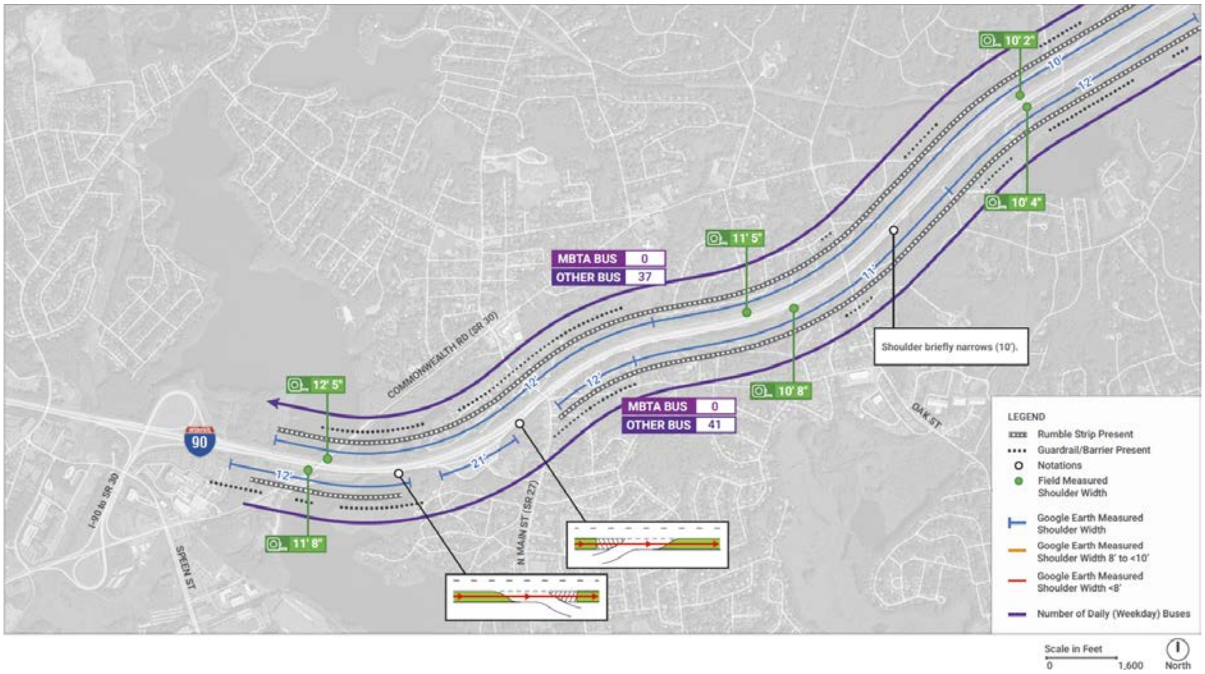


Figure 2.5: Example of detailed shoulder analysis for I-90 ***[3]***

The analysis is based on use of the GIS shapefile for the Boston region's road network, which includes parameters for link length and road classification for all links in the network. Many links also include speed limit data, which is used as the assumed maximum speed for buses operating on these links. For local streets without speed limit data, an assumed speed of 20 mph is used to in order to estimate travel times.

The GIS analysis procedure for quantifying the impact of bus-on-shoulder running for commuter buses is the following:

1. The most direct route that minimizes travel time for each OD pair is identified using the ArcGIS Network Analyst tool. The result is a set of roadway links that represent the route for the express commuter bus. Associated with this route are the length, speed limit, and travel time on each link as well as the route as a whole. The free flow travel time for the route from i to j is denoted by $FFTT(i,j)$.

2. The congested speed on each link is estimated using the ratio of the route's free flow travel time and the reported in-vehicle travel time, $IVTT(i,j)$, from the CTPS data. The estimated congested speed on each link l is denoted by $v_c(l)$ and is calculated as follows

$$v_c(l) = \frac{FFTT(i,j)}{IVTT(i,j)} v_f(l) \tag{6}$$

where $v_f(l)$ is the link free flow speed. Since the only congested travel time data is the aggregate travel time over the whole route, it is assumed that each link in the route is proportionally congested. In reality, it is likely that some links are more congested than others, but this would require higher resolution congestion data that vary from day to day.

3. For links on which bus-on-shoulder running is assumed to be implemented, the speed of the commuter bus is increased by up to 15 mph compared to the congested traffic speed on congested links (and not exceeding the speed limit).

$$v_{cb}(l) = \begin{cases} v_c(l) + 15 & \text{for links with bus-on-shoulder running} \\ v_c(l) & \text{other links} \end{cases} \quad (7)$$

4. New in-vehicle travel times are calculated by summing the estimated travel times for commuter buses on each link in the route.

$$IVTT_{bos}(i,j) = \sum_{l \in R} \frac{d(l)}{v_{cb}(l)} \quad (8)$$

where R is the set of links in the route from i to j, $d(l)$ is the length of link l, and $v_{cb}(l)$ is the commuter bus speed on link l. For each OD pair, the in-vehicle travel time is calculated for both directions, from i to j and from j to i, because the round trip travel time is needed to calculate the number of buses needed for operations.

Two cases are considered: 1) in-vehicle travel time when bus-on-shoulder operations are implemented on feasible links, and 2) in-vehicle travel time when bus-on-shoulder operations are implemented in the entire (ideal) corridor.

The estimated effect of bus-on-shoulder operations is calculated by running the same mode choice and emission models with the new calculated in-vehicle travel times for the AM and PM peak periods.

2.3 Commuter Bus Stop Location

An important consideration for implementing a new express commuter bus service is the specific location of the bus stop in the community served. In the Part I study and the analysis of bus-on-shoulder running, an assumption was made that the commuter bus stop is located at the centroid of the town served. From this point, the average distance that a resident would have to drive or walk to access the bus was estimated as if the town's area were a perfect circle.

The specific location of the commuter bus stop is important for a number of reasons that would likely impact the ridership and performance of the commuter bus route:

1. The location of the bus stop affects the access time for passengers accessing the bus stop by walking or driving. Placement near a population center would allow more passengers to access the stop with a shorter walking distance, for example.
2. Characteristics of the bus stop location can affect the attractiveness to customers. For example, a bus stop that is located in a well-lit, walkable, and otherwise attractive

location is likely to be more appealing to riders than locations that are hard to reach and/or uncomfortable to wait in.

3. The availability of parking at the bus stop location will constrain the number of passengers that can feasibly drive to use the commuter bus service.

The method for evaluating the effect of stop location includes two parts. First, a review of the literature on the characteristics of bus stop locations that affect ridership is presented. This review is followed by a geographic analysis conducted to compare the impact of stop location on out-of-vehicle and in-vehicle travel time for two example communities: Framingham and Woburn.

2.3.1 Review of Literature on Transit Stop Location

Accessibility is a factor that is often considered to affect transit services' usage *[11, 12, 13]*. Various studies have investigated accessibility-related parameters that can affect the ridership of a transit system; many have focused on built environments and transit level of service, among others *[14, 15, 16]*. Pedestrian access to transit stops, with regards to accessibility, is a topic investigated in existing literature for many purposes. For example, walkability indicators are used by Corazza *[17]* to improve sustainability in urban mobility and by Schlossberg *[18]* to compare Transit-Oriented Development (TOD) sites. The importance of the bus stop's surrounding environment is highlighted by the Greater Cleveland Regional Transit Authority in "Transit Waiting Environments: An Ideabook for Making Better Bus Stops" *[19]* in which the surroundings are considered equally important as the stop location itself. A summary of the literature is presented in the Appendix.

An important aspect of studying transit stop accessibility is knowing what distances transit users are willing to travel to reach a stop. Hess *[20]* presents a summary of previous research on walking distances from various study sites. According to Kittelson and Associates *[21]*, users are willing to travel different distances to reach different types of transit stations. More specifically, 75% to 80% of people would walk 0.25 miles to access a bus or tram stop and 0.5 miles to access a rail station. These walking distances are in accordance with the "Pedestrian Safety Guide for Transit Agencies" released by the Federal Highway Administration *[22]*. In this report it is also noted that bicyclists are often willing to ride more than 0.5 miles to access transit stations, so it is important to assure a safe environment for them in a greater area.

Schlossberg *[23]* identifies three measurement domains for neighborhood walkability: quality, proximity, and connectivity. Quality refers to street classification; for simplicity, the authors separate streets in walkable and non-walkable. The technique adopted for measuring proximity is analyzing Pedestrian Catchment Areas (PCA) and Impeded Pedestrian Catchment Areas (IPCA). PCAs are calculated considering both the theoretically walkable area resulting from a walking distance of 0.25 miles and the actual polygon that results from walking this distance on the available street network. Figure 2.6 describes the respective calculations. IPCAs result from removing the major roads (i.e. non-walkable) from the street network, thus including only the network links that can be actually used by pedestrians to access a transit stop. A comparison between the two ratios can reveal the influence of major roads on the network under study. The third measurement domain, connectivity, includes intersection analysis and studies measures related with intersection and dead-end densities, as well as relevant ratios and the respective impeded measures.

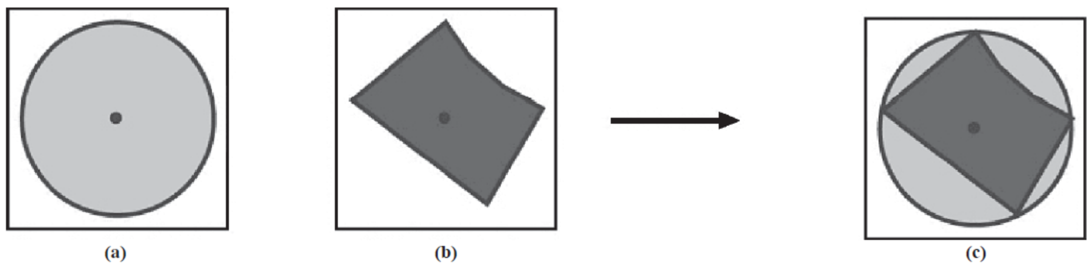


Figure 2.6: Diagram of pedestrian catchment area ratio calculation: (a) theoretical pedestrian service area, (b) network-defined pedestrian service area, and (c) pedestrian catchment area ratio *[23]*

The assessment of a bus stop location on a spatial basis is investigated in Foda *[24]*, which introduces three indexes. Ideal Stop Accessibility Index (ISAI) represents the accessibility to a bus stop by accounting for the total length of the surrounding pedestrian network. A circle of 0.25 miles radius around the bus stop is considered as an ideal access coverage area for the required calculations. Actual Stop Accessibility Index (ASAI) is presented as a more accurate measure, since it accounts for the actual access coverage area around the bus stop, as a result of the existing pedestrian network (i.e., polygon-shaped). Stop Coverage Ratio Index (SCRI) is the third index presented by the authors and can be used to evaluate the ratio of actual access coverage to that of the ideal access coverage of a bus stop. Figure 2.7 describes the respective calculations. It is also important to mention that by knowing the population density within the actual coverage area, we can obtain the population coverage of the stop.

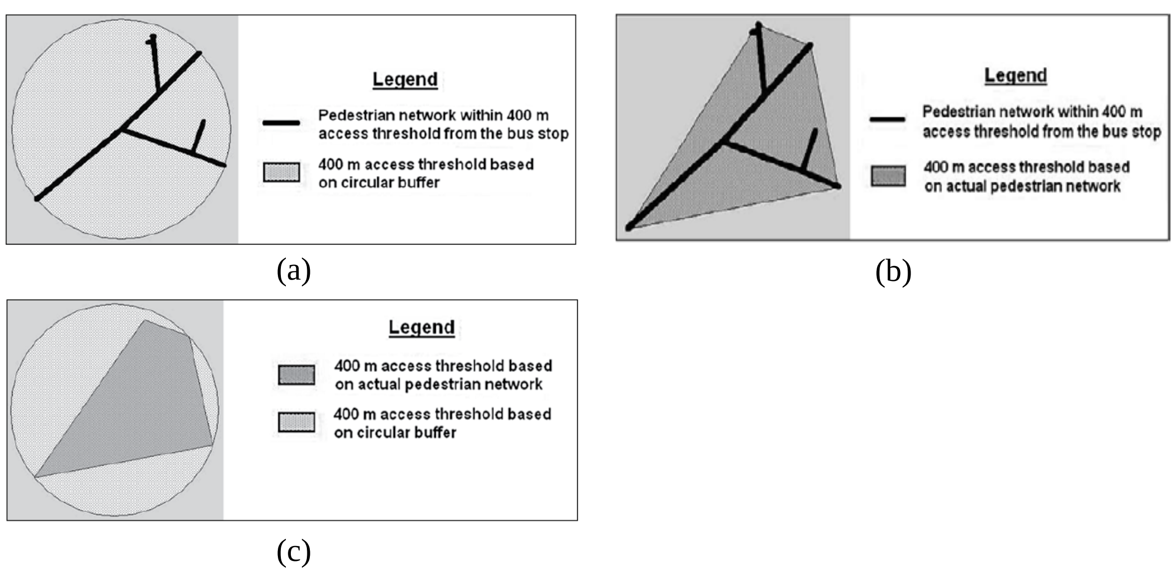


Figure 2.7: Illustration of a) ideal stop accessibility index, b) actual stop accessibility index, and c) stop coverage ratio index *[24]*

The incorporation of urban form indicators into transportation planning and analysis is investigated by Zhang *[25]*, using Boston as their study area. The authors present existing measures that could be used to assess accessibility of transit stops and group them into three categories: geometric, context-sensitive, and behavioral measures. In the first group, geometric measures, they present indices α and γ from Dill *[26]* given in Equations (9) and (10), which quantify the connectivity of a network using the number of links and nodes.

$$a = \frac{n^o links - n^o nodes + 1}{2(n^o nodes) - 5} \tag{9}$$

$$\gamma = \frac{n^o links}{3(n^o nodes) - 2} \tag{10}$$

Dissimilarity, contrast, and entropy indices are included in the context-sensitive group in order to describe the diversity of land use. The strong relationship between transit ridership and land use patterns is highlighted by the Ontario Ministry of Transportation *[27]*. According to Corazza *[17]*, the higher the land use diversity in an area, the more attractive the operating transit lines are. Dissimilarity and contrast indexes can be applied to grid-based approaches, in which a larger analysis area is broken into a grid of smaller cells for evaluation, and were used by Cervero *[14]* and Srinivasan *[28]* respectively.

$$\text{dissimilarity index} = \frac{\sum_j^k \sum_i^8 (X_i/8)}{K} \tag{11}$$

where K is the number of actively developed grid cells in a TAZ or tract and X_i is 1 if land use category of the neighboring grid cell differs from grid cell j and 0 otherwise.

$$\text{land use contrast index} = \sum_i^n \sum_j^n (i - j)^2 \left[\frac{P(i,j)}{R}\right] \tag{12}$$

where P is the co-occurrence matrix, R is the total number of cell adjacencies, and n is the total number of cells in a TAZ. For dissimilarity, in a grid-based approach of 3 by 3 grid cells, the number of the adjacent eight cells that have land use different than the central cell corresponds to added points for the latter's index. Land Use Entropy (LUE) is calculated considering proportions of different land uses within a study area and has been applied by Cervero*[14]*, Srinivasan *[28]*, and Corazza *[17]*.

$$\text{land use entropy} = \frac{-\sum_j P_j \ln(P_j)}{\ln(J)} \tag{13}$$

where P_j is the proportion of land use category j in a TAZ or a grid cell and J is the total number of land use categories.

Corazza *[17]* is the most recent study on evaluating the accessibility of bus stops in the general framework of sustainable urban mobility. The authors proposed a multi-step methodology that incorporates different indicators to provide a unique score for bus stops. The indicators used are road classification, intersection density, network connectivity, LUE, and PCA, among others.

In Holtzclaw *[29]*, in the frame of studying location efficiency, an index determining the pedestrian/bicycle friendliness of a network is presented. This index accounts for the street grid, the mean year that the surrounding buildings are built, as well as some roadway infrastructure characteristics that serve as bonuses (e.g., traffic calming, bike lanes, and bike parking).

$$\text{ped/bike friendliness} = SG + YB + B \tag{14}$$

where SG is a measure of the street grid (number of census blocks divided by the number of developed hectares), YB is an index for the median year that buildings were built (0.7 for 1939 or earlier, 0.6 for 1940-42, 0.5 for 1943-1945, 0.4 for 1946-1948, 0.3 for 1949-50, 0.2 for 1951-52, 0.1 for 1953-55, and 0 for 1953 or newer), and B is a bonus with traffic calming contributing up to 1.0 and bicycle credits contributing up to 0.5.

Existing literature has also highlighted the need to assure equity in transit planning and indices have been developed with this in mind. Both Welch *[30]* and Delbosc *[31]* make use of Lorenz curves to address the inequity of a certain phenomenon's geographic concentration (e.g., distribution of income), among other equality indexes that are included in their studies.

Finally, criminality around a transit stop can be considered as an important index that affects accessibility. D. Wang *[32]* presents a study on the relationship between crimes and mass transit for the Bay Area Rapid Transit (BART) system of San Francisco. Their findings include an observation that peaks in crime are related with the characteristics of blocks and streets. Also, it is interesting that the most "dangerous" BART stops were the car-friendly ones, making the authors conclude that the construction of parking lots could increase criminality. The impacts of built environment on crime is further studied by Loukaitou-Sideris *[33]*. Using evidence from existing literature, the authors describe how network characteristics, such as number of streets turning into a block or major streets and alleys, can increase criminality. In terms of land use, they explain the impact of different land uses (e.g., residential, industrial, commercial areas and multi-/single-family housing) on crime incidents. Also, areas where alcohol is provided (such as bars or liquor stores) and cash transactions are taking place (e.g., ATMs) are associated with increased criminality. Physical and social incivilities (e.g., trash, graffiti, panhandling) are presented as indicators of high criminality, in contrast to areas with increased visibility (e.g., surveillance).

2.3.2 Geographic Analysis of Bus Stop Location

Following from the literature review presented in Section 2.3.1, three measures are quantified for the analysis and comparison of bus stop locations. Using the guideline that 80% of walk-access transit riders walk less than 0.25 miles to bus stops provided insight into the upper limit of distance the commuters are likely to be willing to walk. Therefore, the mode choice model is split into two calculations: a mode choice estimate for commuters that reside within walking distance of the bus stop (walk-access and drive-access are viable choices) and a second one for commuters that live further away (only drive-access is a viable choice).

In addition to accessibility for walk-access and drive-access commuter to get to a bus stop, the location of a bus stop within a community can also affect the in-vehicle travel time depending on how far the stop is located from the highway and the final destination. For example, a commuter bus stop located at a highway interchange will be associated with less in-vehicle travel time than a bus stop located in a town center that is a few miles away on local streets. The effect of the stop location on in-vehicle travel time needs to be estimated. Along with the revised mode choice estimates, this was used to change input to the commuter bus performance model and estimate the impact of stop location on ridership, GHG reduction, and efficiency. Lastly, an analysis of road classification in the vicinity of stops provides a network measure of walkability that is used to consider qualitative impacts on commuter bus performance.

For this analysis, two communities are selected for more detailed evaluation of commuter bus stop locations. Framingham and Woburn are both communities with high-ranking corridors for potential express commuter bus service to Boston CBD. These are both communities in which there are a variety of potential bus stop locations to compare, so they provide a good case study for the effects of selecting different bus stop locations. In each community, three potential bus stop locations are considered: one in a town center location, and two others in locations that are more suburban in character.

Based on the literature review, the criteria for selecting an effective commuter bus stop location were determined to be the following:

- Dense street network in the vicinity of the bus stop
- Many minor (i.e., walkable) links that lead to the bus stop location
- Mixed land use (houses, public buildings, and shops within 0.25 miles of the bus stop location)
- No liquor or cash transaction stores adjacent to the bus stop location
- Good visibility for waiting passengers (i.e., not too many trees and other major obstructions and/or a possibility for coverage by surveillance cameras from surrounding shops)

Catchment Area for Ridership

For each potential bus stop location, the catchment area for potential walk-access passengers is derived by identifying the number of commuters that reside within 0.25 of the bus stop location. This analysis is conducted by using GIS with the TAZ shapefile, which represents the locations of commuter residences with finer spatial resolution than each town. Whereas the average area of a town in the CTPS-defined Greater Boston area is 17.1 square miles, the average TAZ is 1.04 square miles. Using GIS, all TAZs that lie within or intersect a radius 0.25 miles from the bus stop location are considered to be within the walkable catchment area. Since the original OD matrix of commuter flows from CTPS is represented at the resolution of TAZs, the number of commuters residing in these selected TAZs can be summed.

To facilitate a comparison of stops in different towns, the catchment for potential walk-access passengers is expressed as a ratio of the commuters living with the selected TAZs and all commuters residing in the town. This value is denoted by $C(s, i)$, which can be interpreted as the percentage of commuters in origin i that reside within walking distance of stop s.

The mode choice model is then revised to reflect the fact that there are now two populations of commuters in each town:

1. Potential walk-access commuters are the population of commuters multiplied by $C(s,i)$. These commuters now experience an average access distance of 0.167 miles (which is the average distance from the center to a point within a circle of radius 0.25 miles). The same mode choice model is used for this population group, but the calculation of OVTT for commuter bus is the time it would take to drive or walk this short distance.
2. Drive-access only commuters are the remaining population of commuters in the town, which can be calculated by multiplying the population of commuters by $1 - C(s,i)$. These commuters are assumed to live too far from the commuter bus stop to consider walk-access as a viable mode choice. Therefore, the same mode choice model is used with these commuters except with the walk-access commuter bus mode removed. The OVTT for drive-access commuter bus is calculated the same way as before, with an average distance across the whole town used to estimate the drive-access time.

In-Vehicle Travel Time

The selection of different bus stop locations also affects the travel time for the commuter bus between origin i and destination j. In order to incorporate this travel time effect into the modeling, the IVTT values must be revised for the congested periods in which the commuter buses operate. The method for estimating the variation of travel time associated with specific bus stop locations is to use Google Maps to identify the estimated travel time from the centroid of the town to the destination and compare this with the estimated travel time from each bus stop location to the same destination. The difference between the stop-specific travel time and the centroid travel time from Google is then applied to congested travel time reported by CTPS for the IVTT data for cars only traveling between the origin and destination. For example, if Google estimates the travel time from a bus stop location to be 3 minutes longer than the travel time from the town's centroid, then 3 minutes are added to the IVTT used in the base model.

By including the effect of stop location on both OVTT and IVTT, the model reflects the impact of changes in ridership associated with walk-accessibility and any impact of changes in bus travel time.

Percentage of Minor Roads

A final consideration for evaluation and comparison of commuter bus stop locations is the walkability of street network in the vicinity of the bus stop. Although the literature does not provide a clear link between quantitative measures of walkability and transit ridership, a measure of walkability can provide an indicator for comparison of two potential bus stop locations. For this study, the percentage of street network distance with 0.25 miles of the bus stop that are classified as minor roads is chosen as the measure of walkability. Since major roads are uninviting to walk along and difficult to cross, a greater percentage of minor roads in the vicinity of the bus stop indicates greater walkability.

3 Results

The data analysis and modeling methods described in Section 2 led to the results presented in the following sections. The extended model that includes socioeconomic variables is evaluated based on the fit of the uncalibrated model estimates and reported OD flows by mode. The revised model is then used to identify the most efficient potential commuter bus corridors.

Next, the analysis of potential locations for running buses on shoulders is applied to the list of most efficient commuter bus corridors. Six OD pairs are identified that would benefit from shoulder running, and the model is revised to quantify the effect of shoulder running on ridership and GHG reduction. Corridors are evaluated for two scenarios: a feasible case with shoulder sections that are identified as relatively easy for implementation, and an ideal case with all shoulder sections in the corridors of interest.

Lastly, the results for the bus stop location analysis are presented with consideration of three candidate stop locations in Framingham and Woburn. The analysis includes consideration of the effect of stop location on the number of commuters that are able to walk to the stop within 0.25 miles (versus driving from anywhere in the community) and the effect of in-vehicle travel time for buses to get to specific bus stop locations using the local road network. These effects are incorporated into the mode choice model to provide revised estimates of commuter bus ridership for comparison across different locations.

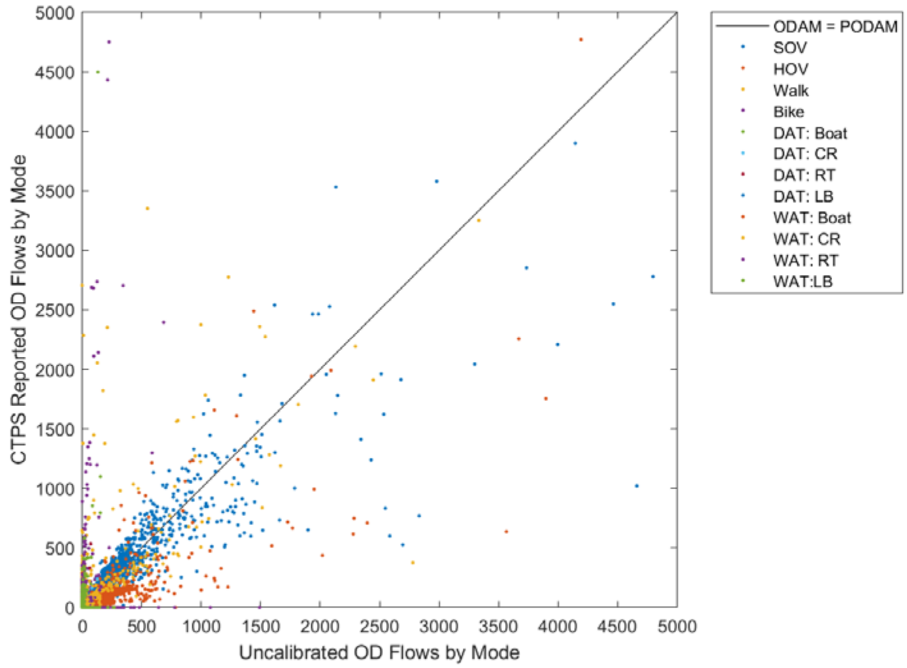
3.1 Calibration and Evaluation of Extended Mode Choice Model

3.1.1 Expanded Nested Logit Model with Socioeconomic Variables

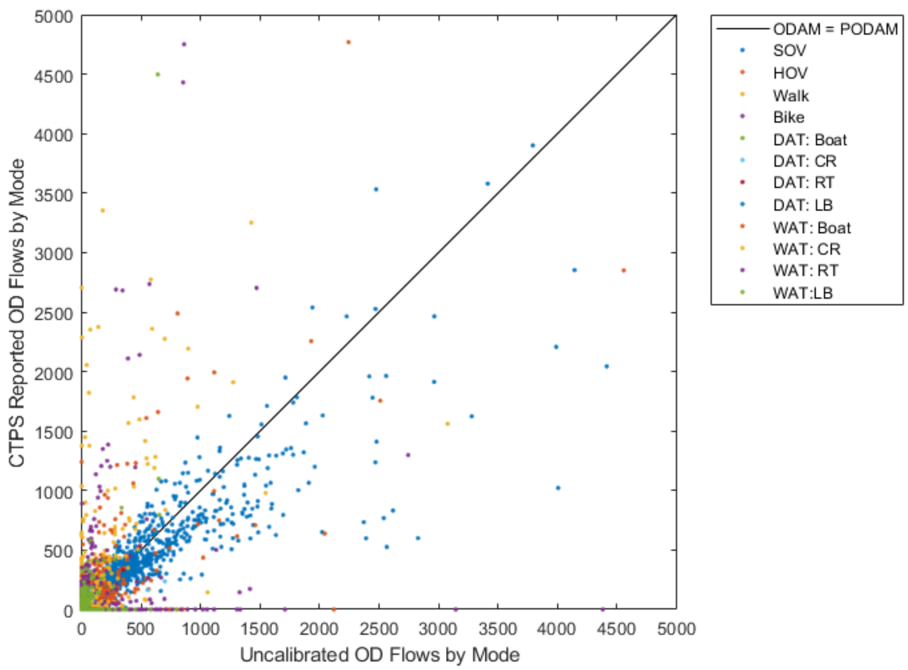
By including the following socioeconomic variables related to each OD pair, the goal of this analysis was to improve the accuracy of the simplified model:

- Vehicles per worker (based on AM origin zone)
- Square root of employment density (based on AM destination zone)
- Walk access fraction (based on origin and destination zones)

This revised model results in new estimated flows for each OD pair by modes that are again compared against the CTPS reported flows. The comparison for the Part I model shown in Figure 1.2 is revised in Part II to Figure 3.1 (the calibration chart from Part I is reprinted on the same page for comparison). A visual comparison of the comparison plots from Part I and Part II does not show much improvement of the model fit, if any. An improved model would be represented by more points lying closer to the ODAM = PODAM line with slope equal to one. If anything, it appears that errors have been introduced, increasing the scatter of SOV trips. There isn't a visual pattern to distinguish what is happening for the other modes. This inclusive result justifies an effort to include additional explanatory variables to explain remaining model errors using regression.



a) Part I Model (impedance variables)



b) Part II Model (impedance + socioeconomic variables)

Figure 3.1: Comparison of uuncalibrated AM mode flows and CTPS mode flows

3.1.2 Expanded Model with Regression of Additional Socioeconomic Variables

With the comparison plot in Figure 3.1 showing a remaining need for improvement, the regression model described in Section 2.1.5 is implemented. The outputs from the nested logit model are explanatory variables along with the mean household income and the number of workers in each of the 11 industry categories, as shown in Equation (5).

The coefficients for each of the mode models are shown in Table 3.1. At the bottom of the table, the overall model fit is represented by the R^2 value, which gets closer to 1 as a “perfect” model is approached. The model fits well for all of the modes except for drive-access to transit (drive access to boat has particularly poor fit), which may be a reflection of the relatively small number of observed trips for drive-access transit modes compared to the others. The root mean squared error (RMSE) is a measure of the magnitude of errors for each of the models, and the low values for drive-access transit support the assertion that there are simply too few trips by those modes to obtain good statistical fit for the model.

Table 3.1: Regression model parameters by mode

Parameter	SOV	HOV	Walk	Bike	D+B	D+CR	D+RT	D+LB	W+B	W+CR	W+RT	W+LB
β_0	-3.46	-4.23	-1.00*	0.07*	0.03*	0.12*	0.12*	-0.03	-0.05	0.18*	-1.11*	-0.39*
β_P	0.43	1.21	1.27	-0.07	0.77	0.41	-0.01	0.00*	0.00	0.21	0.07	0.12
β_{Inc}	0.00	0.00	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
β_{Ind1}	0.23	0.47	0.23	-0.06	0.00*	0.01	-0.04	0.00	0.00	0.00	-0.32	-0.09
β_{Ind2}	1.74	0.45	-0.10*	-0.09	0.01	0.00*	0.01*	0.01	-0.01	-0.05	-1.00	-0.06
β_{Ind3}	1.12	0.36	0.14	-0.03	0.00	0.02	0.03	0.00	-0.01	-0.01	-0.69	-0.08
β_{Ind4}	0.41	-0.47	-2.28	0.10	0.01	0.02	0.01	0.01	0.00*	0.05	-0.02*	0.17
β_{Ind5}	-0.94	-0.28	-0.35	0.09	-0.02	-0.10	-0.06	-0.01	0.02	0.00*	1.54	0.14
β_{Ind6}	0.32	-0.21	0.38	0.06	-0.01	0.00*	0.00*	0.01	0.00	0.00*	-0.42	0.00*
β_{Ind7}	-0.20	0.49	-0.37	-0.02	0.00	0.00	0.04	0.00	-0.01	-0.04	0.49	0.07
β_{Ind8}	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*
β_{Ind9}	-0.29	-0.27	0.43	0.02	0.00	0.00*	0.00	0.00	0.00	0.01	0.22	0.01
β_{Ind10}	1.14	-0.13	0.51	-0.05	0.01	0.12	0.05	-0.01	0.03	0.19	-0.96	-0.36
β_{Ind11}	-0.01	0.04	0.19	0.04	0.00	0.01	0.01	0.00	0.00	0.00	0.18	0.08
R^2	0.93	0.81	0.93	0.90	0.17	0.46	0.63	0.51	0.84	0.81	0.94	0.90
RMSE	48.47	40.05	55.96	6.07	1.08	3.65	3.70	0.78	0.71	5.65	41.44	9.68

Coefficient subscripts are as follows: P is the model number of travelers by mode; INC for mean household income; Ind1 for manufacturing, production, and natural resources; Ind2 for utilities and construction; Ind3 trade; Ind4 for transportation and warehousing; Ind5 for hospitality and entertainment; Ind6 for information; Ind7 for finance and real estate; Ind8 for professional, scientific, and technical services; Ind9 for administration and management; Ind10 for education, community, and social services; and Ind11 for public service administration and other services.

Mode abbreviations are as follows: SOV is single occupant vehicle; HOV is high occupant vehicle; D+B is drive access boat; D+CR is drive access commuter rail; D+RT is drive access rapid transit; D+LB drive access local bus; W+B is walk access boat; W+CR is walk access commuter rail; W+RT is walk access rapid transit; W+LB is walk access local bus.

*Parameter is not statistically significant at the 95% confidence level (p-value > 0.05).

In general, each model has several statistically significant explanatory variables, which implies that for at least some industry sectors those variables are good predictors of mode choice for commuters. Other observations from the regression models include:

- Mean household income in an origin is not a strong determinant of mode choice for any mode, because values for all modes are 0.00.

- The magnitudes of coefficients are larger for the driving modes (SOV and HOV) and walk-access to rapid transit. A larger magnitude of coefficient indicates a stronger effect of the explanatory variable on the number of commuters using a specific mode.
- Commuters employed in utilities and construction (Ind2); trade (Ind3); and education, community, and social services (Ind10) are more likely to drive than use transit.
- Commuters employed in hospitality and entertainment (Ind5) are more likely to walk to transit than to drive.

Using the regression model estimates in place of $PODAM(i, j, m)$, the model fit is visibly improved, as shown in Figure 3.2. Although there is still some scatter in the data, the points now center along the unit slope, which indicates that the bias has been removed from the model. There are no longer modes with clearly biased estimates and points along the axes that indicate a total mismatch between the model estimates and the reported OD flows from CTPS.

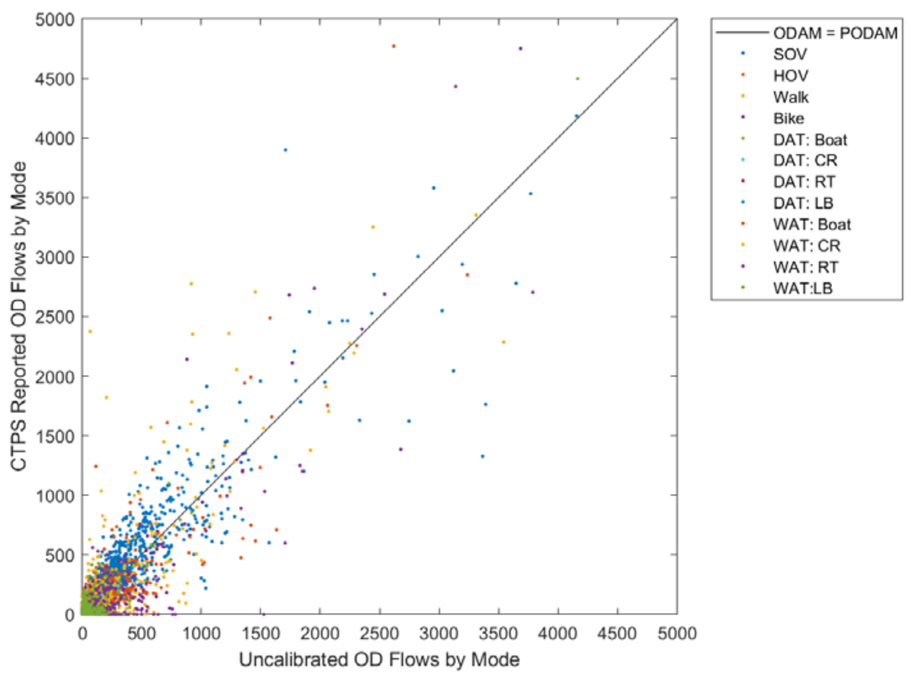


Figure 3.2: Comparison of uuncalibrated AM mode flows and CTPS mode flows (Part II logit model + regression)

3.1.3 Comparison of Models

A comparison of the model performance that is more detailed than the visual representations in Figure 3.1 and Figure 3.2 is important because we are interested in the effectiveness of the model for estimating transit utilization. The extension to estimate commuter bus ridership is based on the model components for other transit modes, so the goal is to have a model that estimates that ridership by transit and cars as accurately as possible, in order to account for the ridership and any mode shift that is associated with new commuter bus services.

The relevant metrics for measuring the performance of each model are the differences between the estimated count of trips and the reported trips for each OD pair by mode. This difference of count or error, ε, is simply the difference between the estimated number of OD trips by mode from the nested logit model, $PODAM$, and the reported number of OD trips by mode from CTPS, $ODAM$.

$$\varepsilon(i,j,m) = ODAM(i,j,m) - PODAM(i,j,m) \quad (15)$$

This value can be summarized as an average value per mode. Ideally, the average should be close to zero, which would indicate that the model makes unbiased estimates of mode flows (i.e., the model is precise). The error can also be summarized as a standard deviation, which should also ideally be zero. A low standard deviation indicates low variability, which means that the model accurately estimates the reported mode flows.

A comparison of the model performance for three cases is presented in Table 3.2: 1) the nested logit model from Part I that includes only impedance variables; 2) the expanded nested logit model from Part II that also includes the socioeconomic variables identified by CTPS; and 3) the expanded model that is further extended with the regression analysis described above.

Table 3.2: Comparison of OD mode flow estimate errors from three models

	Model from Part I (only impedance)		Logit Model from Part II (impedance & socioeconomic)		Extended Model from Part II (logit model & regression)	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
SOV	-1.01	171.39	-5.67	175.22	0.00	48.46
HOV	-5.44	71.27	2.24	47.27	0.00	40.04
Walk	3.16	67.54	5.57	100.90	0.00	55.95
Bike	0.97	14.09	-0.14	33.04	0.00	6.07
DAT+B	0.02	1.17	-0.02	1.17	0.00	1.08
DAT+ CR	0.43	4.45	-0.11	5.76	0.00	3.65
DAT+RT	0.48	5.62	-0.13	20.47	0.00	3.70
DAT+LB	0.05	1.05	-0.10	5.39	0.00	0.78
WAT+B	-0.25	7.79	-0.59	19.24	0.00	0.71
WAT+CR	0.22	8.84	-0.23	13.75	0.00	5.65
WAT+RT	1.10	155.65	-0.75	135.60	0.00	41.43
WAT+LB	0.26	29.60	-0.06	26.66	0.00	9.68
All Modes	*0.00*	*44.87*	*0.00*	*48.71*	*0.00*	*18.10*

Although all three models are unbiased in total (i.e., looking across all modes), there are biases associated with specific modes from the logit model. The first two models also have very high standard deviations associated with some modes, such as SOV, HOV, and WAT-RT. Generally, the magnitudes of errors in the Part II logit model are similar to the Part I model; the bias is mathematically eliminated by the addition of the regression model. These results are summarized in Figure 3.3 comparing error terms by mode. An additional comparison of standard deviation (Figure 3.4) shows that the variability of model estimates is reduced for all modes when including the additional socioeconomic variables through regression.

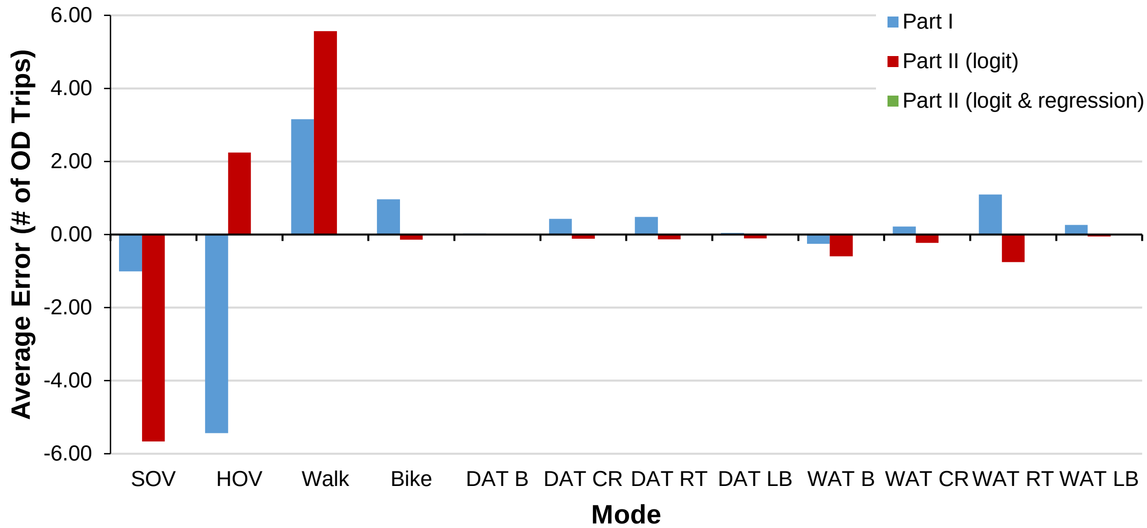


Figure 3.3: Comparison of average errors for the three models

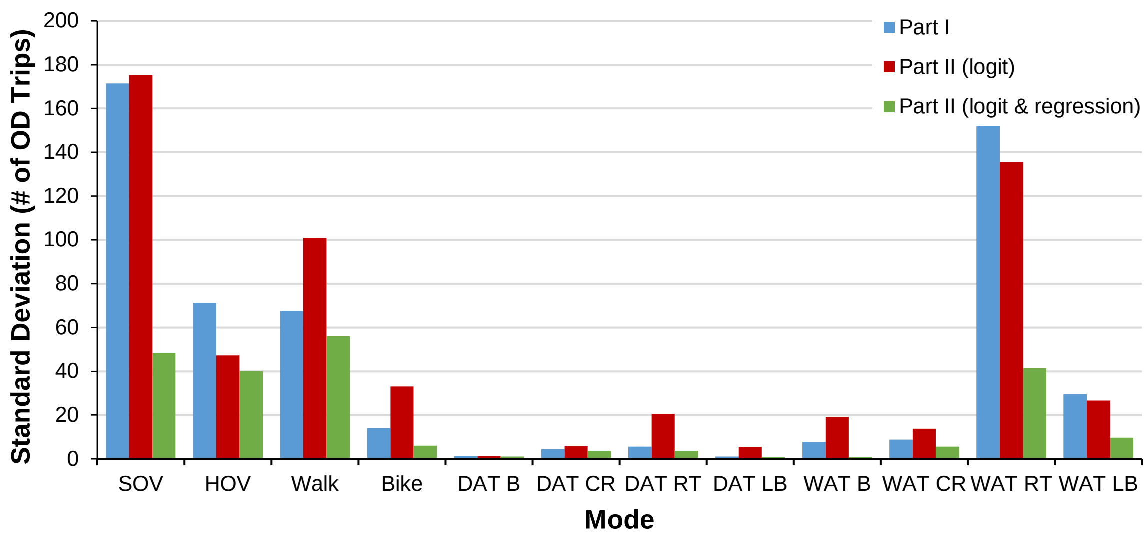


Figure 3.4: Comparison of standard deviation of errors for the three models

The scatter plot shown in Figure 3.2 indicates that there is still a need for calibration. Overall, the attempt to improve the model fit by incorporating additional socioeconomic variables was only a modest success. The regression model, which includes income and industry sector as explanatory variables, yields some statistically significant parameters. However, the need for extensive calibration in order to match reported OD flows in the base case remains.

3.1.4 Revised Model Estimates for Commuter Bus Corridors

The findings in Part I culminated in ranked lists of commute corridors in which new express bus service is expected to achieve the most cost efficient reduction in GHG emissions. With the revised models, this analysis needs to be conducted again. In Part I, optimization of new commuter buses was considered under 10 different scenarios. These scenarios were formed based on the combinations of five fare scenarios:

1. No Fare Charged ($F = 0$ $/ride)
2. Flat Fare Charged ($F = 8$ $/ride)
3. Optimized Fare ($F \in [0, 20]$ $/ride)
4. Optimized Fare, with minimum fare of $6 per ride ($F \in [6, 20]$ $/ride)
5. Existing Fares Not Change ($\Delta F = 0$)

with two capital cost scenarios:

A. Capital and Operating Costs ($c_v = 71$ $/veh per day)
B. Only Operating Costs ($c_v = 0$ $/veh per day)

For this study, we focus on the most general case (3A) in which fares are optimized and the total cost of capital and operations is considered. All of the models and analysis that are developed in the following subsections can be applied to the other cases as well, but allowing fare to be optimized over the widest range from $0 (free) to $20 per ride reveals the outcomes that most efficiently reduce GHG emissions. Any constraints on fares cannot lead to a more efficient solution, because constraints can only limit the possible solutions. The results from Part I also showed that the cost scenarios had little effect on the ranking of the OD pairs that are most likely to benefit from new commuter bus service; the main effects are changes in the magnitudes of cost and efficiency associated with each route.

Revised model estimates for commuter buses are calculated with both the expanded models that were developed: including socioeconomic variables in the nested logit model, and adding the regression model to the logit model outputs. Using the regression model introduces a number of challenges, because it can lead to estimates of negative ridership, which is physically impossible. Efforts to constrain estimates to only allow non-negative ridership values introduce additional errors into the model estimates. Although the coefficients from the regression model can provide some useful insights about differences in commuting patterns, the regression model is not suitable for predicting commuter bus demand.

Model estimates using the expanded nested logit model that includes impedance and socioeconomic variables are presented in Table 3.3, Table 3.4, Table 3.5, and Table 3.6. The results represent only minor adjustments to the findings from the Part I study.

Table 3.3: OD pairs ranked by reduction of GHG (AM peak)

Origin	Destination	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
					Drive Access	Walk Access	Total					
FRAMINGHAM	BOSTON CBD	20.5	2	4	8	111	119	12%	-14572	-0.25%	219.32	-0.015
NATICK	BOSTON CBD	16.4	2	0	5	75	79	18%	-14264	-0.38%	271.33	-0.019
RANDOLPH	BOSTON CBD	12.6	2	0	6	95	101	13%	-10490	-0.31%	223.69	-0.021
MILFORD	BOSTON CBD	31.2	1	0	1	11	12	61%	-8665	-0.26%	227.01	-0.026
PEABODY	BOSTON CBD	15.2	2	0	3	58	61	21%	-4786	-0.19%	241.62	-0.050
MILTON	BOSTON CBD	8.5	3	0	9	149	159	12%	-3107	-0.14%	219.80	-0.071
BRAINTREE	BOSTON CBD	11.9	4	4	15	210	225	11%	-2125	-0.05%	227.21	-0.107
WEYMOUTH	BOSTON CBD	14.6	4	18	13	214	226	10%	-1624	-0.03%	-260.39	0.160
BEVERLY	PEABODY	8.3	1	0	1	10	11	70%	-1408	-0.10%	56.02	-0.040
BILLERICA	BOSTON CBD	19.3	2	0	2	30	32	37%	-1318	-0.04%	308.29	-0.234
WOBURN	BOSTON CBD	11.5	2	14	5	97	102	12%	-852	-0.03%	-70.22	0.082
WALTHAM	BURLINGTON	9.6	1	0	1	7	8	83%	-469	-0.03%	72.06	-0.154
GLOUCESTER	BEVERLY	10.1	2	0	2	54	57	23%	-247	-0.01%	151.56	-0.613
NORWOOD	BOSTON CBD	14.7	4	4	12	219	231	10%	-183	0.00%	367.20	-2.006

Table 3.4: OD pairs ranked by efficiency (AM peak)

Origin	Destination	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($/$gCO_2e$)
					Drive Access	Walk Access	Total					
WEYMOUTH	BOSTON CBD	14.6	4	18	13	214	226	10%	-1624	-0.03%	-260.39	0.160
WOBURN	BOSTON CBD	11.5	2	14	5	97	102	12%	-852	-0.03%	-70.22	0.082
FRAMINGHAM	BOSTON CBD	20.5	2	4	8	111	119	12%	-14572	-0.25%	219.32	-0.015
NATICK	BOSTON CBD	16.4	2	0	5	75	79	18%	-14264	-0.38%	271.33	-0.019
RANDOLPH	BOSTON CBD	12.6	2	0	6	95	101	13%	-10490	-0.31%	223.69	-0.021
MILFORD	BOSTON CBD	31.2	1	0	1	11	12	61%	-8665	-0.26%	227.01	-0.026
BEVERLY	PEABODY	8.3	1	0	1	10	11	70%	-1408	-0.10%	56.02	-0.040
PEABODY	BOSTON CBD	15.2	2	0	3	58	61	21%	-4786	-0.19%	241.62	-0.050
MILTON	BOSTON CBD	8.5	3	0	9	149	159	12%	-3107	-0.14%	219.80	-0.071
BRAINTREE	BOSTON CBD	11.9	4	4	15	210	225	11%	-2125	-0.05%	227.21	-0.107
WALTHAM	BURLINGTON	9.6	1	0	1	7	8	83%	-469	-0.03%	72.06	-0.154
BILLERICA	BOSTON CBD	19.3	2	0	2	30	32	37%	-1318	-0.04%	308.29	-0.234
GLOUCESTER	BEVERLY	10.1	2	0	2	54	57	23%	-247	-0.01%	151.56	-0.613
NORWOOD	BOSTON CBD	14.7	4	4	12	219	231	10%	-183	0.00%	367.20	-2.006

Table 3.5: OD pairs ranked by reduction of GHG (PM peak)

Origin	Destination	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
					Drive Access	Walk Access	Total					
BOSTON CBD	FRAMINGHAM	20.5	2	0	9	94	103	19%	-39011	-0.66%	288.32	-0.007
BOSTON CBD	RANDOLPH	12.6	2	6	6	81	87	19%	-28433	-0.59%	153.02	-0.005
FRAMINGHAM	MARLBOROUGH	9.7	1	0	1	13	13	94%	-19111	-0.41%	81.22	-0.004
PEABODY	BEVERLY	8.3	2	0	1	28	29	80%	-18726	-0.70%	116.43	-0.006
BOSTON CBD	MILTON	8.5	2	0	7	85	92	18%	-13933	-0.48%	151.45	-0.011
BEVERLY	GLOUCESTER	10.1	2	0	4	61	65	26%	-12635	-0.31%	156.59	-0.012
BOSTON CBD	MILFORD	31.2	1	0	1	7	8	95%	-11562	-0.36%	217.86	-0.019
FRAMINGHAM	ASHLAND	9.2	1	4	1	14	14	85%	-11371	-0.34%	45.27	-0.004
BURLINGTON	WALTHAM	9.6	1	0	1	11	11	89%	-10563	-0.42%	77.85	-0.007
CAMBRIDGE	WOBURN	9.2	2	0	5	68	73	20%	-9468	-0.45%	165.29	-0.017
BOSTON CBD	ROCKLAND	20.4	1	0	1	9	10	73%	-8974	-0.33%	165.17	-0.018
BOSTON CBD	LAWRENCE	25.9	2	0	2	30	32	45%	-8679	-0.23%	349.77	-0.040
BOSTON CBD	WILMINGTON	17.2	2	0	4	44	48	30%	-8203	-0.28%	243.77	-0.030
BOSTON	BRAINTREE	10.4	3	0	11	147	158	12%	-6509	-0.07%	304.13	-0.047

Table 3.6: OD pairs ranked by efficiency (PM peak)

Origin	Destination	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
					Drive Access	Walk Access	Total					
BOSTON CBD	WEYMOUTH	14.6	1	20	6	51	57	10%	-220	0.00%	-72.12	0.327
BOSTON CBD	BRAINTREE	11.9	4	20	14	180	195	12%	-3168	-0.05%	-275.37	0.087
BOSTON	WINTHROP	9.4	2	12	5	94	99	12%	-581	-0.02%	-38.13	0.066
BOSTON CBD	WOBURN	11.5	2	20	6	82	88	15%	-3665	-0.11%	-130.78	0.036
BOSTON CBD	NORWOOD	14.7	3	16	11	145	156	11%	-2399	-0.04%	-15.97	0.007
LAWRENCE	HAVERHILL	8.5	2	12	4	57	60	23%	-613	-0.02%	-0.33	0.001
BEVERLY	PEABODY	8.3	1	20	1	14	15	64%	-5116	-0.18%	4.95	-0.001
FRAMINGHAM	ASHLAND	9.2	1	4	1	14	14	85%	-11371	-0.34%	45.27	-0.004
ASHLAND	FRAMINGHAM	9.2	1	12	0	12	12	83%	-6738	-0.22%	27.37	-0.004
FRAMINGHAM	MARLBOROUGH	9.7	1	0	1	13	13	94%	-19111	-0.41%	81.22	-0.004
BOSTON CBD	RANDOLPH	12.6	2	6	6	81	87	19%	-28433	-0.59%	153.02	-0.005
PEABODY	BEVERLY	8.3	2	0	1	28	29	80%	-18726	-0.70%	116.43	-0.006
BURLINGTON	WALTHAM	9.6	1	0	1	11	11	89%	-10563	-0.42%	77.85	-0.007
BOSTON CBD	FRAMINGHAM	20.5	2	0	9	94	103	19%	-39011	-0.66%	288.32	-0.007

3.2 Impact of Buses Running on Shoulders

3.2.1 In-Vehicle Travel Time for Commuter Bus Routes

The procedure to quantify the effect of bus-on-shoulder running was implemented for the OD pairs that ranked highly in the base case (see Section 3.1.4). Conducting the analysis only for the top 15 OD pairs rather than all 27,225 pairs (for the 165 by 165 OD matrix) limits the time required for the manual processes of identifying the optimal routes. Of the top pairs, only 6 routes overlap with the identified corridors for bus-on-shoulder running. The effect on travel time is summarized in Table 3.7.

Table 3.7: In-vehicle travel time for bus-on-shoulder scenarios

Origin	Destination	Ideal Length (mi)	Feasible Length (mi)	Inbound Travel Time (min)			Outbound Travel Time (min)		
				Base	Feasible	Ideal	Base	Feasible	Ideal
AM Peak									
BILLERICA	BOSTON CBD	9.9	6.9	45.7	42.5	40.9	35.8	33.6	32.5
FRAMINGHAM	BOSTON CBD	17.2	6.5	44.8	40.9	31.6	31.1	30.2	24.1
MILFORD	BOSTON CBD	17.2	6.5	68.7	65.5	57.9	48.7	47.9	42.7
NATICK	BOSTON CBD	17.2	6.5	40.3	38.0	32.3	29.9	29.3	25.4
PEABODY	BOSTON CBD	7.8	0.8	34.5	34.1	29.0	29.0	27.4	24.5
WOBURN	BOSTON CBD	9.9	6.9	25.8	22.9	21.4	20.2	18.4	17.5
PM Peak									
BILLERICA	BOSTON CBD	9.9	6.9	38.8	36.4	35.2	45.0	41.8	40.1
FRAMINGHAM	BOSTON CBD	17.2	6.5	34.5	32.0	25.9	40.4	38.8	29.4
MILFORD	BOSTON CBD	17.2	6.5	52.2	50.2	45.4	63.9	62.6	54.4
NATICK	BOSTON CBD	17.2	6.5	32.3	30.7	26.8	38.3	37.4	31.4
PEABODY	BOSTON CBD	7.8	0.8	31.8	31.5	27.0	36.2	33.8	29.7
WOBURN	BOSTON CBD	9.9	6.9	21.6	19.5	18.4	25.0	22.4	21.1

The commuter bus routes that overlap the potential bus-on-shoulder corridors are generally able to utilize shoulders for several miles, even in the feasible case. The exception is the corridor from Peabody to the Boston CBD, which uses US-1, because only a small part of the corridor currently has shoulders that are wide enough to make shoulder running feasible.

The base travel times are the in-vehicle travel times for the existing conditions, without shoulder running, and these times are obtained directly from CTPS data. By comparison, the feasible in-vehicle travel times are typically only a few minutes faster. The ideal travel times are a few minutes faster than the feasible ones. The magnitude of travel time savings associated with bus-on-shoulder running depends on the distance that buses can travel on shoulders and the severity of traffic congestion. On the most severely congested routes, speeding up buses by 15 mph can amount to several minutes of travel time savings. By contrast, routes that are already moving at relatively high speeds benefit less from the same increase in speed.

3.2.2 Effect on Commuter Bus Performance

The effect of bus-on-shoulder running on commuter bus ridership, GHG reduction, and efficiency are presented for the feasible and ideal cases in Table 3.8 and Table 3.9.

Table 3.8: Commuter bus performance in corridors with bus-on-shoulder (Feasible Case)

Origin	Destination	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
					Drive Access	Walk Access	Total					
AM Peak												
BILLERICA	BOSTON CBD	19.3	2	0	2	32	34	37%	-10118	-0.29%	292.80	-0.029
FRAMINGHAM	BOSTON CBD	20.5	3	4	10	137	146	14%	-23204	-0.40%	325.15	-0.014
MILFORD	BOSTON CBD	31.2	1	0	1	12	12	61%	-14731	-0.44%	219.80	-0.015
NATICK	BOSTON CBD	16.4	2	0	5	77	82	18%	-21567	-0.58%	261.31	-0.012
PEABODY	BOSTON CBD	15.2	2	0	3	59	62	21%	-5501	-0.22%	239.07	-0.043
WOBURN	BOSTON CBD	11.5	3	14	7	119	126	14%	-1649	-0.05%	-56.38	0.034
PM Peak												
BOSTON CBD	BILLERICA	19.3	1	0	1	15	16	47%	-12109	-0.34%	146.00	-0.012
BOSTON CBD	FRAMINGHAM	20.5	2	0	9	96	105	19%	-45709	-0.78%	279.17	-0.006
BOSTON CBD	MILFORD	31.2	1	0	1	8	8	96%	-13768	-0.43%	214.49	-0.016
BOSTON CBD	PEABODY	15.2	1	0	3	31	34	22%	-9060	-0.35%	120.51	-0.013
BOSTON CBD	WOBURN	11.5	1	20	4	49	52	11%	-172	-0.01%	-102.30	0.594

Table 3.9: Commuter bus performance in corridors with bus-on-shoulder (Ideal Case)

Origin	Destination	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
					Drive Access	Walk Access	Total					
AM Peak												
BILLERICA	BOSTON CBD	19.3	2	0	2	33	35	38%	-14654	-0.42%	285.07	-0.019
FRAMINGHAM	BOSTON CBD	20.5	3	4	12	154	166	16%	-71754	-1.23%	244.33	-0.003
MILFORD	BOSTON CBD	31.2	1	0	1	14	14	61%	-30202	-0.90%	201.45	-0.007
NATICK	BOSTON CBD	16.4	2	0	5	85	90	19%	-40643	-1.10%	236.40	-0.006
PEABODY	BOSTON CBD	15.2	2	0	3	63	66	22%	-18097	-0.73%	214.91	-0.012
WOBURN	BOSTON CBD	11.5	3	14	7	122	128	14%	-6297	-0.20%	-74.20	0.012
PM Peak												
BOSTON CBD	BILLERICA	19.3	1	0	2	17	18	51%	-27706	-0.78%	127.84	-0.005
BOSTON CBD	FRAMINGHAM	20.5	2	0	10	108	118	22%	-85892	-1.46%	234.04	-0.003
BOSTON CBD	MILFORD	31.2	1	0	1	9	10	96%	-29847	-0.93%	195.01	-0.007
BOSTON CBD	PEABODY	15.2	1	0	3	33	35	23%	-14868	-0.57%	109.94	-0.007
BOSTON CBD	WOBURN	11.5	1	20	4	50	54	12%	-1644	-0.05%	-111.11	0.068

Effect on Ridership
The reduction of in-vehicle travel time for buses running on shoulders amounts to less than 3 minutes for feasible cases and less than 8 minutes for ideal cases. Combined with all of the other costs associated with commuting, this amounts to a relatively small change in the expected utility associated with the addition of a commuter bus, and the resulting effect on ridership is modest. A more clear comparison of ridership is shown in Figure 3.5. The variations in the relative magnitudes of the ridership depend in part on the corridor in which each route operates and the characteristics of the alternative modes for the specific OD pair.

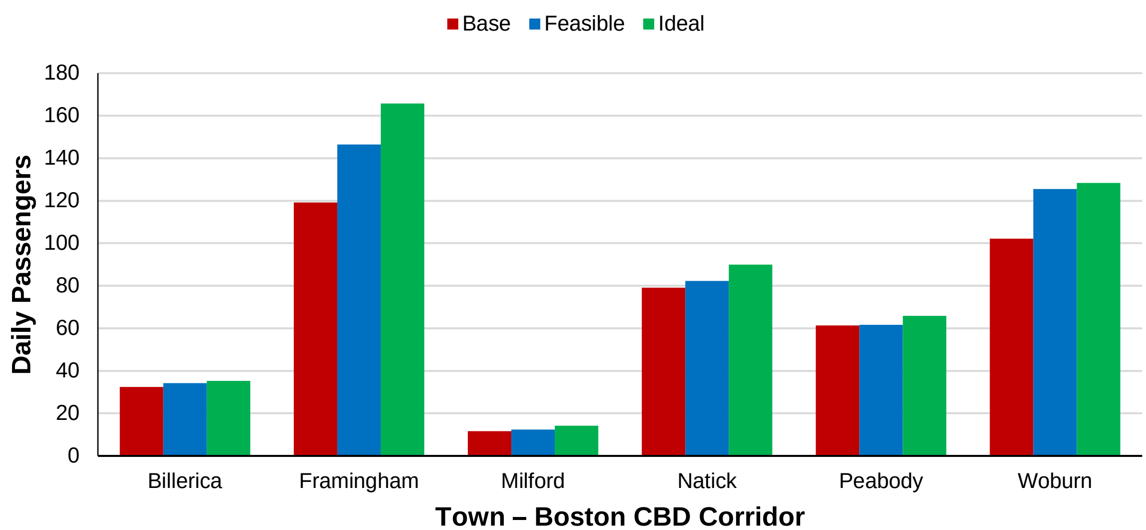


Figure 3.5: Comparison of bus ridership for bus-on-shoulder cases (AM Peak)

Effect on GHG Reduction
The effect of bus-on-shoulder running on GHG reduction is larger compared to the modest effect on ridership. A comparison is shown in Figure 3.6, where more negative values indicate a larger reduction in GHG emissions associated with the introduction of express commuter bus compared to the existing condition (with no commuter bus).

In all cases, the magnitude of GHG emissions reduction is much larger than the increase in commuter bus ridership. This is due to the fact that only part of the emissions reductions are associated with the mode shift of passengers from driving cars. Operating buses at faster speeds is also associated with lower bus emissions per vehicle mile traveled. The EMFAC model (see Figure 1.3) shows that emissions are lowest for buses at highway speeds that are near free flow conditions. As a result, by allowing buses to travel on highway shoulders, the emissions from the new bus operations are reduced.

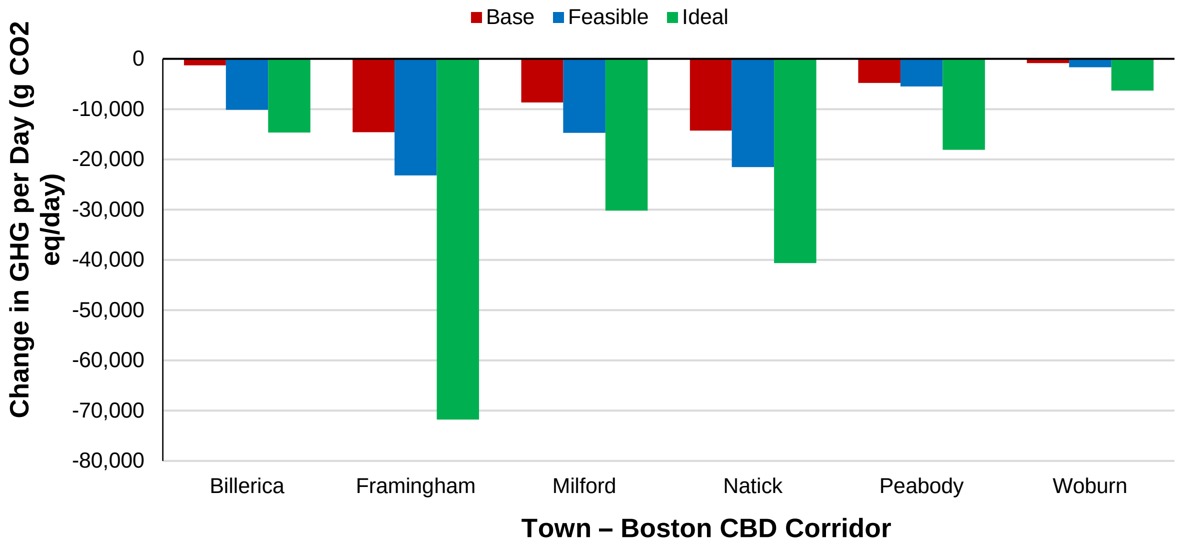


Figure 3.6: Comparison of GHG emissions change for bus-on-shoulder cases (AM Peak)

Effect on Efficiency

Likewise, the greater reduction in GHG emissions corresponds to improved efficiency, as shown in Figure 3.7. The efficiency metric represents the cost per unit of GHG emissions reduced. Negative values indicate an expenditure, so values closer to zero are better. In all cases the greater reduction of GHG emissions associated with bus-on-shoulder running reduces the magnitude of the metric. For the corridors with negative values, this represents an improvement in efficiency. For the case of Woburn, which is associated with an anticipated profit, the smaller magnitude is a consequence of dividing by a larger change in GHG emissions and should not be interpreted as a less desirable outcome.

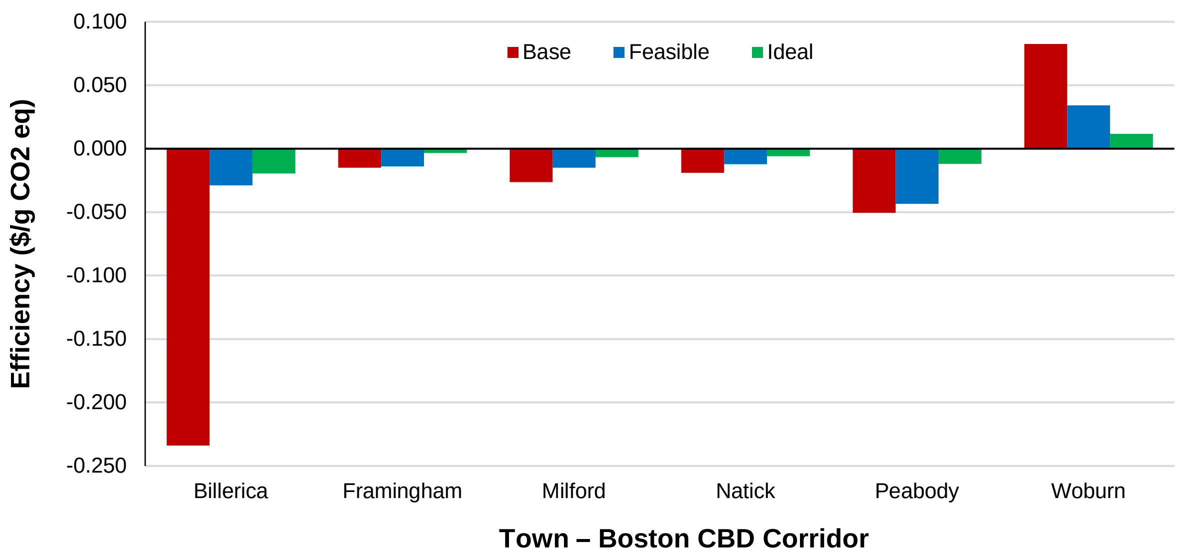


Figure 3.7: Comparison of efficiency for bus-on-shoulder cases (AM Peak)

The effect of bus-on-shoulder running on improving GHG emissions reduction and efficiency is demonstrated here for individual commuter bus routes. If bus-on-shoulder running were actually implemented on the identified corridors, hundreds of other buses would also benefit from bypassing traffic congestion. The improved competitiveness with driving and the reduced emissions from the buses themselves would make the benefits of bus-on-shoulder running much greater than the isolated effect shown in this analysis.

3.3 Impact of Stop Location within a Community

Identification and analysis of specific bus stop locations requires manual consideration of several qualitative factors. The comparison of commuter bus stop locations is considered for two communities, Framingham and Woburn, that consistently appear as ranked contenders for potential express commuter bus service to the Boston CBD; a graphical summary of the potential stop locations in these two towns is shown Figure 3.8. A more detailed view of the stop location, catchment area, and network geometry around each stop is shown in Figure 6.1 through Figure 6.6, in the Appendix. The relevant characteristics of these bus stops are summarized in Table 3.10.

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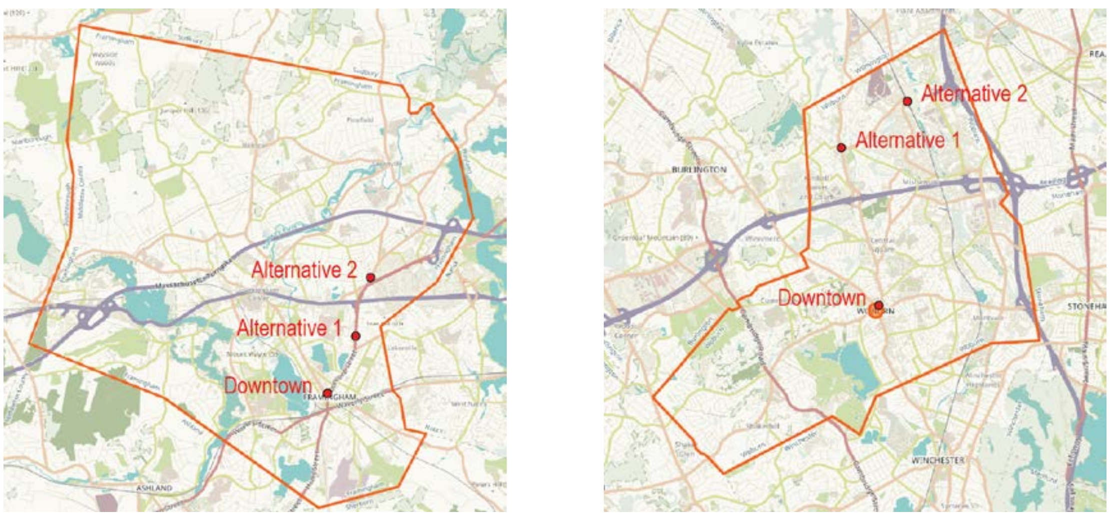

a) Framingham b) Woburn

Figure 3.8: Bus stop locations for detailed analysis

Table 3.10: Bus stop location characteristics

Stop Location	% of Commuters in Catchment Area	AM Travel Time to/from Boston (min)	Network in Catchment Area		Parking
			Length (mi)	% Major Roads	
FRAMINGHAM					
Center: 149 Concord Street	21.2%	46.9 / 31.2	6.1	0%	On-Street
Alternative 1: 541 Concord Street	7.8%	43.9 / 31.2	6.4	0%	On-Street
Alternative 2: 869 Concord Street	10.3%	43.9 / 27.2	5.9	15%	Shopping Center
WOBURN					
Center: 438 MA-38	26.0%	26.8 / 20.2	7.0	1%	On-Street
Alternative 1: 904 MA-38	11.2%	26.8 / 19.2	4.2	0%	On-Street
Alternative 2: 30 Atlantic Avenue	3.2%	27.8 / 18.2	4.6	0%	Park and Ride

The multinomial nested logit mode choice model is re-evaluated using the number of commuters within the bus stop catchment areas and the travel time to and from the Boston CBD. The percentages of commuters in the catchment area that are listed in Table 3.10 apply specifically to the commuters from the town that are traveling to the Boston CBD. Using the methods described in Section 2.3.2, the mode choice model is implemented twice: once for the commuters within the catchment area who may choose to drive or walk to the commuter bus stop, and again for the commuters outside the catchment area who may only drive to the commuter bus. The result is a revised estimate of the ridership for the commuter bus, impact on GHG emissions, and estimated efficiency.

The performance of express commuter bus service associated with different stop locations is compared in using the same schedules and fares optimized for a bus stop located at the centroid of the town. This comparison is illustrated for stop locations in Framingham in Figure 3.9 and Woburn in Figure 3.10. The revised ridership estimates are much lower than in the previous implementations of the model because the limitation on the distance that commuters are willing to walk results in significantly fewer commuters walking to the commuter bus stops. These ridership estimates are more comparable in magnitude with the reported ridership on recently introduced bus service between Framingham and Boston on Metrowest Express, which reported daily ridership averaging 9 passengers per bus dispatch as of January 2019.

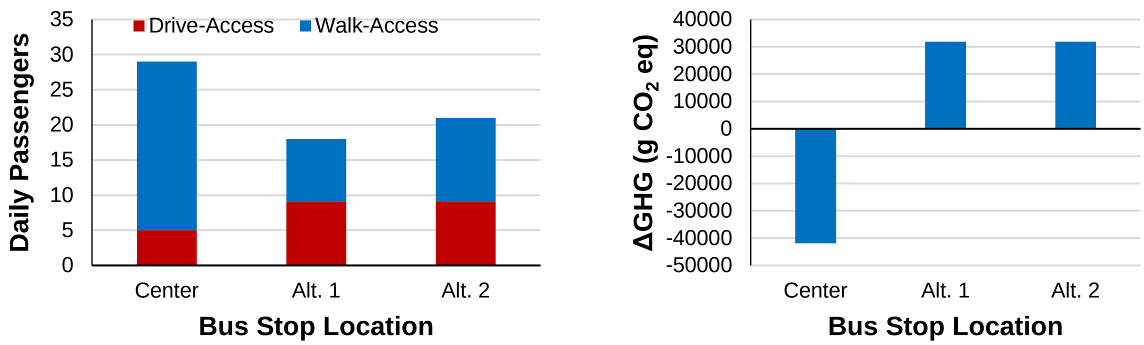

Figure 3.9: Comparison of AM peak ridership and GHG emissions reduction for bus stop locations in Framingham

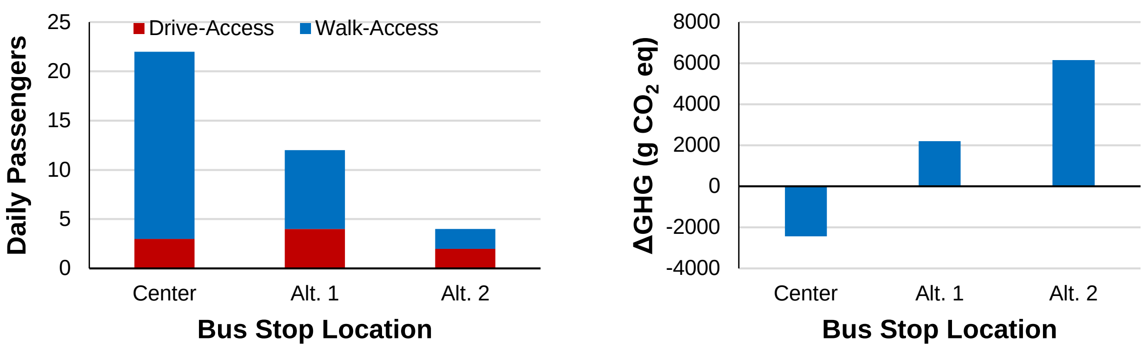

Figure 3.10: Comparison of AM peak ridership and GHG emissions reduction for bus stop locations in Woburn

Table 3.11: Commuter bus performance by bus stop location (AM Peak)

Bus Stop Location	Distance (mi)	Number of Buses, N	Fare, F ($)	Daily Commuter Bus Ridership			% Riders from Driving	Change in GHG (gCO_2e)	% Change of GHG in Corridor	Change in Agency Cost ($)	Efficiency ($\$/gCO_2e$)
				Drive Access	Walk Access	Total					
FRAMINGHAM to BOSTON CBD											
Center: 149 Concord Street	21.4	1	4	5	24	29	36%	-41,492	-0.71%	131.84	-0.003
Alternative 1: 541 Concord Street	20.5	1	4	9	9	18	0%	31,853	1.00%	139.21	N/A
Alternative 2: 869 Concord Street	19.8	1	4	9	12	21	0%	31,853	0.96%	137.34	N/A
WOBURN to BOSTON CBD											
Center: 438 MA-38	11.4	1	14	3	19	22	28%	-2,440	-0.10%	35.84	-0.011
Alternative 1: 904 MA-38	14.0	1	14	4	8	12	42%	2,197	0.04%	62.77	N/A
Alternative 2: 30 Atlantic Avenue	13.7	1	14	2	2	4	100%	6,154	-0.43%	83.09	N/A

The results show that bus stop location has a significant impact on expected ridership, especially for the number of commuters who arrive at the bus stop location by walking. In both Framingham and Woburn, a bus stop location in the town center is likely to attract more than four times as many walk-access commuters as drive-access. Although moving the bus stop to a more suburban location can lead to a small increase in the number of drive-access passengers, the reduction in walking accessibility greatly reduces the total ridership. An important insight from these findings is that the selection of bus stop location can greatly affect the attractiveness of transit as a mode choice for commuters. In fact, the effect of walking accessibility on ridership is much larger than the potential losses from a couple of minutes of increased in-vehicle travel time to and from the town center.

Another important insight from these results is the relationship between GHG emissions savings and bus stop location. The loss of riders associated with moving a commuter bus stop to an inaccessible location, which cannot be reached by safe walking paths, can easily make the difference between a commuter bus service reducing net GHG emissions or increasing net GHG emissions. In both Framingham and Woburn, the town center locations are associated with net reductions in GHG emissions when commuter bus service is introduced. At the alternative (suburban) locations, the change in emissions become positive, because ridership is so low and the commuter bus service does not attract existing drivers, so the new bus operations actually result in increased emissions. For this reason, an efficiency measure is not meaningful for the alternative locations, and it is therefore not calculated

An additional insight from this analysis is that low access cost by walking is of greater importance than a few minutes of additional in-vehicle travel time to the bus stop location. Therefore, it is likely that a commuter bus route that makes a few stops in a community would likely perform very well. For example, the Framingham route appears to be beneficial only if an isolated bus stop is established in the town center. However, the bus stop locations for Alternative 1 and 2 are en route from the town center to the highway (see Figure 3.8), and a commuter bus could stop to pick up passengers at these locations with a minimal increase of in-vehicle travel time for the commuters already on-board. With a minimal increase in in-vehicle travel time for commuter bus operations, it would be possible to increase ridership in a way that would be likely to further reduce GHG emissions and improve efficiency.

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4 Conclusions

This Part II study is an extension of a recently completed study (Part I) to identify the potential for express commuter bus service to reduce GHG emissions associated with transportation in the Greater Boston region. The Part I study involved the development of a mode choice and emissions models based on data for 2,727 TAZs in the Greater Boston area, the parameters of the travel demand model developed and managed by CTPS, and a macroscopic emission factor (EMFAC) model for gasoline-powered cars and diesel buses. The initial study aggregated data to the spatial level of town to form an origin destination matrix with 165 zones, including the Boston CBD. The Part I model showed that there are many commuting corridors for which commuter buses could provide an attractive alternative to driving and result in GHG emissions reduction.

This Part II study addresses some of the limitations and shortcomings of Part I:

1. Heavy reliance on calibration factors for the mode choice model in Part I suggested that there is an opportunity to improve the mode choice model by including socioeconomic parameters.
2. A concurrent MassDOT study of bus-on-shoulder running identified corridors in the regions where buses could potentially bypass congestion by operating on highway shoulders. This presents an opportunity to evaluate the impact of bus-on-shoulder running on the ability of new commuter bus service to attract riders and reduce GHG emissions.
3. Recognizing the that specific location of bus stops is an important consideration for actual implementation of a new commuter bus service, the effect of bus stop location within a town was compared. Specifically, the effect of bus stop location on accessibility for commuters that walk to transit, as well as the impact of bus stop location on ridership, and the resulting effect on GHG emissions reduction were compared.

The conclusions related to each of these study objectives are summarized in the following sections.

4.1 Socioeconomic Variables in the Mode Choice Model

The Part I mode choice model used only the impedance variables from the CTPS nested logit model. These are the variables related to the mode-specific trip characteristics: out-of-vehicle travel time, in-vehicle travel time, and cost. The simplified model that aggregated TAZ-level data into towns and used only these impedance values resulted in estimation errors that had to be corrected with OD-specific calibration parameters. Although the calibration parameters force the model estimates for the existing conditions to match the reported OD flows from CTPS data, they indicate limited explanatory power from the model itself. The model parameters are used to predict commuter bus ridership for which no existing observations exist, because the services are not yet operating. Therefore, an improvement in model fit would provide greater confidence in commuter bus ridership projections.

In this Part II study, the mode choice model was extended in two ways. First, the nested logit model was expanded to include the socioeconomic variables that were included along with the impedance variables in the original CTPS model. These variables are: vehicles per worker, square root of employment density, and walk access fraction. Second, additional socioeconomic variables related to household income and industry sector of employment were used with a regression analysis to explain the errors between the expanded nested logit model estimates and the reported OD flows. The errors left unexplained by both of these model extensions were still corrected with calibration factors, because the same model parameters (as provided by CTPS) are used for all OD pairs in the region.

Analysis of the expanded models, which include socioeconomic variables, led to the following insights and findings:

- Adding socioeconomic parameters to the model leads to only modest improvement in model fit. Calibration factors must still be calculated for each OD pair.
- The expanded nested logit model was consistent with the original TAZ-level CTPS travel demand model. The remaining errors were likely due in large part to the aggregation of 2,727 TAZs into 165 towns and the Boston CBD.
- Household income and industry sector of employment were not included in the original CTPS nested logit model, and the authors did not have access to individual survey data to re-estimate the logit. These variables could only be included in the model as a regression between model estimates and the reported OD flows by mode.
- This regression model demonstrated statistically significant parameters for industry sectors for several modes, but not for household income. Specifically:
    - Commuters employed in utilities and construction; trade; and education, community, and social services were more likely to drive than use transit.
    - Commuters employed in hospitality and entertainment were more likely to walk to transit than to drive.
- The regression model, by mathematical construction, eliminated systematic bias in flow estimates for each mode, however there was still large variance (scatter) in individual estimates.
- The regression model allowed for negative estimated OD flows, which were physically impossible. This created particular challenges for implementation in an expanded model with commuter buses, because it could cause impossible increases in flows on modes other than the commuter bus. Constraining these negative values introduced bias into the model. Therefore, despite some statistical explanatory power, the expanded regression model was not recommended for further analysis, and the updated nested logit model with socioeconomic variables and calibration factors was used for the rest of the analysis.

4.2 Bus-on-Shoulder Running

An analysis of the impact of bus-on-shoulder policies made use of findings from the 2019 MassDOT Bus on Shoulder study *[3]* that identified specific corridors in Greater Boston where buses could potentially operate on highway shoulders. The model of operations was based on the example of Minneapolis, Minnesota, where bus-on-shoulder running is widespread. The policy would allow buses to operate on shoulders that are at least 10 feet wide at speeds up to 15 mph faster than traffic in general lanes in order to bypass congestion. The MassDOT Bus on Shoulder study *[3]* identified three corridors for potential bus-on-shoulder running: I-90 Boston to SR-30 in Wayland, MA; I-93 Boston to SR-125 in Wilmington, MA; and US-1 Boston to Broadway in Saugus, MA.

The analysis of the potential for bus-on-shoulder running led to the following insights and findings:

- In the corridors that have been identified for potential bus-on-shoulder running, only parts of each corridor have sufficiently wide shoulders to make the policy feasible in the short-run with limited investment in infrastructure. Some of the most congested parts of the Boston highway network are also the most spatially constrained, and bus-on-shoulder operations would not be possible in locations without existing shoulder lanes. In these locations, widening highways would be a very expensive infrastructure investment.
- Allowing buses to operate on highway shoulders, whether limited only to feasible links or considering an ideal case with bus-on-shoulder operations through the entire corridor, would lead to modest travel time savings on the order of a few minutes.
- Travel time savings reduced in-vehicle travel time for commuter bus riders, and this led to modest increases in ridership on the order of a few passengers per route per day.
- The reduction in GHG associated with each route was greater than the relative increase in ridership because there were two causes of emission reduction: 1) the shift of passengers from cars to commuter buses is small and results in a small reduction in GHG emissions; 2) increasing the speed of bus operations allows the commuter buses to operate at more efficient speeds (closer to 55 mph) at which emissions per mile are reduced. For example, buses emit 2228 g CO2 eq/mile at 20 mph compared to 1809 g CO2 eq/mile at 35 mph.
- Greater emissions reductions and greater bus operating speeds associated with bus-on-shoulder running led to improved efficiency as more GHG emissions were reduced with lower operating cost. This improvement in efficiency was observed for all corridors that require a net expenditure for commuter bus operations.
- The benefits of bus-on-shoulder running were identified for isolated commuter bus routes in this model. The corridors that were identified in the MassDOT Bus on Shoulder study *[3]* serve hundreds of buses per day. Therefore, bus-on-shoulder running would likely have large benefits for transit ridership and even larger benefits for GHG emissions reduction if implemented. This should justify minor investments in striping and signage that may be required to implement bus-on-shoulder running on existing feasible links.

4.3 Bus Stop Location

A final area of analysis in this Part II study considered the specific location of the commuter bus stop in a community. In the previous analyses, the stop location was assumed to be in the centroid of the town. Out-of-vehicle access time and in-vehicle travel time were calculated as a single average value for all residents. In Part II, this assumption was revised in response to a literature review that shows that commuters are not willing to walk more than 0.25 miles to access a bus stop. By separating the population of commuters into two groups, one within a 0.25 mi walkable catchment area and commuters located outside of the walkable catchment area, the effect that bus stop location has on ridership and GHG reduction could be compared.

The literature review and analysis of stop location led to the following insights and findings:

- The location of a commuter bus stop within a community matters. The number of commuters that are actually able to access a commuter bus stop depends on the proximity of their households to the bus stop. Accessible bus stops are more attractive to commuters for walk-access, and increased accessibility leads to increased ridership.
- From an analysis of bus stop locations in Framingham and Woburn, stop locations in the town center were found to have more commuters with the walk-access catchment area (0.25 miles from the bus stop). As a result, there were more walk-access passengers and fewer drive-access passengers (but more passengers in total) associated with town center bus stop locations.
- Town center bus stop locations tend to have better road network and built environment characteristics that encourage transit ridership in addition to the simple effect of close proximity to commuter households.
- Compared to more suburban stop locations, the increased accessibility of town-center locations led to greater increases in ridership than any negative effect of increased in-vehicle travel time for buses. For Framingham and Woburn, a town center bus stop was associated with a couple minutes of increased in-vehicle travel time but would provide walk-accessibility to more than three times as many commuters.
- Since commuters are more sensitive to the out-of-vehicle access time than in-vehicle riding time, it makes sense to consider making multiple stops in a community. Implementing a commuter bus route with multiple stops would add a couple of minutes of in-vehicle riding time to passengers, which has a very small impact on reducing ridership. Increasing the number of stops would, however, allow many more commuters to be able to walk to the commuter bus, making it a more competitive alternative to driving. This should make commuter bus services more effective at reducing GHG emissions and be able to do so more cost-efficiently.

5 References

1. Christofa, E., E.J. Gonzales, C. Lyman, N. Campbell, and N. Fournier (2018). Commuter Bus Demand, Incentives for Modal Shift, and Impact on GHG Emissions. Final Report. Massachusetts Department of Transportation.
2. California Environmental Protection Agency Air Resources Board (CARB) (2015). *EMFAC2014 Volume III—Technical Documentation*. Retrieved From: https://www.arb.ca.gov/msei/downloads/emfac2014/emfac2014-vol3-technical-documentation-052015.pdf.
3. Massachusetts Department of Transportation (2019a). Bus on Shoulder Workshop, May 8-9. Boston, Massachusetts.
4. United States Census Bureau (2010). 2010 Census. Retrieved From: https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t
5. United States Census Bureau (2017). 2017 American Community Survey. Retrieved From: https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t
6. Central Transportation Planning Staff, CTPS (2016). Boston Region MPO Travel Model: Mode Choice. Technical Memo, CTPS Travel Model Development Group, 24 October.
7. Massachusetts Department of Transportation (2019b). MassGIS Data Layers. Retrieved From: https://www.mass.gov/service-details/massgis-data-layers.
8. United States Census Bureau (2015). Longitudinal Employer-Household Dynamics. Retrieved From: https://lehd.ces.census.gov/data/
9. Fournier, N., E. Christofa, A. Akkinepally, and C. Lima Azevedo (2018). An integration of population synthesis methods for agent-based microsimulation. Paper Number 18-03141. *Transportation Research Board 97th Annual Meeting*, 7-11 January, Washington, D.C.
10. Martin, P., and H. Levinson (2012). *TCRP Report 151: A Guide for Implementing Bus on Shoulder (BOS) Systems*. Transportation Research Board of the National Academies, Washington, D.C.
11. Moniruzzaman, Md. and A. Páez (2012). Accessibility to transit, by transit, and mode share: Application of a logistic model with spatial filters. *Journal of Transport Geography*, 24:198-205.
12. Murray, A.T. (2003). A coverage model for improving public transit system accessibility and expanding access. *Annals of Operations Research*, 123:143–156.
13. Ziari, H., M.R. Keymanesh, and M.M. Khabiri. (2007). Locating stations of public transportation vehicles for improving transit accessibility. *Transport*, 22:99–104.
14. Cervero, R., and K. Kockelman (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D*, 2:199–219.
15. O'Sullivan, S., and J. Morrall. (1997). Walking distances to and from light-rail transit stations. *Transportation Research Record*, 1538:19–26.
16. Rodriguez, D.A., E.M. Brisson, and N. Estupinan. (2009). The relationship between segment-level built environment attributes and pedestrian activity around Bogota's BRT stations. *Transportation Research Part D*, 14:470–478.

17. Corazza, M.V., and N. Favaretto (2019). A methodology to evaluate accessibility to bus stops as a contribution to improve sustainability in urban mobility. *Sustainability*, 11:803.
18. Schlossberg, M., and N. Brown. (2004). Comparing transit-oriented development sites by walkability indicators. *Transportation Research Record*, 1887:34–42.
19. Greater Cleveland Regional Transit Authority, GCRTA (2004). Transit Waiting Environments: An Ideabook for Making Better Bus Stops. Available from: http://www.riderta.com/sites/default/files/twe/TWEIdeabook.pdf
20. Hess, D.B. (2012). Walking to the bus: Perceived versus actual walking distance to bus stops for older adults. *Transportation*, 39:247-266
21. Kittelson & Associates, KFH Group, Parsons Brinkerhoff Quade and Douglas Inc., and J Hunter-Zaworski, K. (2003). *Transit Capacity and Quality of Service Manual*, 2nd ed. Transit Cooperative Research Program TCRP, Washington, DC.
22. Nabors, D., R. Schneider, D. Leven, K. Lieberman, C. Mitchell (2008). Pedestrian Safety Guide for Transit Agencies. Report FHWA-SA-07-017. Federal Highway Administration, Washington, D.C.
23. Schlossberg, M. (2006). From TIGER to audit instruments: Measuring neighborhood walkability with street data based on geographic information systems. *Transportation Research Record*, 1982:48–56.
24. Foda, M.A., and A.O. Osman (2010). Using GIS for measuring transit stop accessibility considering actual pedestrian road network. *Journal of Public Transportation*, 13(4):23-40.
25. Zhang (2015).
26. Dill, J. (2003). Measuring network connectivity for bicycling and walking. Presented at Joint Congress of ACSP-AESOP, Leuven, Belgium.
27. Ontario Ministry of Transportation (1992). Transit Supportive Land Use and Planning Guidelines.
28. Srinivasan, S. (2002). Quantifying spatial characteristics of cities. *Urban Studies*, 39(11): 2005–2028.
29. Holtzclaw, J., R. Clear, H. Dittmar, D. Goldstein, and P. Haas (2002). Location efficiency: Neighborhood and socioeconomic characteristics determine auto ownership and use—Studies in Chicago, Los Angeles and San Francisco. *Transportation Planning and Technology*, 25(1):1-27.
30. Welch, T. F. and S. Mishra (2013). A measure of equity for public transit connectivity. *Journal of Transport Geography*, 33:29-41.
31. Delbosc, A., and G. Currie (2011). Using Lorenz curves to assess public transport equity. *Journal of Transport Geography*, 19(6):1252-1259.
32. Wang, D. (2017). The impact of mass transit on public security—A study of Bay Area Rapid Transit in San Francisco. *Transportation Research Procedia*, 25:3233-3252.
33. Loukaitou-Sideris, A., R. Liggett, H. Iseki, and W. Thurlow (2001). Measuring the effects of built environment on bus stop crime. *Environment and Planning B: Planning and Design*, 28(2), 255–280.

6 Appendix

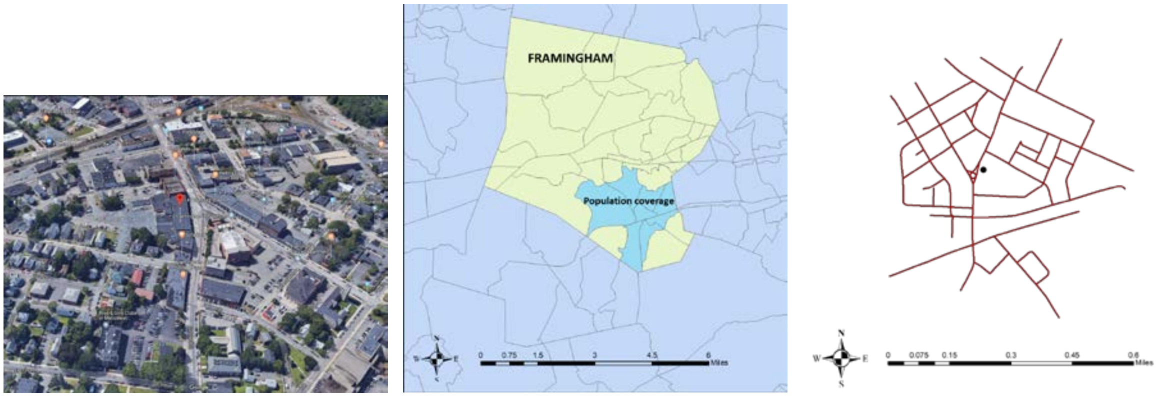
6.1 Review of Transit Stop Literature

Table 6.1: Summary of literature on transit stop accessibility

Indicator	Description	Units	Effect on Accessibility	Source
Network Analysis: Road Classification				
Minor Roads	Total length of minor roads in an area	mi	The longer the total length of minor roads the higher the walkability.	Schlossberg (2006)
Major Roads	Total length of major roads in an area	mi	The longer the total length of major roads the lower the walkability.	Schlossberg (2006)
Minor Road Density	Total length of minor road links over the area size	mi/mi^2	The higher the density of minor roads the higher the walkability (pedestrians have more route options).	Schlossberg (2006)
Minor-Major Road Ratio	Total length of minor over major roads in an area	dimensionless	The higher the ratio the higher the walkability (more viable non-major road options).	Schlossberg (2006)
Network Analysis: Intersection Analysis				
Intersection Density	Number of nodes per unit of area	nodes/mi^2	The higher the value the higher the walkability. Values in the range from 100 to 150 intersections per sq mi qualify areas as highly walkable according to Schlossberg (2006).	Schlossberg (2006), Corazza (2019)
Dead-end Density	Number of nodes per unit of area	nodes/mi^2	The lower the value the higher the walkability.	Schlossberg (2006), Corazza (2019)
Intersection: Dead-end Ratio	Number of intersections over the amount of dead-ends in an area	dimensionless	The higher the ratio the higher the walkability (fewer potential barriers for walkers).	Schlossberg (2006)
Impedance-based Intersection Density	Number of nodes per unit of area when major roads are removed	nodes/mi^2	The higher the value the higher the walkability. When compared to regular intersection density, the higher the difference the higher the impact of major roads on intersection density.	Schlossberg (2006)
Impedance-based Dead-end Density	Number of nodes per unit of area when major roads are removed	nodes/mi^2	The lower the value the higher the walkability. When compared to regular dead-end density, the higher the difference the higher the impact of major roads on dead-end density.	Schlossberg (2006)
Impeded Intersection: Dead-end Ratio	Number of intersections over the number of dead-ends in an area when major roads are removed	dimensionless	The higher the ratio the higher the walkability. When compared to regular ratio, the higher the difference the higher the influence of major streets on pedestrian path connectivity.	Schlossberg (2006)
Change in Intersection: Dead-end Ratio	The difference between the regular and the impeded intersection: dead-end ratio	dimensionless	The higher the value the higher the influence of the unwalkable paths (i.e. major roads) on the area for pedestrians.	Schlossberg (2006)
Network Connectivity	α and γ indexes as in Equation (9) and (10)	dimensionless	The higher the values the higher the walkability (better connectivity). The values of α and γ indexes fall between 0 and 1.	Corazza (2019), Zhang (2005), Dill (2003)
Built Environment: Coverage Area				
Pedestrian Catchment Area	Obtained by dividing the area of a quarter mile (or any distance) by the area of the polygon that results by traveling a quarter mile (or similar distance as before) from the key destination in question.	dimensionless	The higher the values the higher the walkability. A minimum score of 0.50–0.60 (50% to 60% coverage) is a useful threshold. A score less than 0.30 would reflect an inaccessible walking environment (Schlossberg (2006)).	Schlossberg (2006), Corazza (2019)

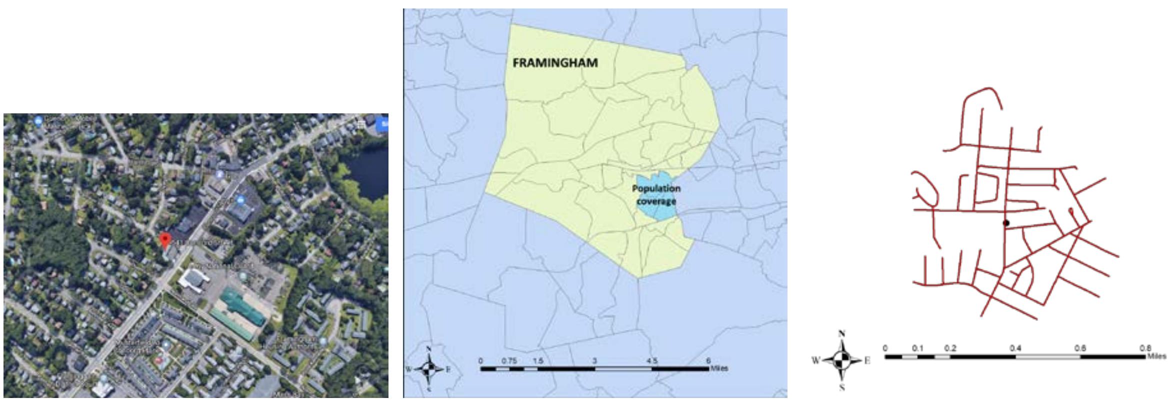
Indicator	Description	Units	Effect on Accessibility	Source
Impeded Pedestrian Catchment Area	Obtained by dividing the area of a quarter mile (or any distance) by the area of the polygon that results by traveling a quarter mile (or similar distance as before) from the key destination in question, after removing major roads	dimensionless		Schlossberg (2006), Corazza (2019)
Ideal Stop Accessibility Index	Obtained by dividing the total length of the pedestrian road network links lying within a walking distance of 0.25 mi measured along the network paths (mi) by the ideal access coverage area of the bus stop measured as a circle with a radius of 0.25 mi and having the bus stop as its center (mi2)	mi/mi^2	The higher the value of the ISAI, the more accessible the bus stop location. (The resulting value of such an index represents the ideal pedestrian road network density within the access threshold from a bus stop.)	Foda (2010)
Actual Stop Accessibility Index	Obtained by dividing the total length of the pedestrian road network links lying within a walking distance of 0.25 mi measured along the network paths (mi) by the actual access coverage area of the bus stop measured on basis of the pedestrian road network serving the same stop (mi2)	mi/mi^2	The higher the value of the ASAI, the more accessible the bus stop location. (The resulting value of such index represents the actual pedestrian road network density within the access threshold from a bus stop.)	Foda (2010)
Stop Coverage Ratio Index	Obtained by dividing the actual access coverage area of the bus stop measured on basis of the pedestrian road network paths (mi2) by the ideal access coverage area measured as a circle with a radius of 0.25 mi and having the bus stop as its center (mi2)	dimensionless	The higher the ratio the higher the walkability (the pedestrian network is closer to the ideal). The index value varies from 0 to 1.	Foda (2010)
Built Environment: Land Diversity				
Dissimilarity Index	In a grid-based approach (3x3 grid cells), the central cell gets points depending on how many of the adjacent eight cells have land use different than the central cell. With K=number of actively developed grid cells in TAZ or tract and Xi = 1 if land use category of the neighboring grid cell differs from grid cell j and 0 otherwise, we have:	dimensionless	The higher the value, the higher the diversity and the higher the attractiveness of the bus service.	Cervero (1997), Zhang (2005)
Land Use Contrast	Land use contrast measures the degree of variation of land use within the study area. With P=co-occurrence matrix, R=total number of cell adjacencies and n=total number of cells in a TAZ, we have:	dimensionless	The higher the mix of land uses, the higher the contrast, and thus the higher the diversity and the attractiveness of the bus service.	Zhang (2005), Srinivasan (2002)
Land Use Entropy	Entropy is calculated based on the proportion of various land uses within the study zone. With P_j the proportion of land use category j in a TAZ or a grid cell and J the total number of land use categories, we have:	dimensionless	The higher the mix of land uses, the higher the contrast, and thus the higher the diversity and the attractiveness of the bus service.	Cervero (1997), Srinivasan (2002), Zhang (2005), Corazza (2019)

6.2 Bus Stop Locations Considered for Analysis



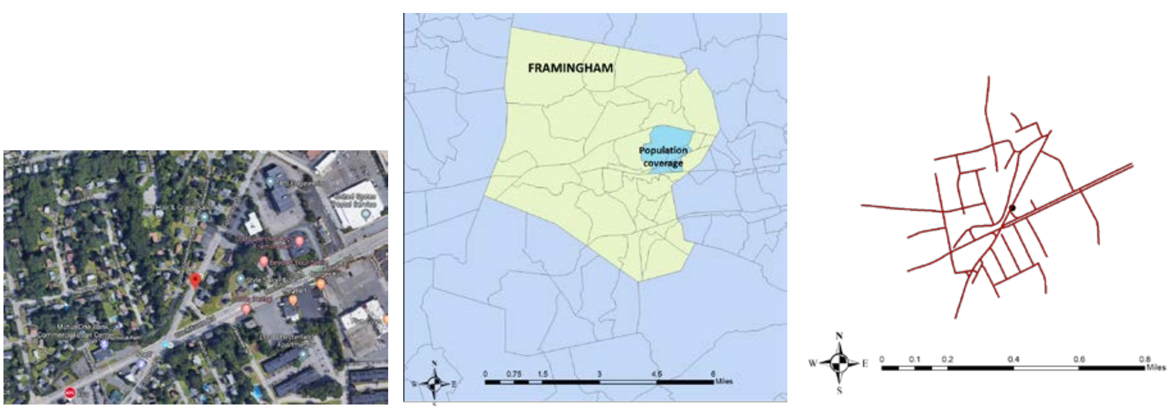
a) Bus Stop Location b) Catchment Area c) Street Network

Figure 6.1: Framingham, Center (149 Concord Street)



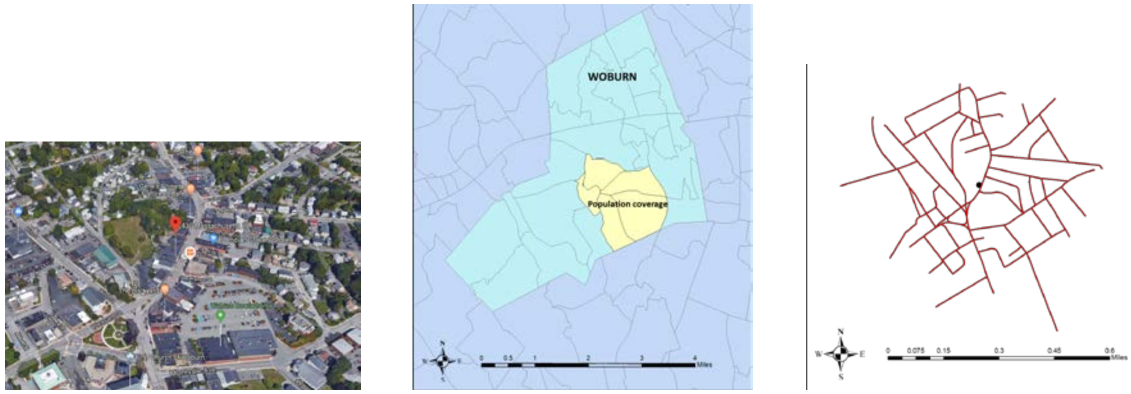
a) Bus Stop Location b) Catchment Area c) Street Network

Figure 6.2: Framingham, Alternative 1 (541 Concord Street)



a) Bus Stop Location b) Catchment Area c) Street Network

Figure 6.3: Framingham, Alternative 2 (869 Concord Street)

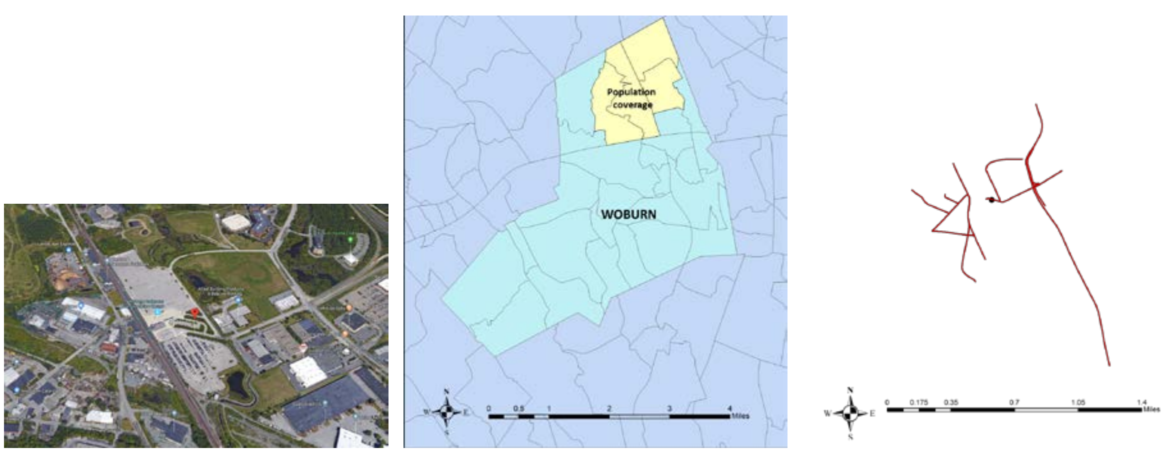


a) Bus Stop Location b) Catchment Area c) Street Network

Figure 6.4: Woburn, Center (430 MA-38)

a) Bus Stop Location b) Catchment Area c) Street Network

Figure 6.5: Woburn, Alternative 1 (904 MA-38)



a) Bus Stop Location b) Catchment Area c) Street Network

Figure 6.6: Woburn, Alternative 2 (30 Atlantic Avenue)